Humanitarian Demining
Innovative Solutions and the Challenges of Technology

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Preface

Landmines (antipersonnel (AP) and anti-tanks mines) and Explosive Remnants of War (ERW), which include unexploded ordnance (UXO) and abandoned explosive ordnance, represent a major threat to civilian. United Nation Department of Human Affairs (UNDHA) assesses that there are more than 100 million mines that are scattered across the world and pose significant hazards in more than 68 countries. The international Committee of the Red Cross (ICRC) estimates that the casualty rate from landmines currently exceeds 26,000 persons every year. It is estimated that more than 800 persons are killed and 1,200 maimed each month by landmines around the world. The primary victims are unarmed civilians and among them children are particularly affected. Worldwide, there are some 300,000-400,000 landmine survivors and this number is increasing. Survivors face terrible physical, psychological and socio-economic consequences. Landmines undermine peace and stability in whole regions by displacing people and inhibiting the use of land for production while subjecting people life to a continuous danger. Besides this, the medical, social, economic, and environmental consequences are immense.

Humanitarian demining demands that all the landmines (especially AP mines) and ERW affecting the places where ordinary people live must be cleared, and their safety in areas that have been cleared must be guaranteed. The canonical approach to humanitarian demining aims to have efficient tools that can accurately detect, locate and deactivate/remove every single landmine and other UXO as fast and as reliable and safe as possible while keeping cost to a minimum level. Any instrument for this process must be 100% reliable for the safety of the operators and the people whom will use the cleared land. The efficient fulfillment of such task with high reliability represents vital prerequisites for any region to recover from landmines and associated battlefield debris by making land safer and allows people to use it without fear.

However, the problem associated with humanitarian demining is characterized by an enormous variability in the nature of explosive ordnance to be removed, climate diversity, and in the type of terrain and vegetation. The terrain to be cleared includes everything from jungle to deserts to mountainsides and every kind of climate. The variety of mines being used is enormous, including many fabricated from sophisticated non-metallic materials. Humanitarian demining is complicated by the fact that unused land for several years in most portions of the world will be covered with substantial vegetation, which makes it impossible to see the ground or to move the detection/clearing equipment freely above the ground. The solution to this problem is very difficult because, given the nature of landmines, the associated problems and the demand for high standards in terms of accuracy and reliability. In addition, landmines are infesting some of the world's poorest countries, where the indigenous personnel available to undertake demining may lack technical skills, experience and education. Although demining has been given top priority, currently mine's detection and clearing operations are a labor-intensive, slow, very dangerous, expensive, and low technology operations. Hence, it becomes urgent to develop detection (individual mine, and area mine detection), identification and removal technologies and creative techniques to reduce false alarms, increase efficiency of demining operations to achieve a substantial reduction to the threat of landmines within a reasonable timeframe and at an affordable cost.

Traditional military countermine techniques and equipment are not directly applicable to humanitarian demining, largely because the philosophy and the standards for successful clearance are different. Technology has become the solution to many long-standing problems, and while current mine detection and clearance technologies may be effective, it is far too limited to fully address the huge complex and difficult landmine problem facing the world. No single approach or technology will soon emerge to offer the complete solution to the landmine crisis. The diversity of the mine threat points out to the need for different types of sensors and equipment to detect and neutralize landmines. Many experts stress the need for a tool-kit that would offer a variety of equipment, which could be combined in different ways for different situations. The challenge is in finding creative, reliable and applicable technical solutions in such highly constrained environment. Improving detection and clearance methods is a formidable technical challenge. The requirements to develop devices and equipment for use by deminers with different training, cultures, and education levels greatly add to the challenge.

Greater resources need to be devoted to demining both to immediate clearance and to the development of innovated detection and clearance equipment and technologies. There is an urgent need to speed up the development to have compact and portable, low cost, technically feasible, fast response, safe, accurate, reliable, and easy to operate mine detector systems that can be reliably used to detect and discriminate accurately all types of available landmines from all the other metal that may be in the ground and support fast and wide area coverage. Appropriate mine clearance technologies are those inexpensive, rugged, and reliable technical products, processes and techniques that are developed within, or should be transferred for use in mine-affected areas. These technologies should be cheap enough to be purchased within the regional economy and simple enough to be made and maintained in a small workshop. We should favor technologies that can be manufactured in mined countries; technologies that are transferable, and which provide employment and economic infrastructure where it is most urgently required.

Developing and applying technology to humanitarian demining is a stimulating objective. To increase mine clearance daily performance by improving productivity and accuracy, and to increase safety of demining operations and personnel, there is a need for an efficient, reliable and cost effective humanitarian mine action equipment with flexible and modular mechanisms, adaptable mobility and equipped with some level of decision making capabilities. Most people in the mine clearance community would be delighted if the work could be done remotely through teleoperated systems or, even better, autonomously through the use of service robots. Searching and removing AP mines seems to be a perfect application for robots. However, this need to have a good understanding of the problem and a careful analysis must filter the goals in order to avoid deception and increase the possibility of achieving results. Many efforts have been recognized to develop effective multi operational mode robots for the purpose to offer flexible, cheap and fast solutions. It is important to remind ourselves that there is little value in a system that makes life safer for the operators but will be less effective at clearing accurately and reliably the ground.

In order to approach proper and practical solutions for the problem, there is a need for the scientists in each discipline and deminers in the field to share their knowledge and the results of their experience and experiments in order to design and test viable solutions for humanitarian demining. Systematic engagement is needed among organizations and members of the demining community. Technologies to be developed should take into account the facts that many of the demining operators will have had minimal formal education and that the countries where the equipment is to be used have poor technological infrastructure for equipment maintenance, operation and deployment.

Innovative solutions and technologies are required and hence this book is coming out to address and deal with the problems, difficulties, priorities, development of sensing and demining technologies and the technological and research challenges. This book reports on the state of the art research and development findings and results. The content of the book has been structured into three technical research sections with total of 16 chapters written by well recognized researchers in the field worldwide. The main topics of these three technical research sections are: Humanitarian Demining: the Technology and the Research Challenges (Chapters 1 and 2), Sensors and Detection Techniques for Humanitarian Demining (Chapters 3 to 8), and Robotics and Flexible Mechanisms for Humanitarian Demining respectively (Chapter3 9 to 16).

Finally, I hope the readers of this book will enjoy its reading and find it useful to enhance their understanding about the problems and difficulties associated with Humanitarian Demining, and helps them to contribute to humanity and initiate new research in the field to help mankind.

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Humanitarian Demining: The Problem, Difficulties, Priorities, Demining Technology and the Challenge for Robotics

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1. Introduction

Landmines and explosive remnants of war (ERW), which include unexploded ordnance (UXO) and abandoned explosive ordnance, represent a major threat to civilian. This demands that all the mines and ERW affecting the places where ordinary people live must be cleared, and safety of people in areas that have been cleared must be guaranteed. UXO is explosive ordnance that has been primed, fuzzed, armed or otherwise prepared for action; that has been fired, dropped, launched, projected, buried, or placed in such a manner as to constitute a hazard to operations installations, personnel or material; and that remains unexploded either by design malfunction, preplanned, abandoned or for any other cause. Landmines are prominent weapons, and they are harmful and effective, yet cheap, easy to make and lay. A typical landmine consists of a firing mechanism, detonator that sets off the booster charge, booster charge (may be attached to fuse, originator, or be part of the main charge), and an explosive charge that constitutes the body of the mine and plastic or metal casing that contains all of the mentioned elements. A landmine is a type of self-contained explosive device, which is placed onto or into the ground to constitute a minefield, and it is designed to destroy or damage, equipment or personnel. A mine detonates by the action of its target (a vehicle, a person, an animal, etc.), the passage of time, or controlled means. A number of fuse activation mechanisms may activate a landmine, such as pressure (step on or drive over), pressure release, movement, sound, magnetic influence (change of magnetic field around the mine), vibration, electronic, and command detonation (remote control).
Landmines can be categorized into two groups, Antipersonnel (AP) and Antitank (AT) mines.

a) AP mines are quite small, weighing a few hundred grams at most. These mines are typically laid on the surface or buried within a few centimeters of the ground surface (Normally but not always, on average 4-50mm), or buried under leaves or rocks. AP mines are widely considered to be ethically problematic weapons with ability to kill or incapacitate their victims and can damage unarmored vehicles. AP mines commonly use the pressure of a person's foot as a triggering means (low triggering pressure), but tripwires are also frequently employed. There exists about 2000 types of landmines around the world; among these, there are more than 650 types of AP mines. Most AP mines can be classified into one of the following four categories: blast, fragmentation, directional, and bounding devices. These mines range from very simple devices to high technology (O'Malley, 1993; US Department of State, 1994). AP minefields are scattered with AT mines to prevent the use of armored vehicles to clear them quickly. The production costs of AP mines are roughly between 1 and 30 US$ while some are more expensive based on the sophistication of the used technology. However, the current cost rate of clearing one mine is ranging between 300-1000 US$ per mine (depending on the mine infected area and the number of the generated false alarms).

b) AT mines are significantly larger with a weight of several kilograms and require more pressure to detonate. AT mines are buried at depths of up to 30 cm below the surface and designed to immobilize or destroy vehicles and their occupants. The high trigger pressure (normally 100 kg (220 lb.) and some are triggered with slightly more pressure) prevents them from being set off by infantry. More modern AT mines use shaped charges to cut through armor. Most modern AT or anti-vehicle mines use a magnetic influence trigger to enable it to detonate even if the tires or tracks did not touch it. AT minefields can be scattered with AP mines to make clearing them manually more time-consuming. Some anti-tank mine types are also able to be triggered by infantry, giving them a dual purpose even though their main intention is to work as AT weapons.

Some minefields are specifically booby-trapped to make clearing them more dangerous. Mixed AP and AT minefields, double-stacked AT mines, AP mines under AT mines, mines with tripwires and breakwires, and fuses separated from mines have all been used for this purpose. Some types of modern mines are designed to self-destruct, or chemically render themselves inert after a period of weeks or months. Conventional landmines around the world do not have self-destructive mechanism and they stay active for long time. Modern landmines are fabricated from sophisticated non-metallic materials. Even more efforts that is radical to develop mines capable of sensing the direction and type of threat. These mines will also be able to be turned on and off, employing their own electronic countermeasures to ensure survivability against enemy countermine operations. In addition, new trends have been recognized in having minefields with self-healing behavior. Such minefields will includes dynamic and scatterable surface mines used to complicate clearance and preserve obstacles by embedding them with capability to detect breaching and simple mobility to change its location accordingly. New, smaller, lightweight, more lethal mines are now providing the capability for rapid emplacement of self-destructing AT and AP minefields by a variety of delivery modes. Minefields may be laid by several means. The most labor-intensive way to lay mines is to have assigned personnel bury the mines. Mines can be laid by specialized mine-laying launchers on vehicles. In addition, mine-scattering shells may be fired by artillery from a distance of several tens of kilometers. Furthermore, mines may be dropped from through both rotary and fixed-wing aircraft, or ejected from cruise missiles.

United Nation Department of Human Affairs (UNDHA) assesses that there are more than 100 million mines that are scattered across the world and pose significant hazards in more than 68 countries that need to be cleared (O'Malley, 1993; Blagden, 1993; Physicians for Human Rights, 1993; US Department of State, 1994; King, 1997; Habib, 2002b). Additional stockpiles exceeding 100 million mines are held in over 100 nations, and 50 of these nations still producing a further 5 million new mines every year. Currently, there are 2 to 5 millions of new mines continuing to be laid every year. The annual rate of clearance is far slower.

The international Committee of the Red Cross (ICRC) estimates that the casualty rate from mines currently exceeds 26,000 persons every year. It is estimated that more than 800 persons are killed and 1,200 maimed each month by landmines around the world (ICRC, 1996a; ICRC, 1996b; ICRC, 1998). The primary victims are unarmed civilians and among them children are particularly affected. Worldwide, there are some 300,000-400,000 landmine survivors. Survivors face terrible physical, psychological and socio-economic consequences as it undermines peace and stability in whole regions by displacing people and inhibiting the use of land for production while requiring extensive healthcare and rehabilitation. For example, in Angola one of every 334 individuals is a landmine amputee and Cambodia has more than 25,000 amputees due to mine blasts (Rosengard et al., 2001). The direct cost of medical treatment and rehabilitation exceeds US$750 million. This figure is very small compared to the projected cost of clearing the existing mines. The major effect of mines is to deny access to land and its resources and subject people life to a continuous danger. Besides this, the medical, social, economic, and environmental consequences are immense (O'Malley, 1993; Blagden, 1993; Physicians for Human Rights, 1993; US Department of State, 1994; King, 1997; ICRC, 1998, Habib, 2002b). The canonical approach to humanitarian demining aims to have efficient tools that can accurately detect, locate and deactivate/remove every landmine, and other UXO as fast and as safe as possible while keeping cost to a minimum. The efficient fulfillment of such a task with high reliability represents vital prerequisites for any region to recover from landmines and associated battlefield debris by making land safer and allows people to use it without fear. Such a process involves a high risk and a great deal of effort and time, which results in high clearance cost per surface unit. However, while placing and arming landmines is relatively inexpensive and simple, the reverse of detecting and removing/destroying them is typically labor-intensive, expensive, slow, dangerous and low technology operation due to their unknown positions. Landmines are usually simple devices, readily manufactured anywhere, easy to lay and yet so difficult to detect.

Applying technology to humanitarian demining is a stimulating objective. Many methods and techniques have been developed to detect explosives and landmines (Habib, 2001a). However, the performance of the available mine detection technologies are limited by sensitivity and/or operational complexities due to type of terrain and soil composition, vegetation, mine size and composition, climatic variables, burial depth, grazing angle, and ground clutter, such as, shrapnel and stray metal fragments that produce great number of false positive signals and slow down detection rates to unacceptable levels. It is almost impossible with the current technology to assure the detection of every single mine that has been laid within an area. It is estimated that the current rate of mine clearance is about 10-20 times lower than the rate of ongoing continuous laying of mines, i.e., for every mine cleared, 10-20 mines are laid. Hence, it becomes urgent to develop detection (individual mine, and area mine detection), identification and removal technologies and techniques to increase demining efficiency by several orders of magnitude to achieve a substantial reduction to the threat of AP mines within a reasonable timeframe and at an affordable cost (Habib, 2007a). Demining is costly and searching an area that is free of mines is adding extra high cost. Hence, the first essential objective should be to identify what areas are mined by having sensing technology that can facilitate surveying and reducing suspected mined-area.

A good deal of research and development has gone into mechanical mine clearance (military and nonmilitary equipment), in order to quickly unearth mines or force them to explode under the pressure. The aim of using machines is typically not to clear land from mines, but to prepare ground for post-machine full clearance. Hence, no equipment has been developed specifically to fulfill humanitarian mine clearance objectives and for this, there is no form of any standalone mechanical mine clearance technologies that can give the high clearance ratio to help achieving humanitarian mine clearance standards effectively while minimizing the environmental and ecological impacts. However, there are positive indications that mechanical mine clearance can highly contribute to the demining process when employing the right technologies and techniques best suited to regional conditions (climate, terrain, type of ordnance, etc.).

Robotized solutions can be helpful to increase mine clearance rate by automating the detection process and contribute to the removal of AP mines. However, this need to have a good understanding of the problem and a careful analysis must filter the goals in order to avoid deception and increase the possibility of achieving results (Nicoud, 1996). Mechanized and robotized solutions properly sized with suitable modularized mechanized structure and well adapted to local conditions of minefields can greatly improve the safety of personnel as well as work efficiency and flexibility. Such intelligent and flexible machines can speed the clearance process when used in combination with handheld mine detection tools. They may also be useful in quickly verifying that an area is clear of landmines so that manual cleaners can concentrate on those areas that are most likely to be infested. In addition, solving this problem presents challenges in robotic mechanics and mobility, sensors, sensor integration and sensor fusion, autonomous or semi autonomous navigation, and machine intelligence. Furthermore, the use of many robots working and coordinating their movement will improve the productivity of the overall mine detection process with team cooperation and coordination.

UXO and abandoned explosive ordnance represent a global challenge as its detection and clearance are difficult and present complex technical problems. The solution to this problem is very difficult and challenging one from a scientific and technical point of view. Greater resources need to be devoted to demining both to immediate clearance and to the development of innovated detection and clearance equipment and technologies. This chapter introduces the problem of mines and its impact. It also, focuses on the aspects of demining, the requirements and the difficulties facing it. Then, the chapter evaluates the available mine clearance technologies along with their limitations and discusses the development efforts to automate tasks related to demining process wherever possible through mechanization and robotization. It aims to evaluate current humanitarian demining situations and technologies for the purpose to improve existing technologies and develop an innovative one. In addition, it introduces solutions and priorities beside the requirements in terms of technical features and design capabilities of a mobile platform that can accelerate the demining process, preserve the life of the mine clearing personnel and enhance safety, and achieve cost effective measures.

2. Military and Humanitarian Clearance Missions

The areas of clearing UXO and the abandoned explosive ordnance missions include Countermine (CM), Explosive Ordnance Disposal, (EOD), Humanitarian Demining (HD), Active Range Clearance (ARC), and UXO Environmental Remediation UER). All areas except HD are classified under military clearance. In relation to demining, the military use the term 'breaching' (the process of undertaken by soldiers to clear a safe path through a minefield that block strategic pathways required in the advance or retreat of soldiers at war) to describe their main mine-clearing concern. It is dictated by the strategies of warfare aiming to speedily clear areas to sustain specific operations, allow an attacking force to penetrate rapidly through mines area as it attacks a target, the pace of this process is very quick as time is a critical factor in military breaching. In military demining, individual mines need not be found, and any clearance rate over 80% is generally considered satisfactory. Military accepts relatively high risk that some of their vehicles and soldiers will still be destroyed and killed during and after breaching has been completed. Military mine clearance equipment tends to be expensive and may be high-tech, large in size, requiring highly trained logistical personnel. The mechanical landmine clearance has been conducted using different type of mechanical machines, such as, ploughs, flails, rollers, tracks, etc.

Humanitarian demining scenarios differ from military ones in many respects. The objectives and philosophy are different in comparison with military demining. Solutions developed for the military are generally not suitable for humanitarian demining. Humanitarian demining is a critical first step for reconstruction of post-conflict countries and it requires that the entire land area to be free of mines and hence the need to detect, locates, uncover and removes reliably and safely every single mine, and other ERW from a targeted ground. The aim of humanitarian demining is to restore peace and security at the community level. It is carried out in a post-conflict context, and the important outcome of humanitarian demining is to make land safer for daily living and restoration to what it was prior to the hostilities. In addition, it is allowing people to use their land without fear; allowing refugees to return home, schools to be reopened, land to be reused for farming and critical infrastructure to be rebuilt (Espirit HPCN, 1997; Bruschini et al., 1999; Habib, 2002b; Goose, 2004).

The standard to which clearance must be achieved is extremely high as there is a need to have at least 99.6% (the standard required by UNDHA) successful detection and removal rate (Blagden, 1993) to a depth of 200 mm from the ground surface, and a 100% to a few centimeter depth according to International Mine Action Standards (IMAS). The amount of time it takes to clear an area is less important than the safety of the clearance personnel and the reliability and accuracy of the demining process. Safety is of utmost importance, and casualties are unacceptable. Any system to be developed should compliment this effort, not to hamper it or simply move the problem elsewhere. The risks to those carrying out the task must also be maintained at a lower level than might be acceptable in a military situation. Another consideration by humanitarian demining is the use of land for development, i.e., there is a need to reduce the environmental and ecological impacts that may results from the demining operation. The currently available technologies are not suited to achieve these objectives of humanitarian demining. Until now, detection and clearance in humanitarian demining very often relies on manual methods as primary procedure. The problem resides primarily in the detection phase first, and then how to increase productivity by speeding up demining process reliably and safely.

3. Landmine Detection and Clearance: The Difficulties

Landmines are harmful because of their unknown positions and often difficult to detect. The development of new demining technologies is difficult because of the tremendous diversity of terrains and environmental conditions in which mines are laid and because of the wide variety of landmines. There is wide range of terrains (rocky, rolling, flat, desert, beaches, hillside, muddy, river, canal bank, forest, trench, etc.) whereas mines are often laid. The environmental conditions may cover different climate (hot, humid, rainy, cold, windy), different density of vegetation (heavy, medium, small, none), and type of soil (soft, sand, cultivated, hard clay, covered by snow, covered with water). In addition, residential, industrial and agriculture areas, each has its own features and needs to be considered.

Landmines are many in terms of type and size. AP mines come in all shapes and colors are made from a variety of materials, metallic and nonmetallic. Metal detector works well with metal cased mines, but metal in modern mines has been increasingly replaced by plastic and wood that making them undetectable by their metallic content. There are many methods to detect explosives and landmines. However, most of them are limited by sensitivity and/or operational complexities due to type of terrain, climatic variables, and ground clutter, such as, shrapnel and stray metal fragments that produce great number of false positive signals and slow down detection rates to unacceptable levels. Soils are contributing to the difficulties as they represent complex natural bodies made up of a heterogeneous mixture of mineral particles, organic matter, liquid and gaseous, materials, etc. In addition soils vary from location to location as a result of soil-forming processes that depend on geological parent material, topography, climate, plant and animal life, and time (Baumgardner, 2000; Hendrickx et al., 2003). IN addition, the spatial variability of soil texture, organic matter, and bulk density has a large impact on soil water variability. However, the performance of a sensor under specific soil conditions can be predicted using a thorough understanding of the physics of the soil-mine-sensor system. Identifying and removing a landmine is a time-consuming and costly process.

AP mines can be laid anywhere and can be set off in a number of ways because the activation mechanisms available for these mines are not the same. Mines may have been in place for many years, they might be corroded, waterlogged, impregnated with mud or dirt, and can behave quite unpredictable. Some mines were buried too deep to stop more organized forces finding them with metal detectors. Deeper mines may not detonate when the ground is hard, but later rain may soften the ground to the point where even a child's footstep will set them off. Trip-wires may be caught up in overgrown bushes, grass or roots. In addition, there is no accurate estimate on the size of the contaminated land and the number of mines laid in it.

4. Humanitarian Demining and the Challenge of Technology

The diversity of the mine threat points out to the need for different types of sensors and equipment to detect and neutralize landmines. The requirements to develop equipment for use by deminers with different training levels, cultures, and education levels greatly add to the challenge. The solution to this problem is very difficult because, given the nature of landmines and the requirements of humanitarian demining, as any instrument must be 100% reliable for the safety of the operators and the people whom will use the land (Blagden, 1993; Habib 2002b). Hence, it becomes urgent to develop detection (individual mine, and area mine detection), identification and removal technologies and techniques to increase the efficiency of demining operations by several orders of magnitude to achieve a substantial reduction to the threat of AP mines within a reasonable timeframe and at an affordable cost.

Technology has become the solution to many long-standing problems, and while current mine detection and clearance technologies may be effective, it is far too limited to fully address the huge complex and difficult landmine problem facing the world. The challenge is in finding creative, reliable and applicable technical solutions in such highly constrained environment. Applying technology to humanitarian demining is a stimulating objective. Detecting and removing AP mines seems to be a perfect application for robots. However, this need to have a good understanding of the problem and a careful analysis must filter the goals in order to avoid deception and increase the possibility of achieving results (Nicoud, 1996). In order to approach proper and practical solutions for the problem, there is a need for the scientists in each discipline and deminers to share their knowledge and the results of their experience and experiments in order to design and test viable solutions for humanitarian demining. Technologies to be developed should take into account the facts that many of the demining operators will have had minimal formal education and that the countries where the equipment is to be used have poor technological infrastructure for equipment maintenance, operation, and deployment.

Greater resources need to be devoted to demining both to immediate clearance and to the development of innovated detection and clearance equipment and technologies. There is an urgent need to speed up the development to have compact and portable, low cost, technically feasible, fast response, safe, accurate, reliable, and easy to operate mine detector systems with flexible mobile platforms that can be reliably used to detect all types of available landmines and support fast and wide area coverage. Appropriate mine clearance technologies are those inexpensive, rugged, and reliable technical products, processes and techniques that are developed within, or should be transferred for use in mine-affected areas. These technologies should be cheap enough to be purchased within the regional economy and simple enough to be made and maintained in a small workshop. We should favor technologies that can be manufactured in mined countries; technologies that are transferable, and which provide employment and economic infrastructure where it is most urgently required.

5. The Core Components of Humanitarian Mine Action Plan

The objective of humanitarian mine action plan is to reduce the risk from landmines to a level where people can live safely where economic, social and health development can occur free from the constraints imposed by landmine contamination, and in which the victims' needs can be properly addressed.

The process of landmine clearance comprises five components (Habib, 2002b),

1. Locate, identify and mark any of the recognized minefields. This includes: Survey, assessment and planning, mapping, prioritization of marked minefields and resources, etc. This should be associated with mine risk education, human skill development and management, public awareness process, information management, safety and benchmark consideration, etc.
2. Prepare the marked minefields for the clearance operation by cutting vegetation and clearance, collecting metal fragments, etc. Area reduction is considered at this component too.

3. Apply suitable mine clearance techniques that suit the relevant minefield to locate and mark individual landmines within the identified area,
4. Remove the threat of the detected mines by neutralization: removal, or detonation,
5. Apply quality control measures (Post clearance inspection). There is a need to verify and assure with a high level of confidence that the cleared area is free from mine.

In parallel to the above, healthcare, rehabilitation, and medical support should be provided to affected persons. In addition, implementing continuous educational and awareness program, infrastructure building, job creation and initiating economical support should be established.

6. Demining Techniques and the Prospect of the Available Technologies

Mine clearance itself can be accomplished through different methods with varying levels of technology and accuracy, but the most laborious way is still the most reliable.

6.1 Manual Mine Clearance

Manual mine clearance represents one of the fundamental components of mine action plan and it has been undertaken in various forms over many decades. Manual mine clearance equipment and techniques have evolved over the years by adapting what were basically military skills to the needs of a specialist, largely civilian activity (GICHD, 2005). Detection and clearance in Humanitarian Demining very often rely on manual methods as the primary procedure that uses ‘prodding’ or ‘probing’ excavation tool within its loop to assure high reliability. The problem resides primarily in the detection phase: once a mine has been found, deminers know well how to remove it or blow it up. When operating in this way the detection phase still relies heavily on metal detectors and/or sniffer dogs, whereby each alarm needs to be carefully checked until it has been fully understood and/or its source removed. This is normally done visually by trained deminer, and by prodding and excavating the ground using long and thin prodders to locate the mine. Sometimes this is the only way to explore the ground, for example when the area is saturated with metallic debris or when the soil is too conductive or magnetic.

Manual demining is still the process that employs the most staff, uses the most resources, and clears the most mines. Manual deminers check the ground inch by inch with a metal detector, a prod and a trowel. Prodder consists of 30 cm long prod that deminer inserts into the soil at a shallow angle (approximately 30 degrees). When the prod touches something hard the operative will begin “feeling” the contour to find out whether it is a rock, debris or a mine. Unfortunately, metal detectors cannot differentiate a mine or UXO from metallic debris. Hence, the contamination of the soil within a minefield by large quantities of shrapnel, metal scraps, etc., leads to have false alarms in the range between 100 and 1,000 for each real mine. Each alarm should be treated as a possible mine and this causes waste of time, induces a loss of concentration, and increases cost.

Manual demining methods are still perceived slow, repetitive, extremely dangerous, expensive, labor intensive and stressful process. At the management level, there are wide variations in the recording of clearance rates (in various soil or vegetation types) and no standardized methodology to calculate the costs and rates of manual mine clearance. Nevertheless, it provides a higher degree of reliability than any other methods and

techniques at present. It has reported an average clearance rate per deminer of about 15-25 square meters a day. Greater emphasis should be placed on hydrating deminers, and thermal and physical comfort to aid their performance. In addition, it is important to consider the use of personal protective equipment as it plays an important role in protecting an individual deminer while certain factors should be considered when using a particular type, as it can impair performance affecting the wearer in several ways (GICHD, 2005).
The lying posture is mandated as the safest posture since it minimizes deminer exposure to danger. Even though lying is safer, deminers in Afghanistan, Bosnian and Cambodian mostly squat or kneel. It is important to consider the proper protection for individual deminer while providing deminers with suitable tool-set to facilitate their work reliably. The tool-set may contain an excavator, an MIT profile probe, a pick-prod, a demining trowel or mini-spade, a brush, shears, mine-markers, root cutters, a tripwire feeler, maintenance tools and a saw. A pulling device is an optional extra. Vegetation clearance in humanitarian demining occurs in two categories, vegetation clearance above and to ground level, and vegetation clearance below ground level (Busuladzic and Trevelyan, 1999). In general practice, the vegetation clearance can be done either manually and/or by mechanical means. Figure 1 shows examples of different manual prodders and different body postures for deminers.

Conventional manual prodder

Prodder with force feedback

Different body posture for deminers

Fig. 1. Examples of different manual prodders and different body postures for deminers

6.2 Mechanical Equipment and Tools for Mine Clearance

A good deal of research and development has gone into motorized mechanical mine clearance in which their early design was influenced by the military demining requirements. The use of such machines aims to unearth mines or force them to explode under the pressure of heavy machinery and associated tools and to avoid the necessity of deminers making physical contact with the mines. A number of mechanical mine clearing machines have been constructed or adapted from military vehicles, armored vehicles, or modified commercially available agriculture vehicles of the same or similar type, with same or reduced size (Habib, 2001b). A single mechanical mine clearance machine can work faster than a thousand deminers over flat fields. They are mostly appropriate and cost effective in large and wide areas without dense vegetation or steep grades. In small paths, thick bush, or soft or extreme hard soil such machines simply cannot maneuver. Mechanical clearance equipment is expensive and it cannot be used on roadsides, steep hills, around large trees, inside a residential area, soft terrain, heavy vegetation or rocky terrain. Mobility and maneuverability where wheeled vehicles cannot travel efficiently on anything other than flat surfaces, tracked vehicles cannot travel in areas with steep vertical walls, machines in general cannot climb undefined obstacles, and machines cannot in general deform to get through narrow entrances. In addition, mechanical clearance has its own environmental impact such as erosion and soil pollution. The logistical problems associated with transporting heavy machinery to remote areas is critical in countries with little infrastructure and resources.

The aim of using machines is typically not to clear land from mines, but to prepare ground for post-machine full clearance by manual and mine detection dog teams (GICHD, 2004) along with other possible technologies. Hence, none of the equipment within this category has been developed specifically to fulfill humanitarian mine clearance objectives and for this, there is no form of any available mechanical mine clearance technologies that can give the high clearance ratio to help achieving humanitarian mine clearance standards effectively while minimizing the environmental impact. It has been suggested that few AP blast mines are left behind in a functional condition after treatment by certain machines in suitable terrain, and in order to achieve better clearance rate, manual deminers and mine detection dog teams should follow up to compensate for the likely residual mine threat left by that machines.

A number of mechanical mine clearing machines have been tested during the past. The general trend goes from "mechanical demining" towards "mechanically assisted demining", adaptable to local circumstances. Some examples of mechanical clearance equipment include but not limited, Vegetation cutters, Flails and Light-Flails, Panther mine clearing vehicle, Armored bulldozer, Ploughs and the rake plough, the M2 Surface "V" mine plow, Earth tillers, Mine sifter, Mechanical excavation, Armored wheel shovel, Mine clearing cultivator, Floating mine blade, Mine rolling, Mine-proof vehicles, Swedish Mine Fighter (SMF), Armored road grader, etc. (US Department of Defense, 1999; Humanitarian Mine Action Equipment Catalogue, 1999; Department of Defense, 2002; Habib, 2002a; GICHD, 2006a). Demining operations conducted by some mechanical machines are showing promising results that need to be enhanced further given suitable conditions against an appropriate target (GICHD, 2004). Figure 2 illustrates examples of some of the available mechanical machines used for demining.

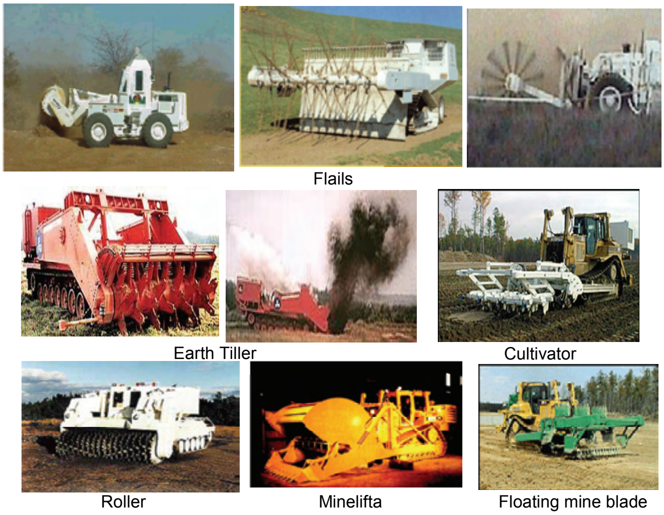


Fig. 2. Examples of demining mechanical machines

In addition, vegetation is a large problem facing demining (mainly in tropical countries) and often poses major difficulties to the demining efforts. The vegetation removal can take up a substantial fraction of the time and for this there is a need to properly mechanized vegetation cutting and removal (See Fig.3 for some examples). These machines should be designed to cut down on the time required for demining. In their simplest form, vegetation cutters consist of adequately modified commercial devices (e.g. agricultural tractors with hedge cutters or excavators). There is an urgent need for effective vegetation clearance technology and techniques that avoid detonating mines.

Examples of Vegetation cutters

Fig. 3. Examples of available vegetation cutters

Cost effective and efficient clearance techniques and mechanisms (flexible and modularized) for clearing both landmines and vegetation have been identified as a significant need by the demining community. Hence, it is important to highlight the importance to extract the clearance potential of current and future mechanical machines in order to use their speed and potential cost-efficiency. In order to enhance the possibility of a successful usage of demining machines, it is important to understand the physical limits imposed upon a demining machine by its operational environment and ecological needs. This would include factors of topography, soil, ordnance type and machine. Furthermore, there is urgent need to standardized method of recording mechanical clearance data (GICHD, 2004) and set up proper benchmarks for evaluations, testings and risk assessment.

6.3 Mine Detection and Sensing Technologies

Mine detection represents the most important step of the demining process, and the quality of mine detector affects the efficiency and safety of this process. The main objective of mine detection is to achieve a high probability of detection rate while maintaining low probability of false alarm. The probability of false alarm rate is directly proportional to the time and cost of demining by a large factor. Hence, it is important to develop more effective detection technology that speed up the detection process, maximize detection reliability and accuracy, reduce false alarm rate, improve the ability to positively discriminate landmines from other buried dummy objects and metallic debris, and enhance safety and protection for deminers. In addition, there is a need to have simple, flexible and friendly user interaction that allows safe operation without the need for extensive training. Such approach needs to incorporate the strength of sensing technologies with efficient mathematical, theoretic approaches and techniques for analyzing complex incoming signals from mine detectors to improve mine detectability. This leads to maximize the performance of the equipment through the optimization of signal processing and operational procedures. Furthermore, careful study of the limitations of any detection device and technology with regard to the location, climate, and soil composition is critically important besides preparing the required operational and maintenance skills. It is important to keep in mind that not all high-tech solutions may be workable in different soil and environmental conditions. The detection technologies are presently in varying stages of development. Each has its own strength and weaknesses. The development phase of new technologies requires a well-established set of testing facilities at the laboratory level that carried out in conditions closely follow those of the mine affected area. In addition, the verification test should be carried out at the real minefield site. This should be followed by extensive field trails in real scenarios to validate the new technologies under actual field conditions for the purpose to specify benefits and limitations of different methods while fulfilling certain benchmark requirements. The work must be performed in close cooperation with end-users of the equipment while real deminers should carry out the test at a real site, in order to ensure that the developments are consistent with the practical operational procedures in the context of humanitarian demining, and that it is fulfilling user requirements. In addition, there is a need to have reliable process of global standard for assessing the availability, suitability, and affordability of technology with enabling technology represented by common information tools that enable these assessments and evaluations. The benchmarking is going to enhance the performance levels that enable the development of reliable and accurate equipment, systems and algorithms.

Most of the available methods to detect explosives and landmines are limited by their sensitivity and/or operational complexities. Methods of detecting mines vary from, simple in technology but exhaustive searching by humans using some combination of metal detectors and manual probing, to a variety of high biological and electronic technologies. Metal detectors find objects containing metal by utilizing a time-varying electromagnetic field to induce eddy-currents in the object, which in turn generate a detectable magnetic field. Old landmines contain metal parts (e.g. the firing pin), but modern landmines contain very small amounts or no metal at all.

Increasing the sensitivity of metal detector to detect smaller amounts of metal results to make it very sensitive to soils with high ferrous content or metal debris often found in war zones and areas where mines may be located. Metal detectors can only succeed in finding anomalies in the ground without providing information about whether an explosive agent is present or not. Another technique that is widely used is the direct detection of explosive material by smell using a dog (Sieber, 1995). Trained dogs are the best known explosive detectors but they need excessive training and inherently unreliable because they are greatly impeded by windy conditions, and have only 50-60% accuracy.

An interesting departure from the use of electromagnetic radiation involves approaches focusing on developing and using detection tools that can identify explosives residue in mined areas as a robust primary indicator with no regards to the mine container. Understanding the behaviors and capabilities of animals, insects and other living creatures, along with close collaboration between biologist and engineers, present unique opportunities for enhancing, genetically manipulating, and creating new capabilities through mimicry and inspiration, developing biosensors through the integration of living and non-living components, such as, genetically engineered bacteria, plants, etc.; and the direct use of complex biological systems, such as dogs, bees, rats, pigs, etc.; with focus to support wide range of applications throughout the process of humanitarian demining (Habib, 2007b).

Detection techniques, for buried low-metal landmines that are in development can be grouped into three main categories: sensors that detect the landmine explosives or chemicals that are associated with the explosives; sensors that recognize an image of the landmine through scattering, and sensors that detect anomalies at the surface or in the soil. Most if not all of these sensors are affected to some degree by soil conditions

New technologies are being investigated to improve the reliability and speedup the detection operation, some of these technologies are: Electromagnetic Induction Metal detectors (EMI), Infrared Imaging, Ground-Penetrating Radar (GPR), Acoustics-to-seismic waves coupling, Acoustic Imaging, Thermal Neutron Activation (TNA), Photoacoustic Spectroscopy, Nuclear Quadrupole Resonance (NQR), X-ray Tomography, Nneutron Back-scattering, Biosensors, Commercial sniffers, etc. (Healy & Webber, 1993; Van Westen, 1993; Hewish & Ness, 1995; Sieber, 1995; McFee, 1996; Cain & Meidinger, 1996; Habib, 2001a, Habib, 2007b).

Mine detection represents the slowest component within the demining process. Currently, there is no single sensor technology that has the capability to attain good levels of detection for the available AP mines while having a low false alarm rate under various types of soil, different weather, all types of mines, natural and ground clutters, etc. If one sensor can detect a mine with a certain success rate coupled with a certain probability of generating a false alarm, could two sensors working together do a better job? The idea of developing multi sensor solutions involving two or more sensors coupled to computer based decision support systems with advanced signal processing techniques is attractive and is advocated by many as a fruitful line of development. Hence, there is a need to use complementary sensor technologies and to do an appropriate sensor data fusion. The ultimate purpose is to have a system that improves detection, validation and recognition of buried items for the purpose to reduce false alarm rates and to overcome current landmine detection limitations. A promising solution will be to apply fusion of sensory information on various sensor outputs through the use of advanced signal processing techniques, by integrating different sensor technologies reacting to different physical characteristics of buried objects. Critical to demining is the ability to distinguish fragments or stones from the target material in real time.

Sensor fusion using soft computing methods such as fuzzy logic, neural networks and rough set theory must be further explored and computationally inexpensive methods of combining sensory data must be designed. These methods should also have the capability to assess the quality of the mined area once the mines have been cleared.

6.4 Robotized solution for Mine detection and Clearance

Many efforts have been recognized to develop effective multi operational mode robots for the purpose to offer flexible, modular, reliable, cheap and fast solutions for the demining operations. The development and implementation of robotics in mine and UXO clearance is attractive and it is building up momentum to spare human lives and enhance safety by avoiding physical contact with the source of danger in mined area, improve accuracy, help in mined area reduction, increase productivity and enhance effectiveness of repetitive tasks such as, probing/prodding, searching patter with sensors, digging, sifting, vegetation removal, etc. Solving this problem presents challenges in robotic mechanics and mobility, sensors and sensor fusion, autonomous or semi autonomous navigation and machine intelligence. In spite of some reported level of success research into individual, mine-seeking robots is still at the early stages. In their current status, they lack flexibility and yet they represent a costly solution for mine clearance operation. But, if designed and applied at the right place for the right task, they can be effective solutions. Four main directions can be recognized in development: teleoperated machines, multifunctional teleoperated robot, demining service robots, and unmanned aerial vehicles.

7. Solutions and Priorities

The priorities for research and development in the field of humanitarian demining require strategies that require to start with the following needs:

a) Develop reliable and accurate techniques/technologies that can enhance the performance of the demining process and allow efficient area detection and reduction of minefields. There is an urgent need to recognize and reliably locate minefields and isolate them by defining proper signs and limits to make the public aware, and to avoid further accidents,

b) Have quality-training programs that fit the needs of local environment. Such training programs need to integrate cultural, environmental and operational considerations when developed,

c) Enhance the safety of deminers by providing them with suitable protective clothing, tools and equipment and isolate them as possible from direct physical contact with the mines and UXOs,

d) Enhance the performance of the sensors and the deminers. To achieve this, there is a need to develop efficient techniques for sensor integration (array of homogeneous and/or heterogeneous sensors) with advance level of data fusion and signal processing algorithms that can confirm the detection in real-time and lead to the identification of mine parameters needed for the next actions.
e) Develop a portable, reliable and easy to use handheld approach to sensor movement that is still required in difficult and physically constraint environments (woods, uneven terrain, residential, etc.) although such approach is slow and hazardous for the individuals. Hence, the sensors can be integrated with vehicle-based platforms to support automatic mine clearance in open areas.
f) Use information and communication technologies with aim to enhance contact, experience exchange, research, planning and to share results and data among all parties and personnel within the demining community.
g) Mechanized vegetation cutting. However, it would be better to find a technology that can detect and mark mines without having to cut vegetation.
h) Develop simple, modular, efficient, compact and low cost mechanical machines for mine clearance that suit the target task and environment aiming to unearth mines reliably and efficiently,
i) Increase mine clearance daily performance by improving productivity, accuracy, and increase safety of demining personnel. There is a need to have a means of moving the portable mine detection device as it searches for landmines. Hence, it is important to automate/mechanize detection and removal of mines, and to improve the safety of the deminers through the use of efficient, reliable and cost effective humanitarian mine action equipment (such as robots, flexible and intelligent mechanisms, etc.), that have minimum environmental impact. It is necessary to have a robot with efficient and modularized surface locomotion and mobility that is well adapted to unstructured environment and different type of terrain. The design should integrate proper balance between maneuverability, stability, speed, and the ability to overcome obstacles. Such robots should have decision-making capability to locate, mark or neutralize individual mine precisely, and
j) To have efficient quality control assurance methods that is reliable and accurate in ensuring that there is no residual mines within an area declared clear of mines.

In order to approach a proper and practical solutions for the problem, there is a need for the scientists in each discipline and deminers to share their knowledge, and the result of their experience and experiments in order to design and test viable solutions for humanitarian demining without ruling out any possible technology or technique.

The challenges associated with configuring humanitarian demining equipments are many. Technologies to be developed should take into account local resources and the facts that many of the demining operators will have had minimal formal education and that the countries where the equipment is to be used have poor technological infrastructure for equipment maintenance, operation, and deployment. The resultant system must be inexpensive and easy to use with minimal training by locals. In addition, the equipment must be flexible and modular to address a variety of clearance tasks and for case-by-case scenarios. Furthermore, the logistical support of the equipment must be consistent with third world countries.

8. Robotics and Humanitarian Demining: The Challenge and Requirements

The portable handheld mine detection approach to sensor movement is slow and hazardous for the individual deminers. Armored vehicles may not thoroughly protect the occupants and may be of only limited usefulness in off-road operations. Most people in the mine clearance community would be delighted if the work could be done remotely through teleoperated systems or, even better, autonomously through the use of service robots. Remote control of most equipment is quite feasible. However, the benefit of mounting a mine detector on a remotely controlled vehicle should have careful considerations that lead to decide whether the anticipated reduction in risk to the operator justifies the added cost and possible reduction in efficiency. A cost analysis should be made to determine to what extent remote control approach is a valid solution.

To increase mine clearance daily performance by improving productivity and accuracy, and to increase safety of demining operations and personnel, there is a need for an efficient, reliable and cost effective humanitarian mine action equipment with flexible and adaptable mobility, and some level of decision making capabilities. Such equipment should have selectable sets of mine detectors and work to locate and mark individual mines precisely, and at a later stage to neutralize the detected mines. Robotics solutions properly sized with suitable modularized mechanized structure and well adapted to local conditions of minefields can greatly improve the safety of personnel as well as work efficiency, productivity and flexibility. Robotics solution can range from modular components that can convert any mine clearing vehicle to a remote-controlled device, to prodding tools connected to a robotic arm, and to mobile vehicles with arrays of detection sensors and area mine-clearance devices. The targeted robot should have the capability to operate in multi modes. It should be possible for someone with only basic training to operate the system. Robots can speedup the clearance process when used in combination with handheld mine detection tools, and they are going to be useful for quick verification and quality control. To facilitate a good robot performance in the demining process, there is a need to employ mechanized systems that are able to remove obstructions that deter manual and canine search methods without severely disturbing soil. Solving this problem presents challenges in the robotics research field and all relevant research areas.

Robotics research requires the successful integration of a number of disparate technologies that need to have a focus to develop:

a) Flexible mechanics and modular structures,
b) Mobility and behavior based control architecture,
c) Human support functionalities and interaction,
d) Homogeneous and heterogeneous sensors integration and data fusion,
e) Different aspect of fast autonomous or semi-autonomous navigation in a dynamic and unstructured environment,
f) Planning, coordination, and cooperation among multi robots,
g) Wireless connectivity and natural communication with humans,
h) Virtual reality and real time interaction to support the planning and logistics of robot service, and
i) Machine intelligence, computation intelligence and advanced signal processing algorithms and techniques.

Furthermore, the use of many robots working and coordinating their movement will improve the productivity of overall mine detection and demining process through the use of team of robots cooperating and coordinating their work in parallel to enable parallel tasks (Gage, 1995; Habib, 1998).

The possible introduction of robots into demining process can be done through surface preparation and marking, speeding-up detection, and mine removal or neutralization. In addition, service robots can be used for minefield mapping too. However, the cost of applying service robot's technologies and techniques must be justified by the benefits it provides. There is no doubt that one of the major benefits would be the safety, by removing the operator from the hazardous area.

It is clear that the development of a unique and universal robot that can operate under wide and different terrain and environmental conditions to meet demining requirements is not a simple task. In the short term, it appears that the best use of robotics will be as mobile platforms with arrays of mine detection sensors and area mine clearance devices. Teleoperations are promising but are limited too, because their remote human controllers have limited feedback and are unable to drive them effectively in real time. There are still some doubts whether such equipment will operate as effectively when the operator is at a long distance or has been removed altogether. Strangely enough, this is particularly true for urban areas normally full of rubble, while agricultural areas seem to be better, but that is not always true. A possible idea in using robots for demining is to design a series of simple and modularized robots, each one capable of performing one of the elementary operations that are required to effectively clear a minefield. An appropriate mix of such machines should be chosen for each demining task, keeping in mind that it is very unlikely that the whole process can be made fully autonomous. It is absolutely clear that in many cases, the environment to be dealt with is so hostile that no autonomous robot has any chance to be used in mid and short terms. The effort devoted to robotic solutions would be more helpful if it is directed at simple equipment improvements and low-cost robotic devices to provide some useful improvements in safety and cost-effectiveness in the short to medium term.

Several practical difficulties in using robots for mine clearance have been highlighted (Treveylan, 1997). There is little value in a system that makes life safer for the operator but which will be less effective at clearing the ground. Accordingly, a serious evaluation and analysis should be done along with having efficient design and techniques. The high cost and sophisticated technology used in robots which required highly trained personal to operate and maintain them are additional factors limiting the possibilities of using robots for humanitarian demining. In spite of this, many efforts have been recognized to develop effective robots for the purpose to offer cheap and fast solution (Nicoud & Machler, 1996; Habib, 2001b).

Before applying robotics technology for the mine clearance process, it is necessary to specify the basic requirements for a robot to have in order to achieve a better performance. These requirements include mechanisms, algorithms, functions and use.

a) It is essential to design a robot that will not easily detonate any mines it might cross on its way, i.e., to apply ground pressure that will not exceeds the threshold that sets off the mines in question. Ground pressure is recognized as an important constraint on a demining vehicle, because ground pressure is what disturbs the ground and triggers many landmines. If a demining vehicle is to safely traverse a minefield, it must exert as low a ground pressure as possible (less than 10 kg). Preferably this would be lower than the minimum pressure value, which would detonate a mine.

b) The robot should be able to cross safely over the various ground conditions. This can be achieved by having adaptable and modular locomotion mechanism both for the mobility and structure. The mechanical structure of the robot should be simple, flexible and highly reliable.

c) The robot must be practical, low purchased cost and cheap to run, small, lightweight, and portable.

d) The robot should have efficient surface locomotion concept that is well adapted to unstructured environment. The design should assure proper balance between maneuverability, stability, speed, and the ability to overcome obstacles.

e) It should employ multi sensors system for detecting and recognizing different mines.

f) It should have suitable mechanism for self-recovery for some levels of the problems that it might face during navigation and searching for mines.

g) Design considerations should be given to have a robot that can resist water, sand, temperature and humidity.

h) The mechanical design of the robot should consider practical technology and should be as simple and low in technology so that anyone can find and replace and possibly make it using locally available materials, such as, bicycle components, bamboo, etc.

i) The robot should work in more than one operational mode, such as teleoperated, semi-autonomous, and autonomous modes while keeping the deminer out of physical contacts with mine areas. Operator safety should be guaranteed.

j) In case of accidentally triggering a mine, the robot should be capable of withstanding the explosive blast without suffering major damage. At the minimum the high tech parts of the robot that cannot be replaced locally should be well protected.

k) The robot should be easy to maintain in terms of service and repair by indigenous users. Ease of maintenance is built in at the design stage so that if repair is ever necessary it may be carried out locally without the use of special test equipment or specialized staff. The robots need to be tested and deployed with minimum cost.

l) Sustaining a reasonable power supply to enable the robot to operate for long period.

m) Efficient navigation techniques with sensor based localization in the minefield, and man-machine-interfaces including the ergonomy of lightweight portable control stations with friendly user interface.

Research into individual, mine-seeking robots is in the early stages. In their current status, they are not an appropriate solution for mine clearance. This is because, their use is bounded by sensing devices and techniques improvements, the difficulties facing automated solutions raised by the variety of mines and minefields, and the variety of terrains in which mine can be found. Examples of such terrains may include dessert, sides of mountains, rocky, forest, rice paddy, riverbanks, plantations, residential areas, etc. Also, robotized solutions are yet too expensive to be used for humanitarian demining operations in countries like Angola, Afghanistan, Cambodia, etc.

9. Robotization of Humanitarian Demining

Many efforts have been recognized to develop effective robots for the purpose to offer cheap and fast solutions. Three main directions can be recognized:

1. Teleoperated machines,
2. Multifunctional teleopeated robot,
3. Demining service robots, and
4. Unmanned Aerial Vehicles and Airships.

9.1. Teleoperated Machines

9.1.1 Light-Flail

Smaller and cheaper versions of the flail systems are developed with chains attached to a spinning rotor to beat the ground and integrated with remotely controlled, line-of-sight, skid loader chases. The use of light-flails aim to safely clear light to medium vegetation, neutralize AP-mines and UXOs from footpaths and off-road areas, and assist in area reduction of minefield (See Fig. 4). These machines are developed to provide a capability to remotely clear AP mines and proof areas that have been cleared (Humanitarian Demining Developmental Technologies, 1998; GICHD, 2006a). The design of such machines was in particular for dealing with vegetation clearance and tripwires as a precursor to accelerate manual clearance. These flail systems are not designed for heavily vegetated or extremely rough terrain. Some systems can clear AP mines from off-road locations and areas that are not accessible by larger mechanical mine clearing equipment. The light-Flail can defeat bounding, tripwire, fuzzed, and simple pressure AP mines. In addition, these machines have flail clearance depth between 150mm and 200mm and range of working width between 1.4m and 2.22m. These machines are designed to withstand blasts up to 9 kg of TNT. They are remotely controlled up to a range of 5,000m through feedback sensors and up to 500m away (line-of-sight distance) if it is working in an open space. An armored hood is available to protect these machines against AP mine blasts. Furthermore, there are set of tracks for installation over the tires when working in soft soil conditions to improve traction. Different machines made by different manufacturers with almost similar concept are available and have been used in real minefields. Some of these are (Humanitarian Demining Developmental Technologies, 1998; GICHD, 2006a; Croatia Mine Action Centre, 2002; Danielsson et al., 2003; Danielsson et al., 2004; Leach, 2004):

a) Two machines of Armtrac 25 are in service with the UK Ministry of Defense with no information for actual usage in a real minefield,
b) More than 110 Bozena machines have been produced. These machines have been, or are currently, in service in Afghanistan, Albania, Angola, Azerbaijan, Bosnia and Herzegovina, Cambodia, Czech Republic, Eritrea, Ethiopia, Iraq, Kenya, Kosovo, Lebanon, The Netherlands, Poland, Slovakia, Sri Lanka, and Thailand,
c) The Compact Minecat 140 was developed in 2001 as a direct follow-up improvement of the MineCat 230 and has not yet been used in real minefields,
d) There are 62 MV-4 light flails have been purchased by various organizations/demining companies. Some of the organizations are, US Army (21 units), Swedish Army (5 units), Croatian Army (2 units), Irish Army (2 units), International Mine Action Training Centre (IMATC) Kenya (1 unit), Croatian Mine Action Centre (CROMAC) (4 units), Iraqi National Mine Action Authority (4 units), Norwegian People’s Aid (NPA) (3 units), Swiss Foundation for Mine Action (FSD) (5 units), etc,
e) Mini-Flails have been tested extensively in Kuwait, Bosnia, Kosovo, and Jordan. Currently, Six Mini-Flails are deployed today in the Balkans, and four systems are

deployed in Afghanistan. The new version `Mini-Deminer` incorporates improvements to the problems associated with the U.S. Army's original Mini-Flail identified during field evaluations. Development testing of the Mini-Deminer took place during the spring and summer of 1999, and

f) There is no information available by the manufacturer on the actual usage of Diana 44T machine in real minefields.

All light flail machines are featured by, small and compact in size, ease to transport on a light trailer, remotely controlled, ease of maintenance and repair, powerful engine with efficient cooling system, etc.

Light flail machines have difficulties to operate with precision from a long distance (this applies to all remotely controlled machines), as they require line of sight operation with suitable feedback. The ground flailing systems creates large dust clouds and the high vegetation will restrict operator's view on the machine. They also exhibit difficulty in flailing in soft soil, and can inadvertently scatter mines into previously cleared areas. All machines are not intended to be used in areas where AT mines are present, and they may not be usable in steep or rocky terrain.

(a) Armtrac 25. (Armtrac Ltd., United Kingdom)

(b) Bozena 4 (WAY Industry J.S. Co, Slovak Republic)

(c) Mini-flail. (US Department of Defense)

(d) Diana 44T (Hontstav S.R.O., Slovak Republic)

(e) Minecat 140. (Norwegian Demining Consortium)

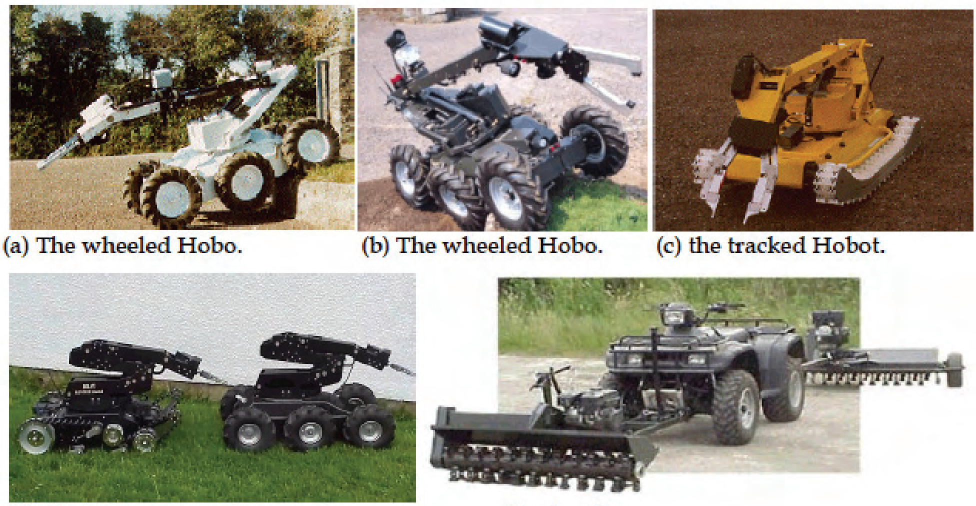
(f) The MV-4. (DOK-ING d.o.o., Croatia)

Fig. 4. Different types of light flails in action

9.1.2 Remotely Operated Vehicles (Kentree Limited)

Kentree Limited has been designing and manufacturing variety of remotely operated vehicles. Hobo was the early developed vehicle and it has a reasonable maneuverability, 6 robust heels to allow carriage goes over obstacles and through water. Many updates have been introduced to meet the continued requirements in Explosive Ordnance Disposal (EOD)/Improvised Explosive Device Disposal (IEDD) applications and those required in

battle zones, nuclear, chemical or fire fighting situations. The most apparent are the articulating rear axle and the Radio Control. The tracked chassis has a front ramp section which lowers to provide a variable footprint. With this additional traction, the vehicle negotiates slopes, stairs and steps with ease. Hobot is the track version of Hobo for use in areas where tracks are the required option as in certain nuclear or chemical environments. The dimension of Hobo L3A15 is L= 148.3cm, W= 70.76cm and H= 88.81cm, the vehicle weight when empty is 228 kg, the payload of the arm is 30 kg, and the maximum speed is 4km/h. Other teleoperated vehicle developed by Kentree includes, Vegabond, Rambler, Max, Brat, Tramp and Imp.
One of the latest additions to the Kentree family of vehicles is the "Thrasher" mobile vehicle designed for the purpose of demining. Kentree and the Irish armed forces are developing Thrasher as cost-effective solution for demining operations. Thrasher is small and it is capable of dealing with narrow laneways. The remotely controlled route clearance flail system is aimed at clearing a 4 feet wide path of booby traps and AP mines to allow safe personnel passage. The vehicle can also be fitted with an offset rear flail attachment, to increase the beat area to 8 feet. This will allow the access of small transport vehicles. The ROV can be controlled via secure radio link from the front passenger seat of a jeep by means of a laptop control console with video feed to virtual reality goggles. Alternatively, it may be operated by backpack style system with hand control for foot-mounted demining operations. No information for demining testing and evaluation is available. Figure 5 shows Hobo, Hobot and Thrasher robots.



(a) The wheeled Hobo. (b) The wheeled Hobo. (c) the tracked Hobot.

(d) The Brat. (e) Thrasher.

Fig. 5. Remotely operated vehicles from Kentree

9.1.3 Pookie

The Pookie has been co-developed and manufactured by Trevor Davies Engineering. The robot named Pookie because of its resemblance to the small wide-eyed African bush baby.

Pookie is a manned vehicle with a possibility to be teleoperated by simply extending its functionalities. Pookie was constructed on a lightweight chassis and carried a one-person armor-plated cab. The cab had a V-shaped undercarriage designed to deflect any blast away from the driver and to combat centre blast mines. The wheels were positioned some distance from the cab, again to protect the driver in the event of detonation by offsetting the seat of explosion. The crucial difficulty was how to avoid detonating the mine and thereby avoid destroying or damaging the detecting vehicle. The solution was to house the wheels of Pookie with the widest and softest tires available, such as Formula One racing tires, to give the Pookie a low pressure they exert a minimum ground force. The width of the tires, in any case, spanned most landmine holes, lessening the chance of a detonation. In addition, the Pookie was propelled by an engine from a Volkswagen Beetle that was capable of taking Pookie to mine detection speeds of up to 60 kilometers per hour. Two drop-arm detectors were mounted left and right and equipped with a detection system that bounced magnetic waves into the ground as well as an acoustic signal to indicate metal.

On first trials, even though Pookie did detonate AP mines and several booby-trapped AT mines in action with the Rhodesian army, this was only at the cost of new wheels and rim replacements. In stage two of Pookie project, trials were conducted combining Pookie with 5 GPRs. These were held in Somaliland. While the results show some promise, it indicate that Pookie would need additional enhancement to do a better job.

As of the second phase of Pookie (Lawrence, 2002), the VW engine was replaced by a hydraulic pump system, a Hatz 40 Horsepower hydraulic motor manufactured in Germany and used on numerous small vehicles in the mineral mining world. The motor is capable of traveling at 10 kilometers per hour, slow for the movement of a Pookie between targets, but a good average speed for quality GPR data gathering. Pookie was set to run on slightly inflated tiers, delivering a weight distribution that exerts a pressure of only four pounds per square inch per wheel on the road surface. The 5 GPRs sensors were fixed to Pookie with aluminum spars designed to overhang the front of Pookie by approximately 1.5 meters. Each sensor is covering a width of 40 centimeters giving a total width of coverage of two meters. The data was integrated to a GPS to give a position that was then translated to a distance measurement along the road. The system recorded both distance from the start point to target and distance in from the edge or verge. A small tachometer mounted on the rear drive axle was used to pinpoint the position of potential mines with an accuracy of up to one meter at 1000 meters. In addition, a hydraulic steering system and steering ram have been used with the new version of Pookie. Figure 6 shows the development phases of Pookie.

In 2001, Pookie was used to scan location on roads in Senafe, Eritrea with two objectives. The first objective was specifically to test the operational issues of the whole system and its performance as a means of gathering data along suspect roads, and the second aimed to assess the steps required to link a Pookie/GPR demining solution to international demining standards. The trail tests of Pookie shows that Pookie had difficulty performing in very stony conditions. The "Formula One" tires are good for most roads experienced in Eritrea. However, if seriously rocky terrain is to be surveyed, a durable tire is needed. Finally, MineTech is also investigating the role of Pookie as a platform for a broad loop metal detector, and a prototype system is currently under construction.

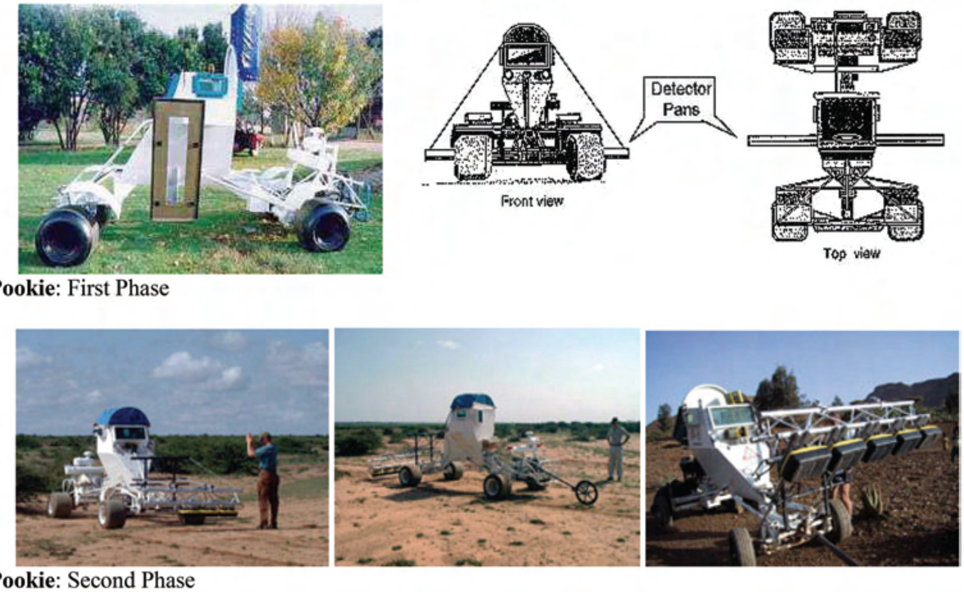


Fig. 6. Development phases of Pookie

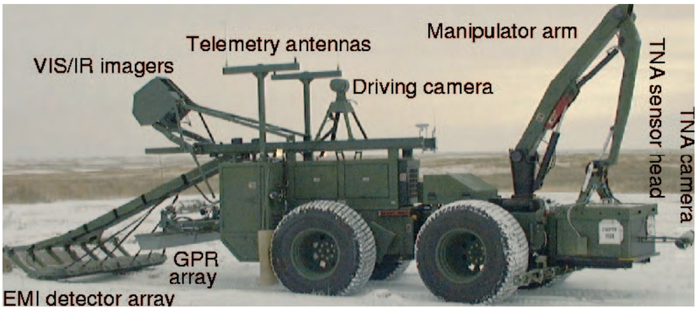
9.1.4 Vehicle Mounted Detection System (VMDS)

This system detects on/off-road landmines using a multi-sensor mine detection suite mounted on a commercial skid steer chassis platform modified to incorporate a remote control capability. This system provides deminers with the ability to detect antipersonnel and antitank mines with minimal metal content using a flexible metal detection array for close-in detection and infrared (IR) and ultraviolet (UV) sensors for standoff detection. The VMDS sensor package consists of a 2m wide Schiebel metal detection array, a Thermal-Neutron Analysis (TNA) sensor and infrared (IR) sensor. The 2m arrays detect metal objects in the vehicle's path, while the TNA indicates those targets that contain explosives. In testing, the 2m-detection array performed well. The TNA found most Anti Tank mines, but had difficulty identifying Antipersonnel mines and proved very complicated to operate. The prototype was built to conduct testing in 1995.

Fig. 7. Vehicle Mounted Detection System

9.1.5 Improved Landmine Remote Detection Vehicle (IL-RDV)

This was a project financed by Defense R&D Canada, Canadian Department of National Defense started in 1994 and a prototype was completed during 1997. The purpose was to design and build an advanced development prototype of a teleoperated, vehicle-mounted, multi-sensor mine detector for low metal content and non-metallic mines to meet the Canadian requirements for peacekeeping on roads and tracks. This project aimed to develop a reliable route mine detection systems with the ability to rapidly detect mines for logistic or even refuge location areas while minimizing the risks to engineering troops who will clear these areas. The development process of this system employed multiple detectors based on technologies which had limited success for the high intensity conflict problem or in a single sensor role, mainly because of high false alarm rates. The system consists of a teleoperated vehicle carrying a 3m wide down-looking sensitive electromagnetic induction sensor array, forward-looking infrared thermal imaging, a 3m wide down-looking ground penetrating radar. The, Suspicious targets are then confirmed by a thermal neutron activation (TNA) detector. Data fusion methodology is used to combine detector outputs for the purpose to reduce individual detector false alarm rates and provide redundancy. A teleoperated platform was chosen to improve safety to the operators and the platform was custom-designed to have a low signature, in particular ground pressure, with respect to anti-tank mine fuzzes to increase system survivability. The IL-RDV is a part of a larger system called Improved Landmine Detection System (ILDS) that consists of two teleoperated vehicles (the RDV and the protection vehicle (PV)), and a command control vehicle. This completion schedule of this system was during 2002. ILDS was deployed in Afghanistan during 2003. In the Bosnian test calibration area, it was reported that the system was able to maintain a detection probability of 94 per cent. (Faust et al., 2005; GICHD, 2006b).



Improved Landmine Remote Detection Vehicle (IL-RDV)

Protection vehicle (PV)

Fig. 8. The two teleoperated vehicles within the Improved Landmine Detection System (ILDS)

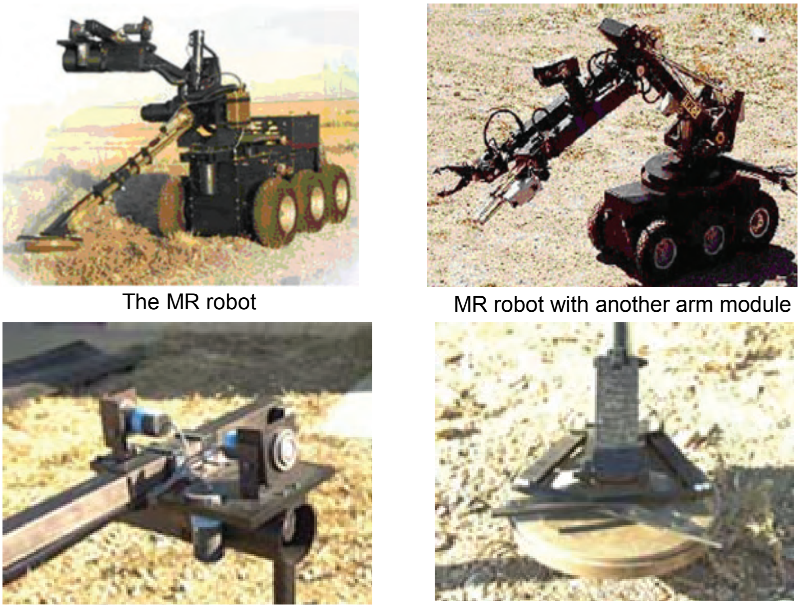
9.2 Multi Functional Teleoperated Robots

Multi functional teleoperated machines would have added values to perform besides demining tasks, other activities, such as: disaster rescue and anti-terrorist operations, or, several civil engineering works. This is the concept of the remotely operated vehicle with on board manipulation robotic mechanisms and sets of task oriented tools for performing particular tasks (Havlík, 2005). This is the concept of modularized teleoperated vehicle with sets of range of task oriented tools for performing that suit to the need of each individual task and environment.

9.2.1 Articulated Modular Robotic Mine Scanner (Engineering Service Incorporation (ESI))

The available conventional vehicle-mounted systems employ an array of sensor heads to provide a large cross-track detection profile. An example of such systems is the Canadian improved landmine detection system that uses 24 metal detector coils to cover a 3 m swath. In addition, it uses 3 Ground Probing Radar (GPR) modules, each consisting of a number of antenna pairs, to achieve the same coverage. Instead of that, another concept has been developed to replace an array of multiple sensors by a single sensor head that moves side-to-side and provides uniform coverage. Such concept incorporates the advantages of manual and vehicle-mounted operations and capable of autonomously moving a mine detection sensor over natural ground surfaces including roads and tracks in a manner similar to a human operator.

The articulated robotic mine scanner is an off-road, modular, teleoperated, multi-sensor mobile platform designed to detect landmines, including those with minimal metal content, and UXO. The robot is a modular system comprising a remotely operated vehicle (ROV), control station communicates with and displays data from the subsystems through a hardwired or radio telemetry link, scanning mechanism consists of two modular arms like devices that can be mounted on any vehicle. The first arm carries the laser range camera and the second arm is the detector arm that carries the metal detector (ESI, 2003). The robot uses a swept metal detector (of-the-shelf unit that can be easily detached and used manually), and a small sensor head that combines laser/ultrasonic based terrain imaging technology that allows the metal detector to adaptively follows the terrain surface while avoiding obstacles. The robot has a small sensor head, which allows the metal detector to adaptively follow the profile of a road or a natural surface at a close range without actually touching it. The robot can perform neutralization of landmines using a modular arm (MR-1) under the supervision of remotely located operator. MR-1 is a ragged modular dexterous robotic arm (See Fig. 9). The currently used ROV is capable of turning 360 degrees in 1.5 m wide hallway, traversing virtually any terrain up to 45 degrees in slope, over 70 cm ditches, curbs, etc. It operates either with wheel or track and quick mount/dismount tracks over wheels. The ROV works at high-speed scanning (up to 5 km/hour) with wide detection path (about 3 m). The MR-2 is a multimode (autonomous, semiautonomous and manual) mine detection system that operates at high speed with minimum logistic burden. The ROV is a high cost and heavy robot that is designed to search for mines in terrain with rich vegetation stones, sand, puddles and various obstacles. The open architecture of the articulated modular robot allows expansion with generic and custom-made modules (semi-autonomous navigation, pre-programmed motion, landmine detection, etc.). Sensor payloads can be extended to include a range of multisensors, such as metal detection array, an infrared imager, GPR and a thermal neutron activation detector. Data fusion methodologies are used to combine the discrete detector outputs for presentation to the operator. No evaluation and testing results in relation to demining are available.



The MR robot

MR robot with another arm module

Laser/US imaging sensor

Mine Detector Head

Fig. 9. Articulated Modular Robotic Mine Scanner

9.2.2 Enhanced Tele-Operated Ordnance Disposal System (ETODS), (OAO Corporation, Robotics Division)

The Enhanced Teleoperated Ordnance Disposal System (ETODS) is a remotely controlled teleoperated system that is based on a modified commercial skid loader with a modular tooling interface which can be field configured to provide the abilities to remotely clear light vegetation, detect buried unexploded ordnance (UXO) & landmines, excavate, manipulate, and neutralize UXO & landmines mines, to address the need of various mechanical clearance activities associated with humanitarian demining (Eisenhauer et al., 1999). ETODS has an integrated blast shield and solid tires.

ETODS includes a heavy vegetation cutter and a rapidly interchangeable arm with specialized attachments for landmine excavation. Attachments include an air knife for excavation of landmines, a bucket for soil removal, and a gripper arm to manipulate certain targets. Remote control capability combined with a differential GPS subsystem and onboard cameras enable the system to navigate within a minefield to locations of previously marked mines. Mines or suspicious objects already marked or identified with GPS coordinates can be checked and confirmed with an on-board commercial detector, and then excavated with a modified commercial backhoe, an air knife, excavation bucket, or gripper attachment. ETODS was developed and configured for the US DoD humanitarian demining research and development Program starting in 1995. It has been through many field test activities,

and they found it suitable for use in humanitarian demining (HD) operations. The HD issues that have been evaluated include accuracy, repeatability, and feasibility of usage in remote environments. In relation to vegetation cutting, three attachments have been tested. One front mounted bush hog and two side mounted boom mowers. In this case, the HD issues that have been evaluated include the ability to cut dense undergrowth, the proper preparation of the ground for ensuing detection activities, and the ability of the operator to effectively and efficiently clear an area under remote control. As for commercial backhoe that can be field mounted to the ETODS, the HD issues that have been evaluated include the effectiveness and efficiency of locating and excavating mines, operator training requirements, inadvertent detonation rates, techniques for deeper excavations, techniques to identify mines and their status (e.g. booby trapped), and blast survivability/repair. A chain flail attachment converts the ETODS into a system capable of clearing AP mines through detonation, and for this case the HD issues that have been evaluated include the minimum sized mine cleared, depth of clearance, effectiveness of clearance, speed of clearance, and blast survivability/repair. During testing, ETODS was subjected to a 12 lb. TNT blast replicating an AT mine detonation. ETODS drove away with field repairable damage. ETODS has proven effective in detonating M14 AP mines and is survivable through repeated 1.0 lb. TNT detonations (OAO-Robotics, website). TODS provides safe, effective delivery of tools necessary for the clearance of landmines and UXO. ETODS is simple, rugged, and can provide a high technology indigenous demining capability in remote environments.
The ETODS has completed operational field evaluations in Jordan and Egypt, where it was found to have several significant limitations that make it less than suitable for humanitarian demining operations (Figure 10 shows the ETODS is action). These include the tendency to become mired in mud or desert sand conditions, as well as the requirement for significant training to develop teleoperation skills (Department of Defense, Development Technologies, 2001and 2002).

Fig. 10. The ETODS in action

9.2.3 TEMPEST.

(Development Technology Workshop (DTW)

TEMPEST is designed to safely clear light to medium vegetation, clear tripwire fuzzed mines, and assist in area reduction as a precursor to accelerated manual clearance. DTW began production of the TEMPEST Mk I in 1998-99 in which it was designed purely as a vegetation-cutting device, and currently, the TEMPEST Mk V is in production. The TEMPEST Mk V is a remotely controlled, lightweight multi-tool system with vegetation

cutting and trip wire clearing abilities (See Fig.11).
TEMPEST is a low cost, small size and light weight radio controlled AP mine blast-protected multi purpose ground based system. These features aim to ease of transport and agility over difficult terrain. It can support a variety of interchangeable clearance heads to clear vegetation, removal of metal fragmentations by using large and small magnets for the removal of metal fragmentations, engage the ground with flail head, and neutralize tripwires, etc. It is designed to clear AP mines from off-road areas inaccessible to large-area mine clearers. The TEMPEST system consists of a diesel powered hydraulically driven chassis, a radio control subsystem, and each of its four hydrostatic wheels is driven by an independent motor to improve maneuverability. The wheels are easy to remove, repair and replace. The TEMPEST also has a 1.2-meter wide horizontal chain flail with vegetation cutting tips, and an adaptable flail head with hydraulic feedback system that can sense the load on the flail, i.e., the operator can set the speed control to maximum and the TEMPEST will automatically control its cutting rate and drive speed, and progress accordingly. The TEMPEST's ground engagement flail is designed to dig into the soil in order to destroy or expose mines by cutting 10 cm deep into the ground to initiate surface and sub surface mines at that level. Its V-shaped chassis and sacrificial wheels minimize damage from anti-personnel mine or UXO detonation and provide some protection against anti-tank mines. TEMPEST's vertical axis "slasher" is capable of cutting through difficult vegetation such as bamboo and vines and its large magnetic array is capable of extracting ferrous material from the ground. It is able to clear up to 200m2/h of light vegetation (500mm tall thick grass) and to cut 100 mm tree in 3-4 minutes. TEMPEST is featured by ease of operation, maintenance, and repair.
TEMPEST is inexpensive to purchase and operate relative to other vegetation clearance systems. Currently, the TEMPEST is produced in Cambodia as well as the United Kingdom, thus representing a regional capability in Southeast Asia (Department of Defense, Development Technologies, 2001 and 2002).
The TEMPEST is an excellent example of how an operational evaluation can lead to improvements that realize the potential of a prototype design. The early prototype of TEMPEST underwent extensive tests in Cambodia for AP and AT mines. The TEMPEST began an operational evaluation in Thailand in January 2001. Although it was effective at clearing vegetation in mined areas, Thai operators identified overheating problems. The unit's promising performance warranted the investment of funds to improve the system. TEMPEST Mk IV has been tested in Mozambique during 2003. The actual use of TEMEST systems and the continuous evaluation results in having TEMPEST Mk V as a reliable system with more speed and engine power capacity compare to the previous versions.
As evaluated by the manufacturer, the hydraulic hoses are vulnerable to fragmentation attacks, and the machine is not intended to be used in areas where AT mines are present. As evaluated by deminers, the TEMPEST requires the operator to maintain direct line of sight with the system from a minimum of 50 meters and the operator can only be this close if behind the system's portable shield. This poses a problem in dense vegetation or rolling terrain. The TEMPEST has limited traction on wet muddy terrain due to the steel wheels clogging with mud. The machine has the ability to clear both mines and vegetation, even though with limitations. The ground flailing system creates large dust clouds. The view of the operator on the machine can be restricted and the air filters can be clogged (Leach et al., 2005).

Currently, there are now 25 machines operating in Angola, Bosnia, Cambodia, DR Congo, Mozambique, Sri Lanka and Thailand. The TEMPEST is currently used by seven demining organizations around the world (GICHD, 2006a). The new TEMPEST Mk VI will mitigate the highlighted problems by use of a new remote control system and the integration of tracks in place of the steel wheels to enable the vehicle to operate on most soil conditions and terrains.

Fig. 11. Tempest during operational field evaluation

10.2.4 The Armored Combat Engineer Robot (ACER) Msea Robotics

Mesa Robotics has developed a series of teleoperated mobile platforms targeting range of applications. Among these are MARV, MATILDA and ACER Robotic Platform,

The mobile base platform of ACER is armored with ballistic steel has a size of 83"Wx62"Hx56"L and it weights 4500 LB. It is powered by (12 VDC) NiMH battery with possible operating time between 1 to 2 hours. It has a hydraulic driven system with maximum speed of 6.3 mph and its payload capacity is 2500 Lb. Driving color camera with IR is integrated with ACER. The vehicle can negotiate obstacle up to 10 inch and moves on slopes of 60 degree up/down. ACER accepts a range of custom and standard attachments such as, flail, blades, buckets, etc. and it has towing capacity of 25000 Lb. and arm lift capacity of 1000 Lb. The vehicle's fording depth is 2 inch with zero turning radiuses (see Fig. 12).

ACER can be remotely controlled by one person through a belly-box operator control unit (OCU) with control range of about 500 meters (see Fig. 13). The OCU is featured by 900 MHz digital control, 1.8 or 2.2 GHz analog video system, 6.4" display and two control joy sticks: one for the vehicle and the other for arm control. ACER weights 6 Lb. and powered by (12 VDC) NiMH with (120 VAC) adapter.

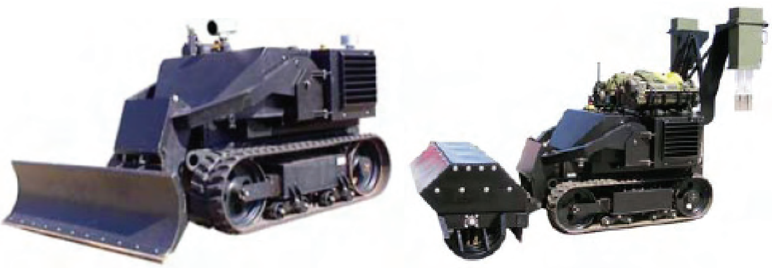


Fig. 12. The mobile base unit of ACER with some of possible attachments

Fig. 13. Belly-Box Operator Control Unit (OCU)

ACER provides a variety of capabilities for remote operations: UXO Handling and Removal, Clearing and Breaching, Combat Engineer Support, Hazardous Material Handling, Logistics Support, Decontamination, and Fire Fighting.
ACER is still new and no testing for demining has been reported yet.

9.2.5 Modular Robotic Control System (MRCS) for Mine Detection

A Modular Robotic Control System (MRCS) has been developed and integrated on a light utility tracked vehicle for landmine detection technology applications. The MRCS architecture incorporates a modular design providing remote control of vehicle functions and control of payload tools while annual operation capability of the platform is maintained. The MRCS system consists of three main elements: a man-portable Operator Control Station (OCS), Platform Control Components (PCC), and a wireless data and video link (See Fig. 14 (top)). Nemesis HD Robotic Platform was used as light-weight, and utility-tracked vehicle. The OCS is a man-portable unit that supports all command, control, and communications to the target platform. Operation of the robotic platform is performed through control of the joysticks and functions on the touch-screen. Architecture of the PCC, located on the robotic platform, is fully modular and highly scalable. Adding a new payload can be accomplished by plugging the payload node into the network on the platform and selecting the payload configuration library at the OCS for control and display. Control for the vehicle platform is accomplished through a single control node on the PCC. MRCS is designed to facilitate change-out of radios as needed. The radios are external to the OCS and other platform components so they can be easily exchanged. Closed-loop speed control was designed to provide the capability to drive very slowly (< 0.5 km/hr) over varying terrain at different engine revolutions per minute levels. Based on field-testing and results evaluation, a stepped frequency ground penetrating synthetic aperture radar (GPSAR) array with 2m wide antenna, and a time domain electromagnetic inductance (EMI) 2m wide array were used as the primary detection sensors to detect both AP and AT landmines for the Nemesis project (See Fig. 14 (bottom)).. Navigation and positioning is provided from the robotic platform to aid in correlation of data from the two sensors. The sensor arrays are capable of 3cm spatial resolution. Finally, the system has been developed but no data is available on testing it for mine detection.

Nemesis HD Robotic Platform with integrated components of MRCS

Platform Control Components (PCC)

Operator Control Station (OCS)

Detection Sensor Arrays Attached to Robotic Platform

Fig. 14. Modular Robotic Control System (MRCS) at the sensor arrays attachment for mine detection

9.3 Demining Service Robots

9.3.1 Three Wheels Dervish Robot (University of Edinburgh/ UK)

Dervish was originally designed to bypass the problem of mine detection by deliberately rolling over the mines with mine-resistant wheels. The Dervish is a remotely-controlled wheeled vehicle designed to detect and detonate AP mines with charge weights up to 250 grams that is equivalent to the largest size of AP mines. It is a three-wheeled vehicle with wheel axles pointing to the center of a triangle. The weight of Dervish closely emulates (a little more than) the ground loading of a human leg (Salter& Gibson, 1999). But, because of its low weight, Dervish will not explode AT mines. The wheels are placed at 120 degrees from each other. The Dervish drive uses three variable-displacement computer controlled hydraulic pumps driven by a 340 cc Honda engine, and controlled by a microprocessor to drive a Danfoss hydraulic motor at each wheel. The steel wheels weight about 80 kg and are 4-6 cm thick. Due to the position of the wheels, if all Dervish wheels were driven at the same

speed then it would merely rotate about its center and make no forward progress. However, carefully timed, small, cyclical variations of wheel speed make the Dervish wheels describe spirals and progressively translate in a chosen direction so that every point in its path is covered, twice, by a loading of about 90 kg in a pattern of overlapping circles. Repeatedly locking one wheel and driving the other two wheels spins the machine through 120 degrees about the locked one and allows traversing. Dervish has a very open steel frame with all members' oblique to the path of blast fragments. It effectively has a zero-radius turning circle. A wide path can hence be stamped by radio control. Figure 15 shows Dervish and illustrates the spiral movements of the robot. It is claimed by the designer that in case of mine explosion, the wheel and the compact hydraulic motor should resist. The tetrahedral structure linking the three wheels and the central power source will be easily repaired.
In normal mine-detonating mode, the Dervish advances at about one meter a minute, a rate set by the requirement that there should be no mine-sized gaps between its wheel tracks, i.e., covering the ground at intervals of only 3cm to avoid any mine-sized gaps between its wheel tracks. A possible change to the wheel design may increase this by a factor of three. With its design structure, it can sweep a 5 meter wide track with a possible coverage of 300-900 square meters per hour. The machine is designed for the clearance of agricultural land. It can operate on open, uneven, or moderately sloping ground. All the electronic equipment is fitted into steel tubes made from old nitrogen bottles with carefully-machined O-ring seals and uses military specification connectors. The Dervish can carry a metal detector placed in a thorn-resistant protective shroud with the sensor head just inboard of the wheel radius at 60 degrees from a wheel. Other sensors for non-metallic targets especially ones that respond to explosives in gram quantities have not been introduced. In a test with a 10kg charge, damage was confined to one corner and the axle and bearings from that test are still in use. The repair cost would be a few hundred dollars. The main limitations of this robot are: not suitable for difficult terrain, hard to navigate, blast-resistant wheels are unsuited to very soft ground, and the inability of the robot with its particular wheel configuration and available power to have enough torque to get out of a hole after a mine blast. This has prompted the team to work on a future complementary design aimed purely at sensor movement with no mine detonation.

Fig. 15. DERVISH robot

9.3.2 Spiral Terrain Autonomous Robot (STAR) (Lawrence Livermore National Laboratory (LLNL)

An autonomous vehicle has been developed for versatile use in hostile environments to help reduce the risk to personnel and equipment during high-risk missions. In 1996 LLNL was in the process of developing the Spiral Track Autonomous Robot (STAR), as an electro-mechanical vehicle that can be fitted with multiple sensor packages to complete a variety of desired missions. STAR is a versatile and maneuverable multi-terrain mobile robot that can to be used as an intelligent search and rescue vehicle to negotiate fragile and hostile environments (Perez, 1996). STAR can help with search and rescue missions after disasters, or explore the surfaces of other planets (See Fig. 16).

Although four-wheel and track vehicles work well, they are limited in negotiating saturated terrain, steep hills and soft soils. The two key mechanical components in the structure of STAR are the frame assembly and the two Archimedes screws. The mechanical frame is made of hollow aluminum cylinders welded together with an aluminum faceplate on each end. The second key mechanical component of the STAR is the screw drive The STAR rolls on a pair of giant Archimedes screws (one left-hand and one right-hand) that serve as the drive mechanism in contact with the local environment to propel itself along the ground. The screws take advantage of ground forces. Rotating the screws in different rotational combinations causes the system to instantly translate and/or rotate as desired in four possible directions, and to turn with a zero turning radius. When they rotate in opposite directions, the robot rumbles forward. When they rotate in the same direction, it scuttles sideways, and when one screw turns while the other holds still, the screw-bot deftly pirouettes. Versatility in directional travel gives the system flexibility to operate in extremely restricted quarters not accessible to much larger pieces of equipment. Furthermore, the Archimedes screws give the vehicle enough buoyancy to negotiate saturated terrain. In water, the hollow screws float and push like propellers. The STAR is compact, measuring 38 inches square and 30 inches high; it has a low centre-of-gravity allowing the system to climb steep terrains not accessible to other hostile environment hardware.

The STAR is also equipped with a complete on-board electronic control system, data/video communication links, and software to provide the STAR with enough intelligence and capabilities to operate remotely or autonomously. During remote operation, the operator controls the robot from a remote station using wireless data link and control system software resident in a laptop computer. The operator is able to view the surrounding environment using the wireless video link and camera system. Remote operation mode is desirous when personnel must enter an unsecured hostile environment that may contain nerve gases, radiation, etc. Ultrasonic sensors are mounted around the external perimeter of the robot to provide collision-avoidance capabilities during remote and autonomous operations. All power is placed on-board the system to allow for tether less missions involving distant travel. The system is responsible for high-level decision-making, motion control, autonomous path planning, and execution. The cost of the STAR is dependent on the sensor package attached. The STAR is equipped with a differential GPS system for autonomous operation and it can accommodate the Micro-power Impulse Radar (MIR) for landmine detection technology developed by LLNL. A disadvantage of STAR is the high friction between the screw wheels and the ground, which keeps the machine to a one-and-a-half-mile-per-hour speed limit while moving forward or backward. STAR has been studied in specific mine projects. The robot is not suitable for environments that are full of rocks. Experiments have shown the ability of STAR to negotiate successfully, hard and soft soils, sand, pavement, mud, and water. No demining testing and evaluation was reported.

Fig. 16. STAR robot in different situations

9.3.3 The MILmine

MILmine Sweeper was originally known as "Little Ranger”. The MILmine project was established to investigate the feasibility of utilizing an autonomous robot to detect and mark landmines in a possible safe and accurate manner (See Fig. 17). MILmine was built and tested at the University of Florida at the Machine Intelligence Lab (MIL). Mine detection was considered through the use of a Schiebel AN-19/2 as a NATO-approved mine detector head, and the marking of mines is accomplished through the use of spray paint when the robot declares the detection of a landmine. The MILmine’s original incarnation included rudimentary collision avoidance via infrared detection in addition to the primary metal-detecting sensor rig. Its processing power was similarly rudimentary, as it used a Motorola 68HC11 EVBU with an expanded 32k of volatile SRAM. The project is being expanded to provide greater mobility and utility for outdoor use, including the addition of a rear-wheel drive system with four-wheel independent suspension. This is an ongoing project where currently the upgrading of the processor is being undertaken to improve the overall functionality as well as to provide the processing power necessary to implement research into machine learning and intelligence. The MIL Mine robot has limited mobility and is not suitable for navigation in difficult and rough terrain. Further development is required but no extension is taken place for this project.

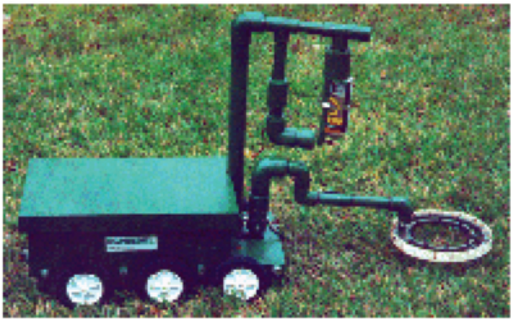


Fig. 17. MILmine robot

9.3.5 FETCH II

The Fetch program is sponsored by the Naval Explosive Ordnance Disposal Technology Division and aims to develop a team of low cost robotic mine hunters that will provide rapid and complete coverage of a mine field. It is being developed by IS robotics. The first phase aims to develop a principal swarm robot structure. The robot features advanced computational and mechanical components, yet are designed for low-cost duplication. The second phase aims to enable these robots to cooperatively clear a field of landmines under the supervision of a single operator.

Fetch I aims to detect, retrieve, and safely deposit munitions in the real world. The main component associated with Fetch I was the autonomous navigational system augmented by a supervisory control station. At a later stage, behavior based intelligence in each Fetch II enables it to navigate through real world terrain using a relative coordinate positioning system and task-specific sensors mounted on its mobility platform. No real minefield test has been reported. Teams of Fetch II robots (See Fig. 18) can be considered to verify an area of interest is free of mines.

Fig. 18. FETCH II demining robot

9.3.6 Finder

The Robotics Institute at Carnegie Mellon University is interested in building a fleet of inexpensive robots so that the cost of losing one robot is minimal. To demonstrate this ability they developed a demining robot called Finder (See Fig.19). Finder carries 16 ultrasonic sensors for obstacle detection and avoidance and a positioning device for coverage. Ultrasound was chosen over infrared for collision detection, as Finder must operate outside, where the sun saturates all infrared sensors. The obstacle sensors, motors, and localization are driven by a set of embedded computers on board Finder. A Pentium single-board computer (SBC) running a custom Linux provides high-level control of the robot, communicating via standard RS-232 serial lines with two Motorola 68HC16 slave micro controllers. One micro controller drives the sonar and buffers the distance-to-object values returned by the sonar board; the other handles low-level motor control and servoing (using feedback from the positioning system to follow a specific trajectory). A second Pentium SBC is used by the visual localization system. For mine detection, Finder will be equipped with a standard metal detector, but this seems to be a naive choice for the most safety-critical sensor on the robot. It is clear that the mechanism of Finder is limited to work in an almost flat terrain with no impact of vegetation and other environmental constraints.

Fig. 19. Finder demining robot

9.3.7 PEMEX-BE (PErsonal Mine EXplorer) (EPFL/Switzerland)

Pemex is a low cost solution for carrying a mine sensor and exploring automatically an area. Pemex is a two-wheeled robot built uses mountain bicycle wheels and aims to investigate cross-country navigation and to evaluate sensors for the detection of AP mines (See Fig. 20). It is a lightweight vehicle (less than 16 kg) and exerts a maximum force of 6 kg on the ground that is not supposed to trigger any of AP mines it detects. The wheels are driven by 90W DC motors from Maxon with 1:72 reductors aiming to give to the robot a maximum speed of 6 km/h power it. When searching for mines the Pemex head oscillates right and left in a zigzag movement covering a 1-meter wide path (Nicoud & Habib, 1995; Nicoud, 1996). The on-board 68331 microprocessor permits autonomous or teleoperated navigation. Polaroid and Sharp PSD ultrasonic sonar sensors detect obstacles. The mine sensor head currently contains as a metal detector. It is intended to be integrated a combination of a metal detector (MD) and a ground-penetrating radar (GPR) that have been evaluated in real minefield. The ERA radar was selected in early 1996, and different metal detectors brands from (Schiebel-Austria, Foerster-Germany and Ebinger-Germany) were used and tested (Nicoud at el., 1998). Pemex has rechargeable batteries that can provide 60 minutes of autonomy.

Mined terrain is often overgrown with dense vegetation. Pemex-BE's mountain bike wheels allow it to move in high grass. With climbing cleats mounted on its wheels, Pemex-BE can climb irregular slopes of 20° to 30°. It can also climb stairs. The wheels go first when climbing to prevent the sensor package leaving the ground. Pemex is equipped with optional water wings that enable it to float and swim. This allows it to operate in environments such as rice paddies and, on land, reduces the pressure on the ground when searching for very sensitive pressure-triggered mines. For transport, the wheels can be removed and attached to the sides of the main chassis. All components can be packed and easily carried by one person.

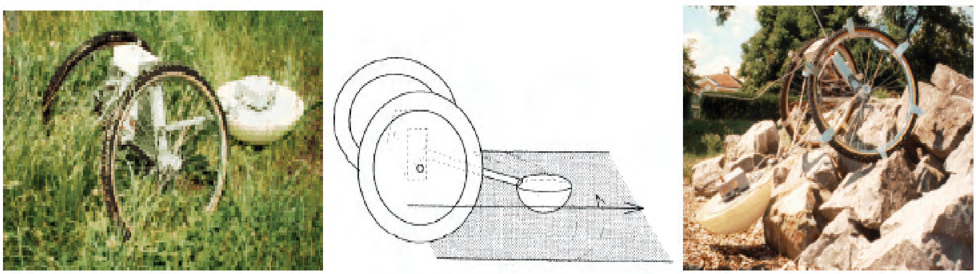


Fig. 20. PEMEX-BE (PErsonal Mine EXplorer)

9.3.8 Shrimp Robot (EPFL/Switzerland)

As part of the field and space robotics activities at the Autonomous Systems Lab (ASL) of EPFL-Switzerland, an innovative robot structure has been developed. The first prototype is called the "Shrimp Robot". Shrimp is a high mobility 6-wheels mobile platform. One wheel is front-mounted on an articulated fork, one wheel in rear directly connected to the body and two wheels are mounted on each of two lateral bogies. The total weight of this first prototype is 3.1 kg including 600 g of batteries and a 1.75 W DC motor powers each wheel. The dimensions are L 60 cm x W 35 cm x H 23 cm; the ground clearance is 15 cm. Shrimp as a new mobile platform shows excellent off-road abilities overcoming rocks even with a single bogie. Shrimp adapts its structure purely passively during motion to insure its stability. This allows very simple control strategy as well as low power consumption. The secret of its high mobility lies in the parallel architecture of the front fork and of the bogies ((Estier et al., 2000a; Estier et al., 2000b). With its passive structure, Shrimp does not need to actively sense obstacles for climbing them. Instead, it simply moves forward and lets its mechanical structure adapt to the terrain profile. With a frontal inclination of 40 degrees, Shrimp is able to passively overcome steps of twice its wheel diameter, to climb stairs or to move in very rough terrain. Shrimp has not been used yet in demining operation, but it can be considered an attractive candidate because of its well-adapted locomotion concept and the excellent climbing and steering capabilities that allow high ground clearance while it has very good stability on different types of rough terrain. In May 2001, the developer announced version 3 of the robot, Shrimp III (See Fig.21). This version is powered by 6 motors integrated inside the wheels and steered by two servos. This robot is able to turn on the spot. It is built in anodized Aluminum and it is equipped with modular electronics.

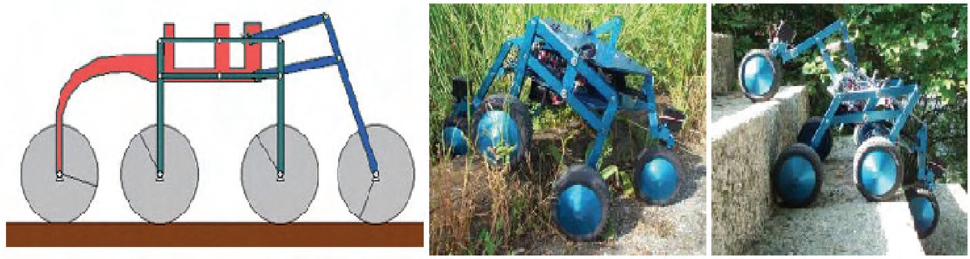


Fig. 21. Shrimp III Robot

9.3.9 Automatic Mechanical Means of Manual Land Mine Detection

The aim is to design an automated, single or multiple-prodding device that can be mounted installed in front of a remotely controlled all terrain vehicles. In this regards, at the suggestion of the Defense Research Establishment Suffield (DRES), the 1996 senior design project the University of Alberta was to design innovative mechanical method to detect non-metallic landmines (Fyfe, 1996). The developed design tries to emulate and multiply the performance of manual prodding done by human operator. The design consists of an automated and hydraulically actuated multiple-prodding device designed to be mounted either in front of a BISON armored personnel or in front of a remotely controlled all terrain vehicle called ARGO. The detection unit consists of a frame, traversing rack and multiple probes. Each of the 41 or 8 probes (depending on the design) used to penetrate the ground, is individually mounted on a hydraulic cylinder (See Fig. 22). The hydraulic fluid pressure in each cylinder is continuously monitored by a computer data acquisition system. When the probe strikes the soil or a solid object, the pressure in the cylinder rises in proportion to the force on the probe. Once this pressure rises above a threshold value, a solid object is determined to be present. A solenoid valve controlled by the computer releases the pressure in the cylinder, thus stopping the probe from further motion. This valve is quick enough to stop the cylinder in order to prevent the accidental detonation of the suspected mine. Based on the probe separation distance, this system ensures that no landmine is going to be missed by passing between the probes.

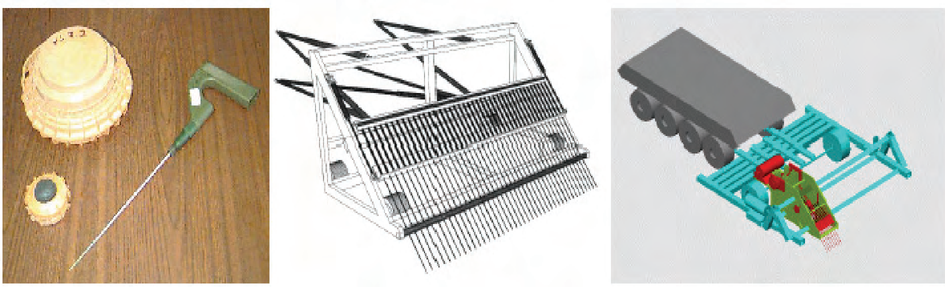


Fig. 22. Design of multiple mechanical means of manual prodding

A similar approach has been developed (Dawson-Howe & Williams, 1997). They have assembled a lab prototype, as shown in Fig. 23, intended to demonstrate the feasibility of automatic probing using on an XY table for the motion (to be fixed on a mobile platform at a later stage), together with a linear actuator, a force sensor and a sharpened steel rod. Probing test was done on an area of 50cm x 50cm and the probing was done at an angle of 30 degrees.

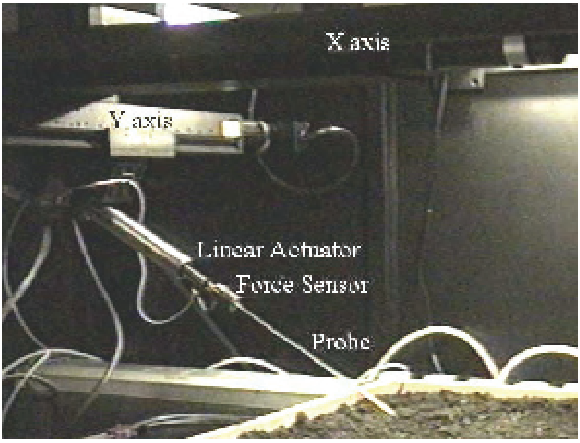


Fig. 23. Laboratory prototype of a single mechanical means of manual prodding

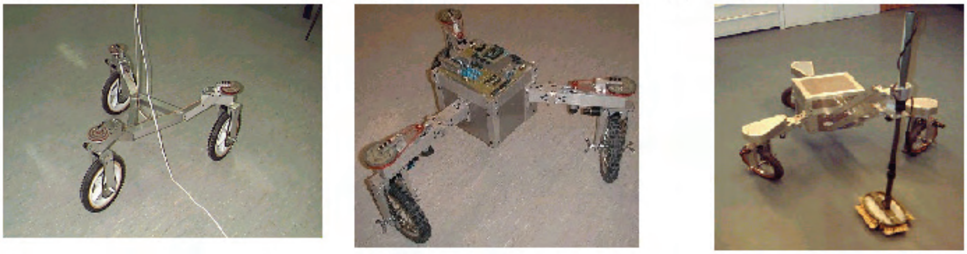
9.3.10 AMRU and Tridem (I and II) (Belgium HUDEM)

The Belgian joint research program for HUmanitarian DEMining (HUDEM) aims to enhance mine detection by a multi-sensor approach, speed up the minefield perimeter determination and map the minefields by robotic platform. Several mobile scanning systems have been developed, such as the AMRU (Autonomy of Mobile Robots in Unstructured environments) series 1-4, have been modified from previously developed walking mobile robots by Belgium Royal Military.

One of the main purposes of developing such robots was to achieve low-cost machines. In order to meet this constraint, simple mechanical systems for the legs were used and high cost servomotors were replaced by pneumatic and other actuation systems. A simple but robust digital control was implemented using industrial PLCs for the early versions. AMRU-1 is a sliding robot actuated by rodless pneumatically cylinders with the capacity to have 4*90 degree indexed rotation. When the metal detector detects something, the robot stops and an alarm is reported to the operator. The robot is equipped with a detection scanner. This robot has poor adaptability to irregular terrain with limited flexibility. AMRU 2 is a six-legged electro-pneumatic robot. Each leg has 3 degrees of freedom rotating around a horizontal axis allowing the transport/transfer phase, a rotation around a horizontal axis used for the radial elongation of the legs and a linear translation allowing the choice of the height of the foot. The first two dofs are obtained by use of rotating double acting pneumatic motors plus double acting cylinders. Other versions have been developed (AMRU 3 and 4) but they are still waiting for testing. The next generation AMRU 5 has 6 legs.

In order to obtain a better mobility, the Tridem robot series have been developed. This series of robots has been equipped with three independent modular drive/steer wheels. Each wheel has 2 electrical motors. A triangular frame connects the wheels. This frame supports holding the control electronics and the batteries. The robot has been design to have a 20-kg payload and a speed of 0.1 m/sec. Two versions of this robot have been developed (Tridem I and II). Figure 24 illustrates different versions of AMRU and Tridem robots.

(a) AMRU1 b) AMRU2 (c) AMRU 5



d) Tridem robot series

Fig. 24. Different versions of AMRU and Tridem robots

9.3.11 WHEELEG (University of CATANIA, Italy)

Since 1998, the WHEELEG robot has been designed and built for the purpose to investigate the capabilities of a hybrid wheeled and legged locomotion structure in rough terrain (Muscato & Nunnari, 1999; Guccione & Muscato, 2003). The main idea underlying the wheeled-legged robot is the use of rear wheels to carry most of the weight and front legs to improve surface grip on climbing surface and overcome obstacles (See Fig. 25). This robot has two pneumatically actuated front legs, each one with three degrees of freedom, and two rear wheels independently actuated by using two distinct DC motors. The robot dimensions are Width=66cm, Length=111cm, and Height=40cm. The WHEELEG has six ST52E301 Fuzzy microcontrollers for the control of the pistons, two DSP HCTL1100 for the control of the wheels and a PENTIUM 200MHz microprocessor for the global trajectory control and the communications with the user. Preliminary navigation tests have been performed showing that WHEELEG cannot only walk but also run. During walking, the robot can overcome obstacles up to 20 cm high, and it can climb over irregular terrain. Possible applications that have been envisaged are humanitarian demining, exploration of unstructured environments like volcanoes etc. The robot mobility and maneuverability is limited, no demining sensors have been used, and no demining testing and evaluation has been reported.

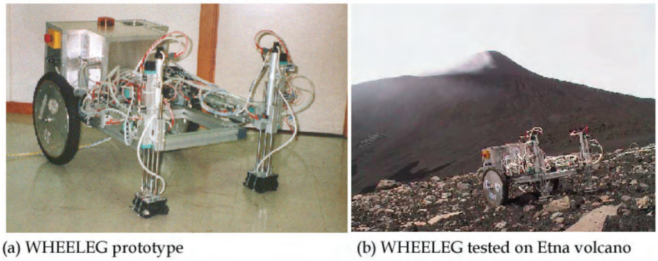


Fig. 25. The WEELEG Robot

9.3.12 COMET I, II and III: Six legged Robot (Chiba University in Japan)

COMET I and II have six legs and is equipped with several sensors for mine detection (Nonami, 1998). COMET III has 2 crawler and 6 legs walking/running robot with two arms in the front. It is driven by hydraulic power. The robot weight 990 kg, its length 4m, width 2.5m, and height 0.8 m. The COMET is made of composite material for legs and manipulators like CFRP to reduce the total weight. Currently, COMET-I can walk slowly at speed 20m per hour with detection mode using six metal detectors. On the other hand, COMET-II can walk at speed 300m per hour with detection mode using mixed sensors of metal detector and GPR at the tip of its right manipulator. In both cases there was no indication to the scanned area during movement. COMET robots are equipped with CCD camera, IR camera and the laser sensor. Different experiments haven been conducted to detect artificially located mines based on the use of infrared sensors that can deal with different terrain (Nonami et al., 2000). Figure 26 presents different versions of COMET. The presented technical solutions are heavy in weight, require logistical and maintenance care, high in cost, and have limited maneuverability.

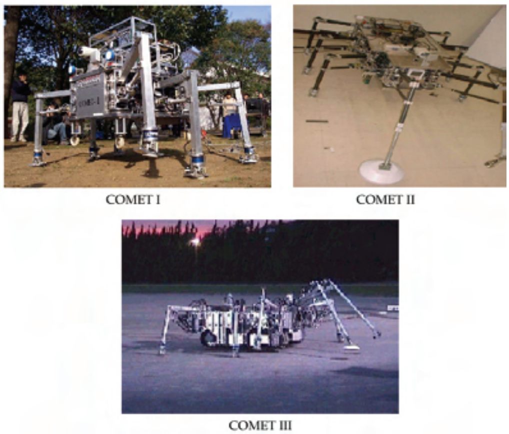


Fig. 26. Different versions of the six legged mobile robot COMET

9.3.13 Buggy and Legged Robots (TIT in Japan)

The research at TIT has been mainly focus to develop biologically inspired robots. Part research group targets are to adapt different robotics technology and mechanisms to support humanitarian demining needs. They have considered quadruped-walking robot “TITAN-IX” among the TITAN series of robots for demining mission (Arikawa & Hirose, 1996; Hirose et al, 2005]. The developers considered having adaptable robot with respect to the terrain and able to handle several tasks by utilizing the legs as a manipulator with different module attachments (see the concept in Fig.27). The dimension of TITAN-IX is L=1000 mm, W=1600 mm, and H= 550 mm. Its weight is 170 kg and powered by 36 volt lead-acid battery. The mechanism of the robot has four legs and it is possible to use the leg as the manipulator of the mobile working platform and also fold the leg to facilitate the portability of the robot. In addition, leg’s joints have wide motion range. The control system of TITAN-IX consists of computer, motor drivers, and DC motors. DC motors are mounted inside base part. TITAN-IX has totally six motors for each leg, four 150 W and two 20 W. Two of 150 W motors drive a knee joint, one drives hip and the other drive turn. The two 20 W motors drive ankle and clamp mechanism cooperatively. In operation, TITAN-IX can be in one of four phases with the ability to transit between them: a) working; b) tool changing; c) walking and d) transportation configuration. In working phase, one leg works as a manipulator and the other three legs try to keep the robot stable. The tool change phase deals with tool changing (digging, sensing, grasping) and the transition between working and walking. In the walking phase, each leg demonstrates its ability to adaptively move and perform various walking styles as needed. No operation, performance evaluations, and testing were presented yet in direct relation to demining.

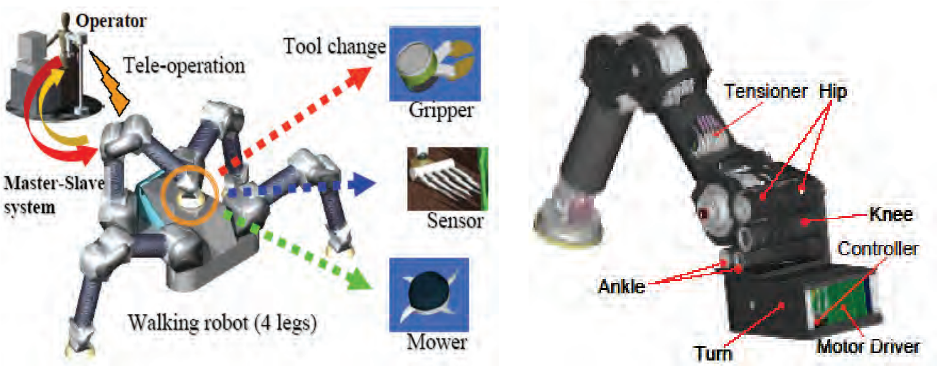


Fig. 27. The concept of TITAN-IX with implementation of the leg unit for the demining mission

In addition to the legged robot, the group has developed a robot system consists of a manipulator mounted on top of an automated buggy system called "Gryphon" with remote control mode (Debenest et al., 2003), and it was enhanced by the development of an energy-weight-compensated manipulator, which is composed of a 5-nodes parallel linkages. Mine detector can be attached to the manipulator arm to scan an allocated area for verification purposes. The buggy system and its arm was integrated with advanced landmine imaging system (ALIS) (see Fig. 28), developed by Tohoku University in Japan and consists of a metal detector and GPR for evaluation test flat terrain in Afghanistan (Dec. 2004) and then in Cambodia (Nov. 2006).

To perform its job, the buggy system requires having a safe lane to the side of the minefield and the manipulator should scan the terrain from the side of the buggy toward the minefield with controlled displacements. No result on the testing evaluation in relation to the control of the robot system has been reported yet. Currently, the group is conducting the dynamic analysis of the robot system.

Fig. 28. Buggy system mounted ALIS and a picture of ALIS

Fig. 29. The Minehand unit

A shielded Minehand unit was developed for demining equipment for the possibility to reduce the physical contact between the deminer and the mines (see Fig. 29). The Minehand unit supports the so-called prodding work stage, or manual excavation of mines. It is a lightweight unit that equipped with a clear shield to protect against blasts. With a range of about 1.6 meters, the Minehand lets operators to interact with the ground and the buried objects. With this system, the operator has a limited visibility and flexibility in feeling and interacting with respect to the buried object and this affects the performance level of the operator and raise safety concern.

9.3.14 Mine Hunter Vehicle (MHV)
Fuji Heavy Industries (FHI)

FHI has developed a crawler type MHV as a portable sensor platform under the sponsorship of Japan Science and Technology Agency's (JST) with aim to support humanitarian demining activities. The vehicle was originally designed to carry two working arms. The first arm is a SCARA type arm to be equipped with interchangeable sensors for detecting buried landmines. The other arm is a six degree of freedom articulated robot that can be equipped with tools to support prodding and uncovering landmines (see Fig. 30).
The development of MHV aims to negotiate tight turns and rough terrain, and safely access to minefields to provide fine underground images through the mine detectors integrated with it. The water and dust-proof sensor system are considered to enable the vehicle to withstand the difficult conditions associated with minefields. The vehicle can be remotely-controlled as a step for possible safety enhancement. Metal-collection electromagnets and air blowers can also be attached to the vehicle's robot arm.
There are two interchangeable varieties of the GPR systems that can be attached to the SCARA robot arm and the selection depends on the operational conditions. The first module is the soil-type adaptation sensor (see Fig. 31(right)). This sensor has a wide bandwidth from 10MHz to 4GHz and SAR technology that can clear up radar clutter in mixed soil. The second module is the high-speed sensor module that is small and lightweight radar (see Fig. 31(left)). The two sensors modules can show underground images in two and three dimensions. The 3D imaging mode allows for mine depth and attitude to be easily determined, while the 2D mode provides more detailed images.
The MHV requires having safe path to the side of the minefield and its scanning area is limited by the reach of the SCARA robot. The vehicle was tested but not in a real minefield and no evaluation results for the robot performance and justification is available. In addition, critical points are directly associated with the required logistics, system and maintenance cost, and operational speed.

Fig. 30. Mine Hunter Vehicle (MHV)

Fig. 31. Two interchangeable Radar sensor modules

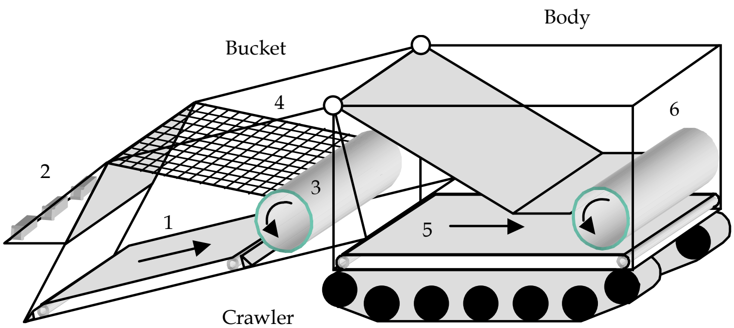
9.3.15 Ares – A Wheeled Robot
IntRoSys

Ares robot has been developed with consideration to have a portable remote monitoring toolkit with possible fleet of robots featured by good mobility, ground adaptability, and reduced in size (Cruz et al., 2005). The design of the robot was developed with aim to have low cost, light, four-wheel steering mobile robot with a biologically inspired locomotion control. The robot is integrated with sensor package that enables navigation within cluttered minefields while achieving helping to achieve its assigned task. To maximize the traction and adaptability in difficult environments, this robot is equipped with four mountain bike wheels, rotating independent axles, and a short wheelbase (see Fig. 32(left)). A compass and upper sonar set sensors have been supported by pendulum system located in the middle of the robot. The sonars are intended for obstacle detection. The Ares robot has a differential steering system to assure better mobility. The robot is capable of executing different locomotion modes, such as a car-like locomotion (Ackerman mode), rotate around its geometrical centre (Turning at a point mode), aligning the wheel to produce linear trajectories (Omnidirection mode), and wheels aligned perpendicular to the main axis of the robot allowing sideway movement (lateral mode).
The first prototype of this robot was aiming to prove the design concept and it has been built using steel frame and weight about 20 kg. The robot was integrated with low cost metal detector and odor sensor. No specific sensors preferences have been assigned to support scanning minefield for mine detection. With the second prototype the developers tackle the slippage problem associated with the first version by having new mechanism (see Fig. 32(right)) that enables the robot to emulate differential, Ackerman and omnidirectional steering. Hence, it would be possible to steer the robot in different direction. Both front and rear axes can freely and independently rotate around a longitudinal spinal axis (Santana et al, 206). By being passive, the robot is capable of being compliant with respect to an uneven terrain. The robot can estimate its posture, tilt, pitch, and yaw using Honeywell HMR 3000 sensor. Speed/position motor control is performed by four RoboteQ AX3500 boards (one per wheel), which among other advantages, accommodates a possible change to more powerful motors. The computational unit is a Diamond Systems Hercules EBX running Linux, and the robot is connected to a wireless network through a conventional wireless access point. The developers are currently investigating the selection of lighter materials in building new version of the robot. The work is still in the progress and neither navigation test nor mine detection test have been reported yet.

Fig. 32. Ares Robot

9.3.16 PEACE: An Excavation-Type Demining Robot

Mori's research group has developed a conceptual design for an excavation-type demining robot *PEACE* dedicated for farmland mine clearance (Mori et al., 2003, Mori et al., 2005). They have considered the clearance of farmland due to its direct effect on people normal life. The conceptual design of the robot is shown in Fig. 33, and it uses crawlers for the locomotion mechanism because of their high ground-adaptability. The robot has a large bucket on its front. A mine crusher is inside the bucket, and a metal separator is in its body.



1. Conveyor belt1, 2. Sensor for ATM, 3. Crusher,
4. Lattice, 5. Conveyor belt 2, 6. Metal separator

Fig. 33. Conceptual design of the robot

10.3.17 The cable suspended searching platform

For searching dangerous terrain and relatively large operation space the conceptual study and analysis of the cable suspended robotic platform was designed (Havlik & Licko 1998). The suggested system consists of three cable winches fixed on mobile columns (See Fig. 34). The ends of cables from particular winches are connected on the platform moving above the working place. Each winch mechanism is equipped by the cable length measuring sensor and the position/velocity control system. The ends of the cables are fixed to the moving platform. Thus, for such a parallel mechanical structure any actual position of the moving platform determine three distances, i.e. measured lengths of cables between the platform and end pulleys of winch mechanisms. The central control system performs transformations and coordinated motion control of the platform with respect to a world reference frame defined on place. The system to be equipped with ultrasonic sensors that enable operators to control its motion within a given distance over dangerous terrain as well as to avoid any obstacles when performing searching motions. The platform carries sensors and tools for detecting and neutralizing mines. When performing scanning motions, it is possible to create a map of detected and marked mines.

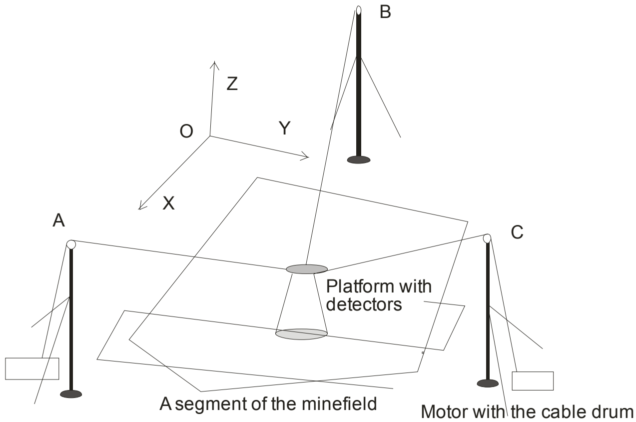


Fig. 34. Cable suspended platform concept of searching dangerous terrain

The presented concept of scanning dangerous terrain has the advantage to cover large operational workspace of that is reconfigurable according to actual terrain conditions, low weight and easy to install and transport, and operation and control can be achieved with Cartesian coordinates. It is obvious that the operation space is given by the triangle created by the fixation positions of the end pulleys. It is approximately above the ground projection of this fixation triangle.

10. Unmanned Aerial vehicles (UAV)

Technology is improving remarkably, and today's air-borne and space-borne technologies that can fly autonomously or be piloted remotely are indispensable with strategic importance for various applications and can be used in different environments where human intervention considered difficult or constrained. UAVs are generally divided into three categories: micro UAVs (very small size and very light payload), tactical UAVS and, strategic "high endurance" UAVs. The latter are further sub-divided into medium altitude long endurance (MALE) and high altitude long endurance (HALE) UAVs. There are also hybrid categories of UAVs with both defensive and offensive capabilities designed for electronic warfare and/or air-to-surface or air-to-air attacks. The UAVs can provide intelligence, disaster response, minefield and surface ordnance survey, surveillance, target acquisition, communication-rely, environmental monitoring, border patrol and reconnaissance for wide range of applications. In case of humanitarian demining, these technologies aim to improve locating and detecting minefield and also greatly enhance wide-area survey and assessment. These technologies can provide a rapid and precise, low risk and cost effective means for surveying a region and producing the large-scale and up-to-date maps which are needed for detailed planning. Advances in sensor technology promise to substantially speed up the process of minefield mapping and survey. The following sensors have been considered for detection of scatterable or pattern minefields from airborne platforms: active and passive thermal infrared imaging and passive hyper-spectral imaging in the visible waveband using a compact airborne spectrographic imager (CASI). Computer based signal processing of airborne gathered data with advance techniques of sensors fusion can lead to the production of important maps as an aid to area reduction as well as clearance planning. These maps also facilitate the process of marking suspected mined areas, and are useful for such requirements as planning access routes and detecting important features hidden from the view of an observer outside the suspect area (Shim et al, 1998; Acheroy, 2005; Santana & Barata, 2005). Currently, commercial solutions are expensive and hence more affordable solutions should be developed for a sustainable humanitarian demining approach. Gaining the capability of designing an Unmanned Rotor Aerial Vehicle (URAV) will be even easier and cheaper due to the availability of know-how in designing manned rotorcraft field. An autonomous and unmanned helicopter is a very attractive solution as a helicopter can operate in different flight modes, such as, vertical take-ff/landing, longitudinal/lateral flight, pirouette, and bank to turn. Due to their versatility in maneuverability, helicopters are capable to fly long period of time. These characteristics make helicopters invaluable for terrain surveying, surveillance, and clean-up of hazardous waste sites. Figure 35 show some of the commercially available URAV (top of the figure) developed by Schieble, and also it shows (bottom) the Airships for mined area detection and reduction under EU-HUDEM project.

The demining community is looking forward to methods and technologies that can reduce the suspected areas as this will save efforts, time, and cost. Due to the fact that the available high aerial photography can not detect AP mines, Space and airborne Mined Area Reduction Tools (SMART) project has been adopted with aims to provide deminers with methodology, user-friendly, cost-effective, safe, and efficient tools that help task interpretation for the monitoring of environment, terrain, and minefields in countries afflicted by landmines (SMART Consortium, 2004; Acheroy, 2005). Information collected using airborne multispectral scanners and airborne full polarimetric SAR, together with context information are integrated through a GIS, and then combined and classified in order to find out any indicators about the presence of mines. In addition, it provides image analysis to help interpreting mine suspected sconces for the purpose of area reduction. Multisensor data fusion technique facilitated by intelligent computational techniques has been developed and applied to enhance tasks interpretation.

Fig. 35. Unmanned aerial vehicles for mined area detection

11. Conclusions

The major technical challenge facing the detection of individual mine lies on having the ability to discriminate landmines from metal debris, natural clutters, and other objects without the need for vegetation cutting. Future efforts to improve detection should focus on providing discrimination capabilities that includes the fusion of information coming from multi heterogeneous and/or homogenous sensors, and the incorporation of advanced signal processing techniques to support real-time processing and decision making. For the purpose of mine clearance, there is an urgent need to have cost-effective and efficient clearance techniques and technologies to clear landmines in different types of terrain and under different climate variations. This should be associated with neutralization of mines, in which there is a need to develop safe, reliable, and effective methods to eliminate the threat of individual mines without moving them while minimizing environmental and ecological effects.

Working in a minefield is not an easy task for a robot. Hostile environmental conditions and strict requirements dictated by demining procedures make development of demining robot a challenge. Demining robots and intelligent mechanisms offer a challenging opportunity for applying original concepts of robotic design and control schemes, and in parallel to this there is urgent need to develop new mine detection techniques and approaches for sensor integration, data fusion, and information processing.

Difficulties can be recognized in achieving a robot or other mechanical solutions with specifications that can fulfill the stated requirements for humanitarian demining. A lot of demining tasks cannot yet be carried out by the available robots because of their poor locomotive mechanism and mobility in different type of terrains. This is because there is still lack of well-adopted locomotion concepts for both outdoor and off-road locomotion. Hence, there is a need to develop modular, light-weight, and low-cost mobile platforms with flexible mechanisms that can deal with different types of terrain and climate. Modularized robotic and teleoperated machine solutions properly sized and adaptable to local minefield conditions is the best way to enable reconfiguration that suite the local needs, greatly improve safety of personnel as well as improving efficiency. In order to be able to design and build successful robot or mechanized solution, it is necessary to carefully study conditions and constraints of the demining operations relevant to the targeted area and the type of the ordnance. The technologies to be developed should take into account the facts that many of the demining operators will have had minimal formal education and that the countries where the equipment are to be used will have poor technological infrastructure for servicing and maintenance, spare parts storage, operation and deployment/logistics.

Research into individual, mine-seeking robots is still in the early stages. In their current status, they don't represent an effective solution for mine clearance. This is due to the gap between scientists developing the robots and the deminers in the field, and because none of the developed robots (specifically these presented in section 10.3) yet entered a minefield for real and continuous mine detection and removal operations. Several large research efforts have failed so far to develop an effective mine clearance alternative to the existing manual technique. Robots have been tried at great expense, but without success yet. There is still a large amount of skepticisms on the role and use of autonomous robots for demining purposes. In general, experts in robotics know little about the practical challenge of demining: hence the robot is designed like all other autonomous robots attempting to navigate an unknown environment. Although some aspects of navigation may be extended to demining robots, it will be more reliable if robots were designed specifically for the purpose of landmine detection than as an after thought. High cost and high tech features are additional constraints in using robots for using it for demining in poor and low infrastructures countries. Understanding the current and previous failed research efforts may help to avoid similar mistakes. Detecting and removing AP mines seems to be a perfect challenge for robots. But, this requires having a good understanding of the problem and a careful analysis must filter the goals in order to avoid deception and increase the possibility of achieving results. In addition, the development of new flexible and intelligent mechanisms, such as small and modular snake like, and small scale lightweight (flapping and fixed wings) flying robots supported by the progress of new technologies in the filed of smart materials and new actuations technologies are promising directions to facilitate the progress of humanitarian demining. However, this depends on the type, weight and reliability of sensors that will be integrated with such flexible and intelligent mechanisms.

The approach to solve the humanitarian demining problem and fulfill its needs requires a strategy for research and development with both short and long-term components. In the short and mid terms, robots can help to accelerate searching and marking mines. In addition, it can be helpful to be used for quality assurance stage for verification purposes. Teleoperated and modular demining machines is feasible and may be a good intermediate step toward full autonomy. Any single breakthrough in technology should be viewed as yet another tool available for use in the demining process, and it may not be appropriate under all conditions. Furthermore, careful study of the limitations of any tool with regard to the location and environment is critical; not all high-tech solutions may be workable everywhere. The knowledge required to operate a machine may not match the skill level of the deminers, many of whom are drawn from the local public. In addition, cost of maintenance, spare parts and its availability are critical parameters too. While current technology may be slightly effective, it is far too limited to fully address the huge mine problem facing the world. Finally, today's companies are not ready financially of doing long term research and development for humanitarian demining, simply because it does not turn a fast profit and as such there should be a recognized contributions from the developed countries and international organizations to support humanitarian demining efforts.

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2

Research Challenges

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1. Introduction

Initial Approach

Research is seldom linear.

Often the objective is further than first expected. It can be like an unclimbed mountain peak, standing clear in a blue sky that seems just a short climb from the base camp. Yet as one climbs each ridge, only to find one has to descend another hidden defile to reach the next, the summit seems to recede into the distance, and may even be out of sight much of the time. One constantly changes direction. Precipices reshape strategy: obstacles that force new approach routes so obvious in hindsight. What seemed to be the summit at first turns out later to be only a shoulder on the mountain hiding a higher summit from view. Sheer faces and overhangs divert those seeking technical climbing challenges from the more distant summit. Early climbers may run short of supplies or endurance and give up, but may write their accounts and leave maps to guide others. They will have improved their climbing techniques and may go on climb other peaks. This analogy captures my own path through demining research.

My research would not have been possible without the support of many colleagues and students and the support of organizations in Australia, USA, Pakistan and Afghanistan.

1995 brought a chance meeting with Gen. John Sanderson, then Australian Chief of General Staff who had commanded the 1993 UN mission in Cambodia. He encouraged me to see if robotics could help with landmine clearance, perhaps a slightly easier challenge than shearing sheep had been (Trevelyan 1992). He opened doors to Australian military expertise evolved from experience in Cambodia and other UN peacekeeping operations.

With students I developed a suspended cable concept (Trevelyan 1996) but a visit to Pakistan forced a reality check. I came into contact with Australians working with UN mine clearance teams in Afghanistan who described apparently simple problems with heavy helmets and primitive tools for investigating metal detector indications. They also provided a detailed description of working conditions in Afghanistan which ruled out the naïve ideas developed in Australia.

I had to revise my approach route. Robotic solutions ultimately depend on mobility on the one hand, and sensing capabilities that offer a more efficient solution than brute force (Trevelyan 1997b). Resolving the sensing problem presented a triple obstacle: (a) intrinsic performance challenges associated with either low detection probability or high false alarm rate or both, (b) the likely cost which would influence the economic viability, and (c) my limited experience and access to the appropriate expertise in these technologies. Sensing the explosive directly by electromagnetic or particle radiation methods (e.g. NQR, thermal neutrons, neutron backscatter), at the time, required a combination of high electrical power demand and operating times of several minutes to accumulate sufficient signal relative to background noise. These were expensive prospects. There were also lower cost indirect methods such as low frequency eddy current induction detectors, thermal infrared emissions from the ground, ground penetrating radar (GPR) and acoustic techniques. Since these methods detect ground anomalies that happen to be associated with landmines, they would also respond to other anomalies such as metal fragments and discarded trash, even tree roots, stones and ant nests in the case of GPR (Bruscini and Gros 1998).

I made a strategic decision to take a different route by exploring low cost improvements to the current manual demining methods (Trevelyan 1997a). A further factor in this decision was that many military-related research projects had started to pursue multiple sensing technologies with far more access to financial resources and expertise than I could reasonably hope for. On the other hand, it seemed that no one had thought of pursuing incremental improvements to methods already in use.

Fig. 1. Left: Prodding to investigate metal detector indication: Afghan deminers normally squat instead of the required prone position shown in this posed photo. Note the bayonet prodding tool and 1.5 kg military helmet with scratched visor. Right: Light weight helmet, visor, prodder with hand protection, and ballistic apron developed through research in Australia and Pakistan. The visor outer surface is protected by a replaceable scratch-resistant film. (photos: UN Mine Action Centre for Afghanistan, J. Trevelyan)

By the turn of the millennium this alternative approach had yielded significant progress. Working with a small Pakistan-based organization we produced improved head protection by adapting methods developed in Africa for producing better quality light weight protective visors (Trevelyan 2000a). By directly interacting with Afghan deminers in their own language we were able to devise low cost tools and solutions that suited their real working conditions and cultural sensitivities. Some tools could be locally manufactured, using imported components and materials. The work on visors added to pressure on existing manufacturers to improve their products and lower their selling prices providing world-wide benefits to demining organizations. Development has been continued by others and improvements are still occurring (Figure 5).

A detailed investigation of technology needs led to the creation of a web-based resource providing background information and an extensive photograph collection on the technical challenges and needs associated with land mine clearance in several countries (Trevelyan 2000a). It was this investigation that led to the notion of a "no-mines" detector. Most researchers have attempted to provide deminers with an improved mine or explosive detector. By carefully analyzing interviews with many deminers and the agencies that support them, we built a strong case for developing technology to sense minute explosive traces. The absence of explosive traces would indicate that there was no need for costly demining over a reasonably large area, thus enabling the land to be released for agriculture or housing. Explosive detection dogs can provide one way to do this, but are still relatively expensive to operate, train and support.

Analysis of accident reports compiled by the Afghanistan Mine Action Centre provided the stimulus to develop prodding tools with hand protection (Trevelyan 2000a). Most accidents were associated with prodding: investigation of metal detector indications usually by using a bayonet to dig through and clear soil to locate the source of the indication. Facial and eye injuries were common resulting in blindness because deminers did not have visors in place at the time. The visors were attached to heavy and uncomfortable helmets and the visors made from polycarbonate had became scratched, obscuring clear vision, so deminers worked with their visors raised or even took off the helmets. Accidental triggering of blast mines by prodding also resulted in major trauma to the hand holding the prodder, but otherwise only temporary deafness and superficial grazing injuries. Light weight scratch-resistant visors and hand protection for prodders could eliminate both problems, as detailed by Trevelyan (2000a). A relatively light weight apron could greatly reduce grazing from secondary fragmentation while still permitting deminers to work in their favoured squatting position (Trevelyan 1999).

Efforts by the Afghan demining NGOs such as Afghan Technical Consultants to reduce the incidence of accidents were so successful that the need for protection was greatly reduced (Trevelyan 2000b).

Careful analysis and measurement of the actual time required for deminers to investigate and locate metal fragments with metal detectors and prodders revealed that deminers work much faster and more reliably than many had thought possible, even with primitive tools (Trevelyan 2002; Trevelyan 2004). This work showed that advanced technology mine detectors were unlikely to be cost effective except in certain locations.

2. Evolution of Landmine Clearance Techniques

Removing landmines is difficult. It is important to distinguish between humanitarian mine clearance and military mine clearance methods (sometimes called "breeching"). Military mine clearance has to work fast, in all conditions (even under fire), and therefore it is unrealistic to aim for 100% clearance. In humanitarian operations there is less time pressure and work can be suspended in unfavourable conditions, and the aim is 100% clearance to a depth considered to be practical in given working conditions. Recent political expectations of low casualties often demand very high clearance standards even in military operations.

Humanitarian mine clearance typically starts years, perhaps decades after the mines were laid. The mines lie buried or hidden from view. They deter people from entering the land so vegetation often grows thickly. Drainage systems rapidly become clogged denying access in wet conditions.

The traditional "manual" method for removing landmines has been to use a metal detector to locate metal fragments close to the ground surface and then to carefully check each metal fragment to see if it is associated with a mine or explosive device. Any tripwires and vegetation have to be removed, with great care, before a metal detector can be used. In many areas deminers have to investigate hundreds or thousands of metal fragments for every mine found. Manual mine clearance also requires careful organization and marking of the ground to ensure safety and thorough clearance. Currently it is still the method that guarantees the lowest risk of residual mine contamination but it is expensive, typically costing US$1 - $5 /m^2.

Fig. 2. Typical ruined house overgrown by vegetation in a village in northern Croatia, possibly containing mines or booby traps. The entire village population was forced to leave in 1991 and the houses were looted and intentionally severely damaged. Vegetation problems like this must be taken into account in considering practical mine and unexploded ordnance (UXO) clearance devices. August 1999 (photo: J. Trevelyan)

Armoured mine clearance machines using hammers mounted on the end of rapidly spinning chains (flails) first appeared in the 1940s but have not been able to neutralize mines with sufficient reliability for most humanitarian applications (GICHD 2004).

In the late 1990s commercial mine clearance organizations operating in thick vegetation in Bosnia Herzegovina and Croatia realised that flails spinning just above the ground could rapidly remove vegetation and trip wires to prepare the ground for manual clearance, often assisted by mine detection dogs. Clearance costs have been reduced by up to 80% (particularly in thick vegetation) using different combinations of machines, detection dogs and manual clearance.

Ground milling machines use metal drums studded with hard cutters that shred buried objects. They require more power than flails but can operate with greater levels of reliability. Both flails and ground milling machines have been extensively used in Croatia to recover large areas of formerly productive agricultural land. Both kinds of machines can withstand a limited number of anti-tank (AT) mine and moderate size UXO explosions before main bearings and other components need to be replaced.

Naturally, machines operate best on flat or gently sloping ground that is also the land that is most valuable for agriculture and human habitation. Thick forest and mountainous terrain still requires traditional manual clearance and in most countries will not be cleared of mines for a long time, if ever.

Fig. 3. Flail machine using hammers on the ends of spinning chains to clear vegetation and tripwires. This machine will also detonate a proportion of buried mines (inset). (photos: Scanjack AB, Sweden)

Mechanized clearance methods continue to evolve with improvements to machines and techniques. Machines can be used for survey, risk assessment and risk reduction tasks to help determine the need for more expensive manual clearance methods. Mine action programs are gradually shifting from an emphasis on total clearance in the 1990s to one of progressive prioritized risk reduction involving a series of measures including high security fences, mechanized survey and risk reduction methods and selective manual clearance (GICHD 2005a, part 4). Protective measures applied to agricultural machinery offer cheaper alternatives in low AT risk areas (Trevelyan et al. 2002).

3. Evolution of Demining Research Priorities

Unlike mountain climbing, researchers in demining have had to contend with shifting objectives. A combination of slow progress with research, political developments, and changes in public perception has changed research priorities over a relatively short time-scale and it is valuable to reflect on this. By far the most significant factor affecting mine clearance priorities was the American response to the September 2001 attacks in New York.

Technological development in landmine clearance from within the demining community has mainly been driven by the search for improved safety for deminers and productivity.

In the mid-1990s there was the expectation that, with sufficient research, advanced technology detectors could replace eddy current metal detector technology that had been in use since the 1940s. Metal detectors also react to metal fragments in the ground. A detector that could confirm the presence of explosive, it was thought, would save having to investigate all these false alarms. The most promising line of research seemed to be data fusion: combining signals from a metal detector, ground penetrating radar, infrared detectors, thermal neutron detectors, even acoustic detectors. Astute observers at research conferences have pointed out that these signals were often well correlated, even in the presence of false alarms. Producing a reliable detector was going to be hard work. Their forecasts turned out to be very accurate. Only one such detector is currently in operation: the HSTAMIDS detector used by US military forces in Afghanistan employs a combination of ground penetrating radar and eddy current metal detection. Little information on its effectiveness has been released and no independent trials have been reported. Experienced research groups report that ground penetrating radar requires accurate alignment of the detector with the ground surface (to eliminate ground surface returns) and also with the target centre point to enable the target to be characterized reliably. If the principal metal component of the landmine coincides with its geometric centre, a common feature of minimum metal mines, the metal detector can be used for alignment. However this is not always the case and one cannot guarantee the absence of other metal fragments near the mine. Ground penetrating radar provides confusing returns in very dry or very wet conditions and is also susceptible to false alarm indications from underground discontinuities such as stones, sticks, animal burrows etc. Research reports mostly downplay these difficulties and prefer only to report positive results. These issues only emerge from discussions with developers who have seriously evaluated technology in field conditions. (Many of the comments in this section are based on numerous discussions with experienced demining personnel who have tried new technologies in the field. References have been cited only where further detailed written information is available.)

The major performance improvements in sensing have been obtained by compensating eddy current metal detectors for soil magnetization, enabling them to work in a much wider range of soil conditions. Improvements in sensitivity can help with minimum metal mines but can also result in a large number of false alarms from smaller metal fragments. Metal detector arrays have been fitted to vehicles to speed up clearance of paved areas and roads (Bruschini et al. 1998).

By the late 1990s slow progress with sensors had become more apparent and research priorities after 2000 gradually turned to mine detection dogs and large demining machines.

The Afghanistan Mine Action Centre started using mine detection dogs around 1993 but it was not until 1998 that this program was running effectively. There were several difficulties. The first challenge was that close association between humans and dogs was socially unacceptable in Afghanistan. The second challenge was to devise ways to use dogs and manual mine clearance in an effective combination providing reliable clearance with high productivity. This was much the greater challenge but by 1998 the cost of clearance using dogs was around one third the cost of manual clearance. It was then that the problems started to appear: the occasional missed mine that could not be explained by lack of organization or failure to follow procedures. At the same time, carefully controlled trials of mine detection dogs in Bosnia had returned highly variable results. On several occasions dogs had walked past blocks of TNT lying almost visible in the ground. Yet, at the same time, a number of commercial demining agencies were routinely declaring land free of mines using similar dogs. In late 1999 the Bosnian Mine Action Centre ran a carefully controlled test in which around 80% of the dogs failed to achieve the required performance standard. The results were hotly contested at the time and the international community organized a systematic trial of mine detection dogs through the Geneva International Centre for Humanitarian Demining (GICHD).

By 2001 it was apparent that there had been little scientific research on the fundamental physiological mechanisms that enable dogs to locate sources of explosive vapour. Dogs had been able to find mines using explosives (such as HMX) with vapour pressure far below measurable detection thresholds. The mechanism by which TNT vapour and its breakdown products reach the ground surface was the subject of considerable scientific debate. By 2003 a systematic trial in Afghanistan, scientific studies at SANDIA Laboratories in the USA and in Scandinavia, explosive trace detection studies with dogs at Auburn University, several other investigations provided some insight into this problem for the first time (Göth et al. 2003). However, the precise physiological mechanisms for canine explosive detection remain unclear, especially for lower vapour pressure explosives. We do not know for sure whether dogs are reacting to vapour, minute particles of explosive suspended in the air, biochemical breakdown products, or a combination.

In 2003 a US company, NOMADICS, demonstrated the FIDO detector, the first that could reliably measure the presence of TNT vapour with more sensitivity than a highly trained dog. However field trials showed that TNT vapour could be detected everywhere in a mine contaminated area! An explosive vapour sensor was just the beginning of the story and warns of a complex task ahead.

By 2004 the international community realised that the early confidence in a breakthrough resulting from advanced sensor technology, demining machinery and mine detection dogs had been misplaced. GICHD commissioned the first serious study of manual demining to see whether productivity improvements could be made. A systematic series of trials were conducted in Africa to determine the effectiveness of several innovations such as magnets and rakes. The final report issued in 2005 revealed that greatly improved productivity was possible but it would depend more on improving contracting arrangements, management and training than technology.

The American response to the New York attacks in September 2001 fundamentally changed research priorities. After the invasion of Afghanistan, removing UXO resulting from ammunition dump explosions and cluster bomb strikes became the top priority for the next 12 months. Resistance to the US and international occupation of Iraq and the easy availability of explosive both from former Iraqi armed forces and UXO from US military operations led to the proliferation of Improvized Explosive Devices (IEDs) to attack organized military forces and police. Similar tactics have appeared in Afghanistan, albeit at a lower intensity. IEDs, therefore, are now considered to be the main threat and the focus for much of the funding and operational and research expertise formerly available to support mine clearance operations. This development has also placed ordnance disposal teams at the front line for the first time, rather than working in well protected and secure areas. Iraqi insurgent groups attack ordnance disposal teams both because they are attempting to disarm some of the insurgents' most effective weapons and also because they remove the main sources of explosives available to insurgent groups.

Improvised explosive devices, when detected, are often investigated and neutralized using remotely operated robots. While there are non-destructive methods to neutralize IEDs, the fastest method usually involves placing a small demolition charge on the device. Operational details remain confidential to reduce the risk that IEDs will be modified to defeat current neutralization methods.

Fig. 4. Bozena teleoperated demining vehicle (Way Industry, Slovakia)

Paradoxically it is this development that has enabled robotics to make a greater contribution to the problem by contributing improvements in remote manipulation technology. These improvements come more in the form of low-cost commercial off-the-shelf components (mobile platform, motors, TV cameras etc) than from fundamental research advances. Improvements are still being made: improved remote manipulation, blast survivability, operator interface improvements and mobility improvements have all contributed significantly to performance and reduced operating costs.

Military counter-mine priorities have shifted in the mean-time. Slow progress in development of multi-sensor fusion devices and significant improvements in mine-resistant vehicle design have moved the priority from mine detection to protection. Much of the vehicle design technology originated in Rhodesia and South Africa in the 1970s and has since been refined in Australia and elsewhere, mostly in the defence sector.

4. Response to Change

The relocation of the Afghanistan Mine Action Centre from Islamabad to Kabul in 2002 significantly reduced our ability to maintain working level contacts with Afghan demining agencies. I initially refocused our research resources in Pakistan on water supplies for settlements near Islamabad: a problem with just as much significance in terms of human disease and suffering as landmines in Afghanistan. An investigation into the relative cost-effectiveness of several alternative solutions led to a startling discovery. The real cost of water, even in areas of Pakistan where water supply schemes had been installed, was much higher than expected and up to 30 times the cost per litre in Australia (Trevelyan 2005). This led to a realization that difficulties in obtaining cost-effective engineering solutions in Pakistan were occurring on a large scale. Here there seemed to be a close link with the surprising observation that demining costs in Afghanistan and Cambodia were at least as expensive as in Croatia and Bosnia where labour costs are at Western European levels, and could be even more expensive.

One of the main issues encountered with our demining research in Pakistan (in support of Afghanistan mine clearance) was an unexpected difficulty with dissemination of technology improvements. Part of the reason for researching low cost incremental improvements to existing demining methods was to eliminate potential difficulties with implementing costly high-tech solutions. One example of this was a suggestion to improve the quality of saws issued to Cambodian deminers. Commercial saws available in hardware stores in industrialized countries could provide around 10% productivity improvement because Cambodian deminers spend much of their time cutting thick vegetation and use low quality tools that quickly became blunt. However, with a deminer pay rate of US$120 per month, the benefit from using the saws was insufficient. The anticipated 10% performance improvement would be outweighed by the cost of the saw at $35 and expected saw life of 1 month.

However, by focusing on the deminers' pay rate one falls victim to a common and widespread myth that countries with low pay rates provide a low cost operating environment. The simplistic argument against using improved saws in Cambodia misses the cost of supporting, feeding, housing, training, equipping and supervising deminers in the field, typically between US$1500 and US$3000 per month. A 10% performance improvement then provides a monthly benefit of at least $150, far exceeding the cost of a saw.

A further issue with even greater financial effects is the almost complete absence of engineering management skills available from people supervising demining operations in countries like Cambodia and Afghanistan. Two examples will illustrate this problem. In Afghanistan, demining organizations using mechanized equipment (before the US invasion) achieved very low utilization and hence relatively high costs in real terms. (In practice the consequences were mainly frustration among sponsoring organizations because the equipment had actually been donated.) In Cambodia, close examination of demining productivity revealed wasted efforts clearing large areas where the evidence strongly suggested localized patterns of landmine contamination (GICHD 2005a). While the demining organizations report impressive clearance statistics, a significant proportion of the effort achieves no useful results other than distributing donated funds among demining agency staff. Yet demining operations are supervised by engineering staff who have qualified in institutions with curricula and standards roughly equivalent to engineering schools in any industrialized country. If one examines engineering practice elsewhere in Cambodia and Afghanistan, even in Pakistan, in India and many other developing countries one finds similar patterns. This helps to explain the high costs for water observed in Pakistan, for example. GICHD(2005a) identified these skill gaps as the main reason inhibiting productivity improvements in demining.

5. Engineering Practice: An Enigma

These observations raised an intriguing issue: how does one define engineering management skill? How and why to these skills develop in industrialized countries but not in developing countries, noting that many highly competent engineers in industrialized countries obtained their education in developing countries?
These questions led me to interview and make observations of engineers in Pakistan with the expectation that comparison with reference data on engineering practice in countries like USA, Europe, Japan, Canada and Australia would soon indicate the essential differences. Solving this problem could lead to large productivity improvements, not only in mine clearance, but also with critical engineering services like transport, energy distribution, food processing and water supply in most developing countries. Unfortunately we found that the anticipated reference data on engineering practice does not yet exist. This was a remarkable discovery: it is astonishing that at the start of the 21st century there is no systematically researched account that explains what engineers and technologists actually do in their daily work, except for a handful of narrow case studies and some work on glamorous aspects of high-tech design processes (Trevelyan and Tilli 2007).
Thus, the author has reached a critical turning point in this journey that started with research on landmine clearance. Such an obvious question "what do engineers do?" with such universal significance presented an irresistible change in approach. With the help of around 20 colleagues, this author is now working on answers that offer significant long term improvements in engineering practice (e.g. Trevelyan 2007). That offers, in turn, the prospect of making significant improvements in living standards in both industrialized and developing countries and also substantial improvements in demining practice.

6. Future Prospects for Robotic Demining

Figure 4, a teleoperated flail machine, represents the current state of the art in robotic demining. Teleoperated devices, often known as 'bomb disposal robots' and similar in principle, are used for neutralizing IEDs. What, then, are the research challenges for robotics researchers working on landmine and unexploded ordnance clearance in the future that could lead to significant advances?
We need further advances in mechatronics design, sensing and accurate understanding of the problems to be solved using robots.
The best starting point for research is to witness people undertaking mine clearance operations which are often readily accessible in many countries. It is unfortunate that many researchers think a visit would be far too hazardous and, as a direct result, have failed to appreciate the practical difficulties involved. Photographs taken at mine clearance operations are available to provide researchers with a web site for reference purposes, partly in answer to this need to understand the practical realities (Trevelyan 2000a).
One of the main motivations for robotics researchers has been the perception that mine clearance is a hazardous occupation and that it would be more preferable for robots to be exposed to minefield risks than human beings. While mine clearance is certainly a hazardous occupation it is not necessarily dangerous. Accident records show that mine clearance in Afghanistan in 1998 resulted in about half the rate of injury of the United States forestry industry and about one third the rate of injury for the United States building

construction industry per hundred thousand working hours. Mine clearance agencies use advanced techniques to improve safety when possible (Trevelyan 2000b). In terms of deaths, demining is considerably less hazardous than mining, construction of building foundations, and especially offshore drilling rigs (GICHD 2005b, p11-14).

Another motivation for research is to reduce deaths and injuries among local people who have to live with the daily threat of landmines and unexploded ordnance. Again, there are misperceptions of risk. The incidence of death and injury from mine explosions is often very small compared with disease, for example. The main priorities for local people tend to be improvements for water and food supplies, education, sanitation and physical security: landmine clearance is usually a much lower priority and it is often hard to justify significant local resources.

Fig. 5. Evolution in deminerprotection – visor and upper body protection by ROFI. (Photo: Andy Smith)

It is also important that robotics researchers intending to contribute to the solution of this problem, understand the relatively small size of humanitarian demining operations which have been funded from a combined international humanitarian aid budget of approximately US$400 million. These programs spend an estimated $20 million annually on all equipment needs. The market for specialized humanitarian demining detectors is therefore very small and manufacturers cannot afford research and development specifically to support humanitarian demining solutions (Newnham and Daniels 2001). Adapting technology developed for other purposes, such as military equipment or civil engineering construction machinery, is more likely to be feasible.

The last 10 years has seen significant improvement in mine clearance techniques but progress is still slow and robotics may well provide the final solution in the long term. There is plenty of time to develop robotic techniques that ultimately could provide the only cost-effective method for removing this menace.

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3

Mine-suspected Area Reduction Using Aerial and Satellite Images

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1. Introduction

A huge amount of antipersonnel (AP) mines is polluting the environment in at least 84 countries (ICBL, 2005). Thanks to the Mine Ban Treaty, also known as the Ottawa Convention, mine clearing operations have been organized in a more controlled and effective way. Nevertheless, mine clearance remains a very slow and resource demanding process. On average, a mine-clearance expert clears an area of 10m² every working day with conventional tools, i.e. metal detectors and prodders. Five years were needed to clear only 146km² in Cambodia, which gives an idea of the large scale of the problem (ICBL, 2005). Therefore, humanitarian mine clearance operations must be understood and designed correctly, with the conviction that their main goal is to provide efficient aid to innocent people, who may be severely injured by this dreadful pollution. In this context, it is important to keep in mind the recommendations made during the Standing Committee on Mine Clearance, Mine Risk Education and Mine Action Technologies. These recommendations clearly state that (i) technologists should avoid building technologies based on assumed needs and should work interactively with end-users, (ii) appropriate technologies could save human lives and increase mine action efficiency and (iii) nothing is more important than understanding the working environment (Acheroy, 2003; JMU, 2007).
The analysis of current mine clearance campaigns not only reveals the far too long time needed to clear polluted terrain, but also brings to the fore a far too large false alarm rate, the threat of plastic mines, difficult to detect by classical means such as metal detectors, and the large variety of mine clearance scenarios, depending on the country, the region, the climate and the place of pollution (houses in villages, roads, agricultural fields, etc). This tends to make mine detection a very complex problem for which no silver bullet solution exists. Further, the concept of mine action itself is evolving. Indeed, as most of the time mine detection and removal are still done manually and as there is still a huge amount of contaminated areas, obviously, it will be impossible to reach a mine-free world at the horizon 2010 as required by the Mine Ban Treaty (GICHD, 2007). Consequently, the first priority of mine action becomes to allow affected countries, regions and people to reach a normal way of life according to local socio-economic standards. This new vision tends to increase the importance and the development of management tools facilitating prioritisation and contributing to a rational and efficient distribution of the resources available. Danger

and risk assessment maps provided by the SMART[1] project described in this Chapter, are possible entries of such management systems.
This Chapter is subdivided in 11 Sections. Sections 2 and 3 discuss the problem of close-in detection and area reduction, and sketch the SMART approach as a tentative to solve the problem of mine-suspected area reduction. Sections 4 to 11 describe the SMART processing tools. Section 4 presents the available data. Section 5 introduces the image-processing concept. Section 6 summarizes the pre-processing algorithms. Section 7 sketches the anomaly detection tools. Section 8 describes feature extraction methods. Section 9 summarizes the classification algorithms, while Section 10 and 11 address the change detection and data fusion approaches respectively.

2. The Problem of Mine-suspected Area Reduction

In order to understand the incurred risks, let us consider the event A : "*occurrence of an alarm*'' in a given position $\mathbf{x} = (x, y)$ (obviously depending on the field reality but also on the detection system in use) and two contradictory events M : "*the presence of mines*'' and $\overline{M}$ "*the absence of mine*''. The probability $p_A(\mathbf{x})$ of the occurrence of an alarm in $\mathbf{x} = (x, y)$ can be expressed as follows:

$$p_A(\mathbf{x}) = p_M(\mathbf{x}).p_{A/M}(\mathbf{x}) + p_{\overline{M}}(\mathbf{x}).p_{A/\overline{M}}(\mathbf{x}) \quad (1)$$

Therefore, the important parameters characterizing the mine detection problem, are the mine occurrence probability, the detection probability and the false alarm probability (Acheroy, 2007):

- The *mine occurrence probability* in a given position $\mathbf{x}$ of a minefield, $p_M(\mathbf{x}) = 1 - p_{\overline{M}}(\mathbf{x})$, expresses the local mine density of that minefield. Obviously, it is impossible to control this parameter which depends on the field reality. Nevertheless, this parameter is very important for assessing the probability of an alarm in a given location $\mathbf{x}$ of the minefield.
- The *detection probability*, $p_{A/M}(\mathbf{x})$, is the probability of having an alarm in a given position $\mathbf{x}$ of a minefield for a given sensor system, if there is at least one mine in that position. This probability gives an indirect measure of the non-detection probability of that sensor system as well.
- The *probability of false alarm*, $p_{A/\overline{M}}(\mathbf{x})$, also called *false alarm rate*, is the probability of having an alarm, for a given sensor system, in a given location $\mathbf{x}$ if there is no mine in that location.

The two latter definitions are extremely important to understand the mine action problem and to design mine clearance systems. Note that a more precise expression for (1) should in particular take into account a sensor sensitivity area around the mine, but this is out of the scope of this Chapter. Obviously, the detection probability $p_{A/M}(\mathbf{x})$ should be as close as possible to one. Evaluating the detection probability also amounts to evaluate the risk

[1] "Space and airborne Mined Area Reduction Tools" (SMART), project funded in the 6th framework program by the European Commission / DG / INSO

$p_{\overline{A}/M}(\mathbf{x})$ of the occurrence of a mine that is not detected, since $p_{\overline{A}/M}(\mathbf{x}) = 1 - p_{A/M}(\mathbf{x})$. This risk is concerned with human safety and is therefore of the utmost importance. No such risk is acceptable and it is therefore an absolute requirement that a mine clearance system should decrease the probability of such a risk to the lowest upper bound possible. Therefore, any mine clearance operation enhancement must result in the highest possible detection probability $p_{A/M}(\mathbf{x})$ (close to one) and in the smallest possible false alarm rate $p_{A/\overline{M}}(\mathbf{x})$, all that at the lowest price. Unfortunately, increasing the detection probability generally results in increasing the false alarm rate. The most efficient way for increasing the detection probability while minimizing the false alarm rate consists in using several complementary sensors in parallel and in fusing the information collected by these sensors (Milisavljević &Bloch, 2002). The problem of sensor fusion is discussed in more detail in Chapter 4.

Let us now discuss the problem of mine-suspected area reduction. This important challenge consists of finding *where the mines are not*. Mine-suspected area reduction, recognized by the mine action community as a mine action activity at least as crucial as close-in detection, enables to reduce mine clearance time and resources.

Mine-suspected area reduction means finding the set of positions **x** for which $p_M(\mathbf{x})$ equals zero. Under this condition, Equation (1) yields

$$p_A(\mathbf{x}) = p_{A/\overline{M}}(\mathbf{x}) \tag{2}$$

and mine-suspected area reduction with classical tools (e.g. metal detectors) is affected by the high false alarm rate ($p_{A/\overline{M}}(\mathbf{x})$) of current sensors, making, as said earlier, the corresponding operations slow, tedious and resource demanding. Further, long-term empirical data from the Croatian Mine Action Centre (CROMAC) show that around 10% to 15% of the suspected area in Croatia is actually mined (SMART, 2003). The minefield records alone, beyond the fact they are not always reliable and complete, do not contain enough information for the proper allocation of limited mine clearance resources to really mined areas. Decision makers need additional information.

This means that a broader approach is needed, which has to include *a priori* knowledge. Indeed, if no *a priori* knowledge is available about context as conflict history, strategies and tactics of the parties, communication networks, terrain configuration, power lines, land use, etc., the *a priori* probability of having a mine in a given location $p_M(\mathbf{x})$ is distributed uniformly in **x** and the only method to clear of mines is the classical close-in detection. If on the contrary *a priori* information is available on the distribution of $p_M(\mathbf{x})$, especially by deducing from the context where the mines are certainly not (e.g. agricultural fields in use) and where the mines are possibly present (e.g. along the confrontation lines, in the vicinity of trenches, on tops of hills that are possible artillery positions, etc.), it makes sense to build a risk map ($p_{M/\text{context}}(\mathbf{x})$) of the affected areas. This assumes to define a list of indicators of mine presence ($p_{M/\text{context}}(\mathbf{x})$ is not negligible) and absence ($p_{M/\text{context}}(\mathbf{x})$ is close to zero) as well as a list of tools and methods to detect them. One of the most appropriate methods to build a risk map is associating airborne and satellite data, with context and ground truth data collected during field campaigns. Analysing the collected data with modern remote sensing tools, as land use classification, anomaly detection and change detection, considered as experts, and fusing their "opinions" enables to produce the so-called risk or danger maps. The main advantage of airborne methods rests in the possibility to reduce areas located in

regions that cannot be accessed without very costly safe lanes and full safety procedures that are mandatory when entering the minefields. Further, the assessment of areas for reduction and assessment of spatial danger distribution can be performed in short time over large areas.
In the context of mine action, a frequently asked question concerns the possibility of directly detecting mines using high-resolution airborne sensors. As part of their policy to assist Developing Countries, the European Commission (the former DG-VIII) and the participating member states have funded in 1997 a "Pilot project on airborne minefield detection in Mozambique" which has clearly shown that it is impossible to find antipersonnel landmines even with a very high-resolution (order of magnitude of a few millimetres) airborne sensors neither using objective signal processing tools nor using subjective photo-interpretation (Druyts et al, 1998).

3. The SMART Approach

There are different well-known methods in use to perform mine-suspected area reduction, especially mechanical ones. Nevertheless, most of the time these methods are changing (very often damaging) the environment and the ecosystem, and are expensive. Therefore, several approaches have been developed, trying, when possible, to acquire the necessary information remotely from space or air. In those cases, the information is collected using appropriate sensors, associated with context information collected from the field, and integrated in a geographical information system. Different projects have been initiated in this context (ARC, MINESEEKER, etc., see EUDEM2 website (EUDEM, 2007), for more information). This chapter is intentionally limited to the description of SMART, one of the most promising projects on this matter, applied to Croatia.
The goal of SMART is to provide the human analyst with a GIS-based system – the SMART system – augmented with tools and methods specifically dedicated to SAR and multi-spectral data processing in order to assist him in his interpretation of the mine-suspected scenes, during the area reduction process. The advantages of such tools and methods rest in the possibility to process automatically a large amount of data and to summarize and visualize large amounts of information (SMART, 2004). The use of SMART includes a field survey and an archive analysis in order to collect knowledge about the site, a satellite data collection, a flight campaign to record the data, – multi-spectral with the Daedalus sensor and polarimetric SAR with the E-SAR from DLR[2] –, and the exploitation of the SMART tools by an operator to detect indicators of presence or absence of mine-suspected areas. A data fusion module based on belief functions and fuzzy sets helps the operator to prepare thematic maps that synthesize all the knowledge gathered with these indicators. These maps of indicators, transformed into *risk maps* designed to help the area reduction process, show how dangerous an area may be according to the location of known indicators and into *priority maps* indicating which areas to clear first, accounting for socio-economic impact and political priorities. Figure 1. presents an example of a risk map. Table 1. presents a summary of the results obtained with SMART and shows a global substantial area reduction rate of 25% and a misclassification rate of 0.1% for what SMART considers as not mined and is actually mined. Further, it must be noted first, that the reduction rate strongly varies from

[2] DLR: Deutsches Zentrum für Luft- und Raumfahrt

one test site to another (from 10 to 50%), but that the error rate remains relatively constant, second, that the marginal errors (0.1%) lie at the frontier of contaminated areas.

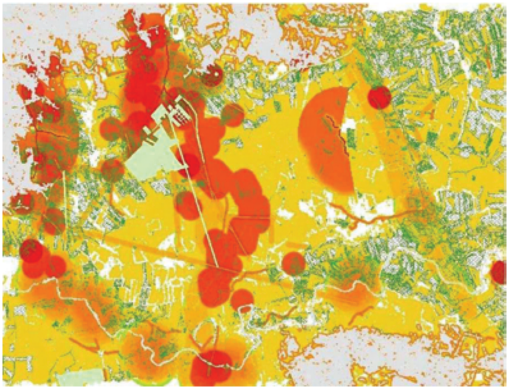


Fig. 1. : Continuous 'risk map' - the scale of risk ranges from red (danger) to green (no danger), white means no status (forests) - Source: ULB

Test site	Area subject to validation (km^2)	Area proposed for reduction (km^2)	Reduction rate (%)	Error rate (%)
Total	3.9	0.98	25	0.1

Table 1. Global results obtained by SMART

4. Available Data

The available data include SAR, multi-spectral, high resolution optical and satellite data. SAR data were collected with the ESAR system of DLR in vv-polarization (waves are vertically transmitted and received) X- and C-band, and in fully polarimetric (hh, hv, vv, vh-polarizations) L- and P-band. Table 2., where SLC stands for Single Look Complex and ML for Multilook, summarizes the characteristics of these SAR data. SAR and multi-spectral data have been geo-coded.

Bandes	**Polarisation**	**Resolution in range**	**Resolution in azimuth**	
			SLC	**ML**
X	vv	2.0 m	0.6 m	1.5 m
C	vv	2.0 m	0.6 m	1.5 m
L	vv, hh, hv, vh	2.0 m	0.8 m	2.0 m
P	vv, hh, hv, vh	4.0 m	1.6 m	4.0 m

Table 2. Characteristics of SAR data

Multi-spectral data were collected at very low altitude (330 m to get a high spatial resolution) in 12 different channels, ranging from visible blue to thermal infrared, with the

Daedalus scanner of DLR. Table 3. summarizes the characteristics of these multi-spectral data.

Channel Number	Spectral range (µm)	Wavelength of maximum sensitivity (µm)	Resolution
1	0.41-0.46	0.44	0.8 - 1.0 m
2	0.44-0.53	0.51	
3	0.51-0.62	0.58	
4	0.58-0.65	0.61	
5	0.61-0.72	0.65	
6	0.67-0.80	0.73	
7	0.73-1.00	0.83	
8	0.85-1.10	0.95	
9	1.45-1.82	1.71	
10	1.95-2.42	2.20	
11	8.20-14.0	10.00	
12	8.20-14.0	10.00	

Table 3. Characteristics of multi-spectral data

DLR also provided the SMART teams with a complete set of RMK photographic aerial views recorded with a coloured infrared film at a resolution of 3 cm. This latter data set, which is not geo-coded and far too large to be processed, has only been used as evidence to control the good working of processing tools and for qualitative interpretation by photo-interpreters. In the latter case, RMK images were registered manually with SAR and multi-spectral data. Finally, geo-coded KVR-1000 black-and-white satellite images recorded before the war in Croatia, with a resolution of 2 m, have been purchased in order to assess the changes in the landscape due to the war. Table 4. summarizes their characteristics.

Site	Date of record	Resolution	Type
Glinska Poljana	May 13, 1992	2.0 m	Panchromatic
Pristeg	May 13, 1992		
Ceretinci	June 04, 1988		

Table 4. Characteristics of KVR-1000 data

5. Image Processing Tools Concept

On basis of field campaigns and discussions with mine action specialists of CROMAC, it clearly appeared that the first step to achieve was to set up a list of features (called indicators) to look for in the data, based on what could be seen in the data and what could be related to the absence or presence of mines or minefields.

Indicator of mine absence	Indicator of mine presence	Data	Methods and Tools
Cultivated fields		MS	Classification
Asphalted roads		MS, SAR	Classification and detection
Infrastructures In use		MS, SAR	Classification and detection
	Trenches and man-made embankments	MS, SAR, RMK	Detection of linear features and interactive processing
	Bunkers	RMK	Interactive processing
	Concealed paths to trenches or bunkers	RMK	Interactive processing
	Shores of rivers	MS	Classification and detection
	River banks, shallow rivers or creek	RMK	Interactive processing
	Bridges (destroyed bridges included)	MS, RMK	Detection of linear features and interactive processing
	Tracks no longer in use	MS, KVR, RMK	Detection of linear features and interactive processing
	Agricultural areas no longer in use	MS, KVR	Classification and change detection
	Crossroads, especially with no longer used tracks	MS, KVR	Detection of linear features
	Irrigation/drainage	MS, SAR	Detection of linear features
	Edges of forests	KVR	Classification
	Hedges (defensive lines)	SAR	SAR specific detector
	Power supply poles	SAR	SAR specific detector
	Soft edges of hardtop roads	MS, SAR	Classification and detection
	Tank and canon holes	RMK	Interactive processing
	Mine accidents and Incidents	MAGIS	
	Minefield records	MAGIS	+ Analysis of confidence
	Confrontation zones	MAGIS	+ Conflict history reconstruction
	Hilltops and elevated Plateaus	DEM	Dedicated tool
	Dominant slopes and heights	RMK	Interactive processing
	Houses used as rooms, ammunitions stores, HQs, bunkers	Fieldwork	Interactive processing
	Damaged or destroyed houses	RMK	Interactive processing

Table 5. Indicators with corresponding data and processing tools

Obviously, indicators of absence of mine are the most important for helping to decide if a mine-safe area is actually mine-safe. Unfortunately, these indicators are not numerous. Although a key indicator of mine absence seems to be the cultivated fields, most of indicators available are indicators of mine presence. Therefore, SMART has two uses: (i)

area reduction as such - by detecting indicators of mine absence -, and (ii) suspicion reinforcement - by detecting indicators of mine presence (Yvinec, 2005).
The next step consists in developing methods and tools to detect these indicators. The developed methods and tools are based on two approaches: (i) anomaly detection (detecting specific objects in the data) and (ii) classification, i.e. assigning each pixel (pixel-based classification) or region (segment-based classification) to a specific land use class. Table 5. summarizes the list of indicators with the corresponding tools developed in SMART (MS means multi-spectral, MAGIS mine action GIS and KVR KVR-1000 satellite images). If 'Methods and tools' are called ``interactive processing", it means that the resolution of the multi-spectral and SAR data is not sufficient and that other means have been added as the photo-interpretation by image analysts of manually registered RMK high-resolution aerial views, recorded originally on films (coloured infrared) with a resolution of 3 cm and digitised on CD-ROM with a resolution of 10 cm.
The last step fuses the information produced by anomaly detectors and classifiers, considered as experts in a framework of belief functions or in a fuzzy approach, and builds the so-called risk maps as a probability map of mine presence (or mine absence) given the context.

6. Pre-processing

The pre-processing tasks consist in registering and geo-coding the available data as well as restoring the SAR images. The latter operation is necessary to reduce the speckle existing in SAR images. Appearing as a random granular pattern, speckle seriously degrades the image quality and hampers the subsequent pattern recognition processing.

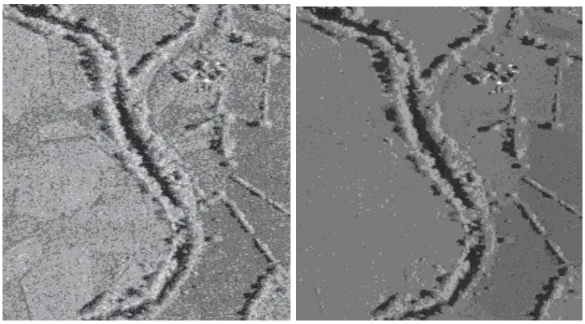


Fig. 2. Speckle reduction in SAR images.

The restoration process is based on the non-decimated wavelet transform. Each wavelet coefficient is multiplied by a given shrinkage factor (soft threshold), which is a function of the magnitude of the coefficient. In contrast with other methods, the algorithm used achieves a *soft* spatial adaptation, from the homogeneous to the highly heterogeneous areas.
The wavelet coefficients are not filtered in different regions according to different rules, but a unique shrinkage function is applied, that accounts for local statistics of the wavelet coefficients, and automatically adapts to the local spatial activity in the image (Pizurica et al, 1999; Duskunovic et al, 2000). Figure 2. gives an example of speckle reduction using this method.

7. Anomaly Detection

7.1. Bushes/Hedges, Trees, Water and Radar Shadow

Hedges growing on the border of agricultural fields are often used as defensive lines, protected by mines and are therefore good candidates of mine presence. In multi-spectral data, hedges and trees look very similar as only the top of the vegetation, the leaves, is seen. Radar waves penetration depends on the wavelength. While X-band waves (λ=3cm) are reflected mostly by the top of the vegetation (a few centimetres), L-band waves (λ=24cm) penetrates deeper into the vegetation structure and gets reflected into the volume of the vegetation. For larger wavelengths (λ =67cm for the P-band), the vegetation volume becomes invisible and the waves undergo double reflections at the ground and the trunk of trees. Because of this backscattering process, trees are clearly visible in the P-band thanks to double reflections between the trunk and the ground while bushes and hedges, not visible in the P-band, provoke volume reflections in the L-band, and the combined use of L- and P-band SAR data allows to distinguish efficiently trees from bushes and hedges. The cross-polarized L-band data[3] L_{xx} is best sensitive to backscattering in the vegetation volume while co-polarized P-band data (e.g. P_{hh}) is best sensitive to double reflections on the horizontal ground and the vertical trunk.

For a better separation of both targets from other objects additional parameters are used: the X_{vv} and P_{xx} channels[4], the 4th channel of the multi-spectral sensor, and the ratios P_{xx}/X_{vv} and P_{xx}/X_{hh}. Figure 3. gives an example of detected bushes and trees, using a composite image where red is P_{hh}, green L_{xx} and blue X_{vv} (Keller et al, 2004).

An area is classified as water if the backscattering is very low in the X_{vv} and L_{vv} channels (because of the specular reflection of very smooth areas), if the thermal infrared channel response of the multi-spectral sensor is very low (because of the low emission of cold objects), if the 4th channel response of the multi-spectral sensor is neither very dark nor very bright and if the area fulfils some size conditions.

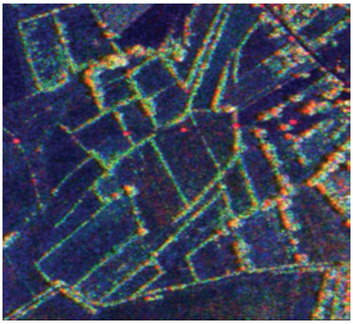


Fig. 3. Detection of hedges (green), trees (light red) and power line poles (dark red) from SAR data. Image courtesy of DLR

[3] For a monostatic configuration $L_{xx} = \frac{L_{vh}}{2} + \frac{L_{hv}}{2}$

[4] For a monostatic configuration $P_{xx} = \frac{P_{vh}}{2} + \frac{P_{hv}}{2}$

7.2. Power Lines

Power lines as important infrastructure are often considered as strategic targets protected with mines. Detecting automatically power lines can prove much more cost effective than extracting them manually on old and inaccurate maps.
Usually, in SAR images, power line poles induce strong double bounce reflections between the pole foot and the ground in the P-band, independent of the sensor flight direction. The absence of volume scattering distinguishes them from the vegetation (tree crowns) and makes easier discriminating between poles and tree trunks. Further, power line poles are too small to be detected using the multi-spectral data and only SAR data are used in the algorithm – a simple threshold operation (see poles in dark red on the image of Figure 3.).
In order to reduce the number of false alarms and to find power lines considered as an alignment of poles, a Hough transform applied on all detections in the image and makes for finding the aligned objects that with high probability belong to a power line.

7.3. Hilltop Detection

The detector allows the user to create contours and to determine an area where the altitude is higher than or equal to a given altitude. Obviously, this operation is performed using a DEM provided by the user if it exists (as it is the case in Croatia) or computed from interferometric SAR data.

7.4. Road and Abandoned Road Detection

7.4.1. Bright Line Detector in Multi-spectral Images

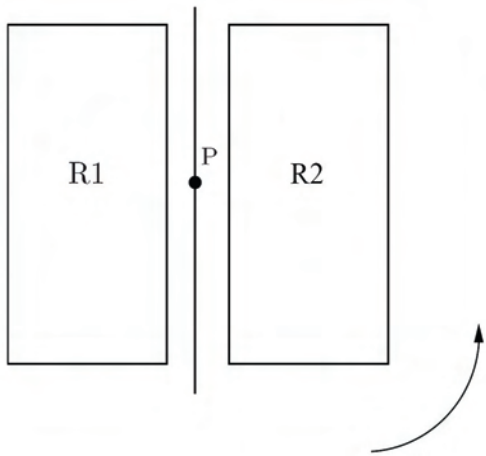
Detecting roads and paths on multi-spectral images involves detecting bright lines in single channels. A line is characterized by an edge at both sides of it. The gradient is positive at one side of the line and negative at the other side (anti-parallel gradients). This principle is used in line detection.
After applying a gradient operator on the image, the line response image consists of the detected anti-parallel gradients. Next, suppressing recursively the non-maxima of the line responses perpendicularly to each line results in a line strength image.
After breaking possible squares (clusters of four adjacent pixels), to convert the detected lines into vector objects, a minimum line strength is set to start each line object and to continue the line following.
To suppress false targets, the line candidates are filtered based on the grey-value of their underlying pixels, in order to secure sufficient absolute line brightness, and the candidates with a too small length are rejected.
All channels, in which roads appear as bright lines (i.e. channels 2, 3, 4, 9 and 10), are selected and a new image is made with in each of its pixel the maximum grey-value of the corresponding pixels of the selected channels. Finally, the algorithm just described is applied to this new image.
The previous method applies also to dark edges after obvious adjustment.

7.4.2 Multivariate Edge/Line Detector in SAR Images

The presence of speckle makes pixel-wise methods using a simple filtering mask inappropriate for edge detection in SAR images. The solution that is commonly adopted is to take into account larger neighbourhoods of each pixel for deciding whether an edge passes through that pixel.

For deciding whether a vertical edge passes through pixel P in the images (see Figure 6. (a)), two rectangles are constructed around the point P and statistics are calculated in both rectangles. If the statistics differ, an edge passes; otherwise, there is no vertical edge. The test is repeated in every pixel for a given number of orientations of the set of scanning rectangles and the final edge strength is the maximum of the statistics differences for all orientations. The orientation corresponding to that maximum is the edge direction in the point.

The user can choose between different statistical tests (e.g. Hottelings, Levene, Student or Median tests) for comparing the statistics inside the scanning rectangles. For multi-channel data techniques, multivariate statistical hypothesis tests are used. For single channel SAR data a Touzi ratio detector[5] is implemented (Touzi et al, 1988). A few other methods are also possible (Borghys et al, 2002).



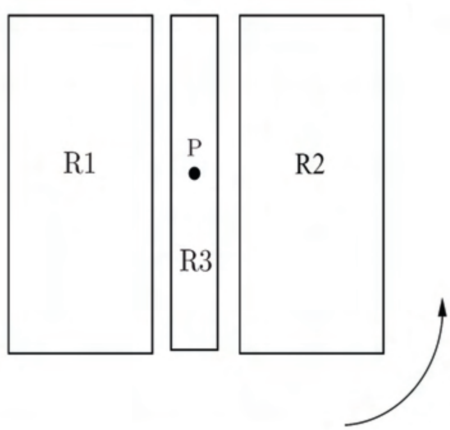


Fig. 6. (a) Multivariate edge detector. (b) Multivariate line detector.

For deciding whether a line passes through pixel P in the images (see Figure 6. (b)), three rectangles are used. The middle one is centred on the current point P and is narrower than the two others. In order to detect whether a line in a given orientation passes through point P, the statistics of the two outer rectangles are compared with those of the middle one. The response of the detector is the response corresponding to the smallest difference in statistics. This allows avoiding false alarms due to (single) edges. The width of the central rectangle is chosen such that it corresponds approximately to the possible widths of the lines (e.g. roads) to be detected.

[5] The Touzi edge detector is based on the ratio of averages in intensity images. The edge detector response between rectangle i and j is defined as $F_{R_i R_j} = 1 - \min\left(\frac{\mu_i}{\mu_j}, \frac{\mu_j}{\mu_i}\right)$

In SAR images it is often possible to predict whether a given object will appear as a bright or a dark line. Roads for instance will almost always appear as dark lines, because their surface is very smooth compared to the wavelength of the radar and only induces single reflections. In this case an extra condition can be applied in the line detection algorithm. The condition is based on a comparison of the average image intensity of the centre rectangle with the one found in the two outer rectangles. The user can choose between different tests for comparing the statistics inside the scanning rectangles.

For multi-channel log-intensity SAR data or multi-spectral data, a multivariate statistical hypothesis test of Hotellings is used. For single channel log-intensity SAR data, either a Student test (also valid for multi-spectral data) or a Touzi ratio detector (only for SAR data) can be performed.

All tests are applied after speckle reduction, either on the slant or the geo-coded SAR images. The best results are obtained after speckle reduction on the geo-coded log-intensity images, using the Hotellings test applied on all polarizations (or all bands in multi-spectral) at the same time. Although this gives the best results, applying the Student test to a single polarization is a lot faster. An example of line detection in a full polarimetric SAR image is given in Figure 7.

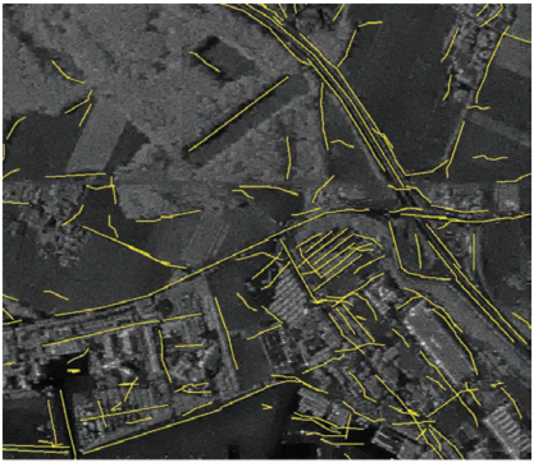


Fig. 7. Detection of lines in a full polarimetric L-band SAR image.

7.4.3 Road Tracker

The tool ``road tracker'' is used to follow a linear feature from an original point given by the user. As SAR data are subject to speckle, this tool is only applied on multi-spectral data. In an initialisation phase, the input image is smoothed using a Gaussian filter, the gradient and the Hessian of the smoothed image are computed at each pixel and for each pixel, the eigenvectors and eigenvalues of the Hessian are computed and the eigenvector associated to the largest eigenvalues is kept (if the pixel lies on a linear feature, this eigenvector is normal to the direction of the linear feature).

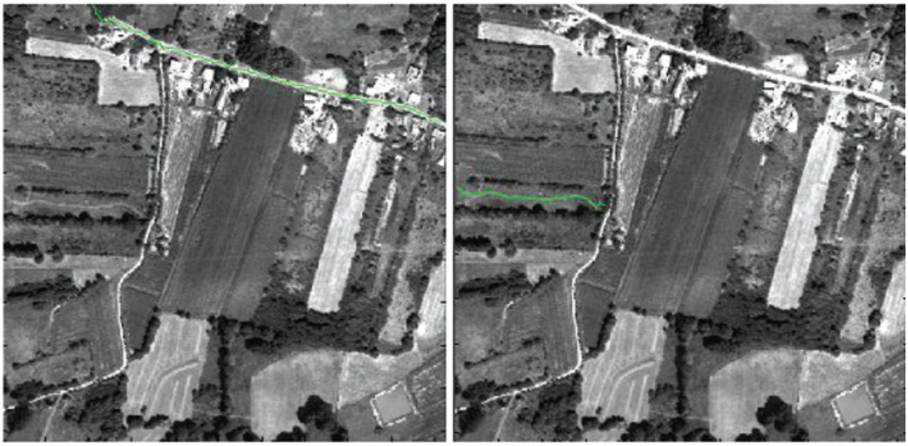


Fig. 4. Tracking of a road (left) and of a small path (right)

In a production phase, the starting point given by the user is improved by trying to move it closer to the middle of the linear feature. Therefore, a Principal Component Analysis (PCA) optimises the direction of the linear feature computed during the initialisation phase. Then, in the direction normal to the direction of the linear feature and in a surrounding window, the pixel with the smallest gradient (the new location of the starting point) is determined. A tracking algorithm is used in the best (from previous step) direction and its opposite. The tracking algorithm is based on a Kalman filter to correct and predict the next point. Figure 4. gives two examples of tracking results in green.

7.4.4 Abandoned Road Detection

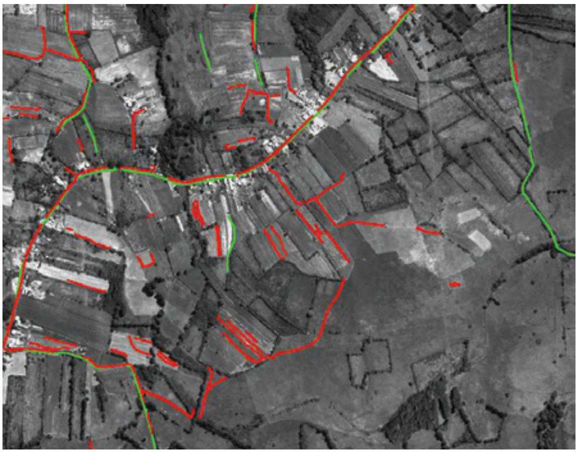


Fig. 5. Abandoned road detection

The methods described above can be used to detect changes in order to find abandoned roads. These methods are respectively applied to a pre-conflict panchromatic satellite image (KVR image) and a post-conflict airborne multi-spectral image (acquired with the Daedalus line scanner). For the multi-spectral image, the method is applied on three of the bands on which the roads appear as bright lines. The detection results are fused using a "AND" operator. Figure 5. shows the final result superimposed on a panchromatic Daedalus image, in red the detection on the Daedalus images, in green on the KVR image. Candidate abandoned roads are the lines which only appear in green. An interactive processing on the RMK images allows reducing the number of false candidates.

8 Feature Extraction

8.1. Texture Generation with a Gabor Filter Bank

Convolving an image (e.g. a channel of the multi-spectral images) with a bank of Gabor filters produces texture images. Each convolution with a specific filter from the bank produces a specific texture image. These texture images can be used as additional input images in the classification process to improve the detection of classes with specific textures. The Gabor filter bank consists of the following centred filters:

$$G(x, y, k_x, k_y) = e^{-\frac{x^2+y^2}{\sigma}} . e^{j(k_x x + k_y y)} \qquad (3)$$

where x, y, k_x and k_y are respectively the spatial coordinates and the spatial frequencies.

Two simplifications are introduced to compute the convolution: (i) the Short Time Fourier Transform is used to compute the effect of the complex exponential and (ii) the Gaussian is approximated with a binomial window (Lacroix et al, 2005). A set of feature images is obtained by convolving the input image with each filter and by computing a local energy (the squared module of the result) in each pixel.

8.2. Polarimetric SAR Feature Extraction

8.2.1. Pauli Decomposition

The SAR complex backscattering coefficients (module and phase) are represented in each pixel by the backscattering or Sinclair matrix S:

$$S = \begin{bmatrix} S_{vv} & S_{vh} \\ S_{hv} & S_{hh} \end{bmatrix} \qquad (4)$$

where, in the considered pixel, S_{xy} stands for the backscattering coefficient, which corresponds to a wave sent under polarization x and received under polarization y, x and y being h or v, respectively horizontal and vertical polarizations. The Pauli decomposition consists in the construction of the Pauli target vector **k** and the 3×3 coherence matrix T, given by (Cloude & Pottier, 1996):

$$\mathbf{k}^T = \frac{1}{\sqrt{2}}\left[(S_{hh} + S_{vv}) \quad (S_{hh} - S_{vv}) \quad 2.S_{hv}\right] \qquad (5)$$

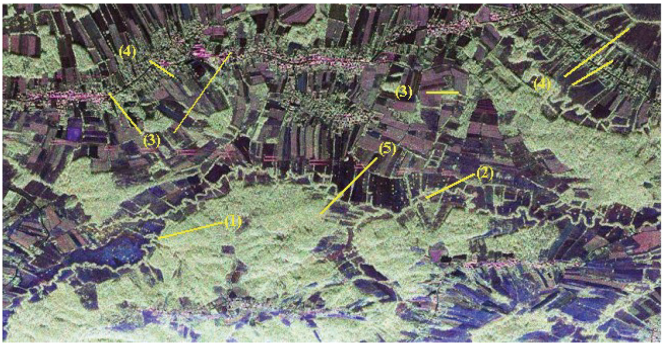


Fig. 8. Pauli decomposition in composite colours: (1) and (2) odd bounces in blue, (3) double bounces in red (4) double bounce at 45° w.r.t. the flight direction and (5) volume scattering in green. Image courtesy of DLR

where the superscript (T) stands for transpose, and

$$T = \mathbf{k}.\mathbf{k}^{*} \tag{6}$$

where the superscript (*) stands for transpose conjugate. The diagonal terms of (6), given by $|S_{hh}+S_{vv}|^2$, $|S_{hh}-S_{vv}|^2$ and $2.|S_{hv}|^2$ are close related to physical and geometrical properties of the scattering mechanism. The first one corresponds to odd bounce scattering (typically rough surfaces), the second one to double bounce scattering (typically in urban areas) and the third one to volume scattering (typically vegetation and forests). Figure 8. gives an example of Pauli decomposition in the region of Blingskikut.

8.2.2. Polarimetric Decomposition and Polarimetric Features

In 1997, S.R. Cloude and E. Pottier have developed a method that is free of the physical constraints imposed by assumptions related to a particular underlying statistical distribution (Cloude & Pottier, 1997). They derive important features as the entropy H, the anisotropy A and the angle α.

Let us consider an estimate $\overline{T}$ of the coherence matrix T, representing the averaged contribution of a distributed target over n pixels and given by:

$$\overline{T} = \frac{1}{n}\sum_{1}^{n}\mathbf{k}_i.\mathbf{k}_i^{*} \tag{7}$$

with eigenvalues λ_1, λ_2 and λ_3 of $\overline{T}$, ordered by decreasing value, as well as the corresponding orthonormal eigenvectors $\mathbf{u}_i$ (i=1…3), columns of the following 3×3 parametric unitary matrix:

$$e^{j\varphi_1}.\begin{bmatrix} \cos\alpha_1 & \cos\alpha_2.e^{j\varphi_2} & \cos\alpha_3.e^{j\varphi_3} \\ \sin\alpha_1.\cos\beta_1.e^{j\delta_1} & \sin\alpha_2.\cos\beta_2.e^{j(\delta_2+\varphi_2)} & \sin\alpha_3.\cos\beta_3.e^{j(\delta_3+\varphi_3)} \\ \sin\alpha_1.\sin\beta_1.e^{j\gamma_1} & \sin\alpha_2.\sin\beta_2.e^{j(\gamma_2+\varphi_2)} & \sin\alpha_3.\sin\beta_3.e^{j(\gamma_3+\varphi_3)} \end{bmatrix} \tag{8}$$

$\overline{T}$ may be rewritten as:

$$\overline{T} = \sum_{i=1}^{3}\lambda_i.\mathbf{u}_i.\mathbf{u}_i^{*} \tag{9}$$

where the eigenvalues λ_i represent statistical weights of three normalized targets $\mathbf{u}_i.\mathbf{u}_i^*$ (i=1 … 3).
The entropy H, or degree of randomness, is defined by

$$H = -\sum_{i=1}^{3} P_i.\log_3(P_i) \tag{10}$$

where the P_i's are probabilities estimated from the eigenvalues of $\overline{T}$:

$$P_i = \frac{\lambda_i}{\sum_{j=1}^{3} \lambda_j} \tag{11}$$

The entropy shows to which extent a target is depolarizing the incident waves. If H is close to zero, the target is weakly depolarizing ($\lambda_2 = \lambda_3 = 0$) and the polarization information is high. If H is close to one, the target is depolarizing the incident waves and the polarization information becomes zero and the target scattering is a random noise process. An object with a strong backscattering mechanism, e.g. a corner reflector (three reflections) or a wall (two reflections) will only show one scattering mechanism that will dominate all others, as the surface backscattering from the surrounding ground, and will have a very low entropy. A forests, because of the multiple reflections in the crown of the trees, will show a backscattering mechanism with polarization characteristics that are less and less related to the polarization of the incoming waves. All extracted scattering mechanisms will have a similar strength (the same probabilities P_i), and the entropy will be close to one.
The anisotropy A is defined as:

$$A = \frac{\lambda_2 - \lambda_3}{\lambda_2 + \lambda_3} \tag{12}$$

Most structures of the SAR intensity image are not longer visible in an anisotropy image, as λ_1, which contains the information of the most important scattering mechanism, does not appear in the latter expression.
Nevertheless, structures, invisible in other data sets, may appear. Anisotropy should never been used without considering the entropy.

The angle α is defined as:

$$\alpha = P_1.\alpha_1 + P_2.\alpha_2 + P_3.\alpha_3 \tag{13}$$

where the α_i's are defined in the parametric unitary matrix built with the eigenvectors of $\overline{T}$. It is easy to show that angle α, built from the eigenvalues and the eigenvectors of $\overline{T}$ and taking its values between zero and $\frac{\pi}{2}$, is a measure for the scattering mechanism itself. α angles close to zero mean that the scattering consists only of an odd number of bounces (e.g. single bounce from the ground, or triple bounce from a corner reflector or from corners at houses). α angles close to $\frac{\pi}{2}$ correspond to double bounce scattering, while α angles close to $\frac{\pi}{4}$ correspond to volume scattering.
Further, it can be shown that the eigenvalues λ_i, thus the probabilities P_i, the entropy H and the anisotropy A, as well as α are all roll-invariant, that is these quantities are not

sensitive to changes of the antenna orientation angle around the radar line of sight. Figure 9. presents an example of image obtained with entropy H, angle α and backscattered intensity.

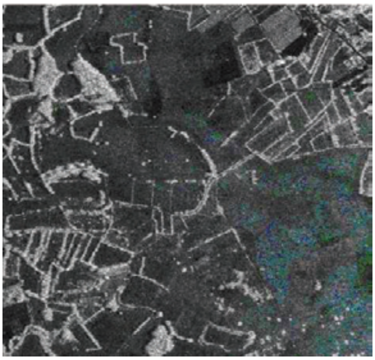


Fig. 9. Example of polarimetric decomposition: hue-saturation-value colour composite of respectively angle α, inverse entropy 1-H and backscattered intensity. Image courtesy of DLR

8.2.3. Interferometric Coherence

In order to define the polarimetric interferometric coherence, the polarimetric complex coherences first need to be defined. In this case, two polarimetric image sets (A and B) are analysed. Stacking the above-defined target vectors $\mathbf{k}_A$ and $\mathbf{k}_B$ of polarimetric image sets A and B respectively provides the new target vector $\mathbf{k}_6$:

$$\mathbf{k}_6 = \begin{bmatrix} \mathbf{k}_A \\ \mathbf{k}_B \end{bmatrix} \quad (14)$$

The 6×6 corresponding interferometric coherence matrix T_6 is estimated by $\overline{T}_6$ given by averaging over n pixels:

$$\overline{T}_6 = \frac{1}{n}\sum_n \mathbf{k}_6.\mathbf{k}_6^* \quad (15)$$

or

$$\overline{T}_6 = \begin{bmatrix} \overline{T}_{AA} & \overline{\Omega}_{AB} \\ \overline{\Omega}_{AB}^* & \overline{T}_{BB} \end{bmatrix} \quad (16)$$

where $\overline{T}_{AA}$ and $\overline{T}_{BB}$ are the estimates of coherence matrices for the image sets A and B respectively, $\overline{\Omega}_{AB}$ is the 3×3 polarimetric cross-coherence matrix. From the elements of this latter matrix, the three polarimetric complex coherences (γ_1, γ_2 and γ_3) can be computed as follows:

$$\gamma_i = \frac{\overline{k}_{A_i}.\overline{k}_{B_i}^*}{\sqrt{\overline{k}_{A_i}.\overline{k}_{A_i}^*.\overline{k}_{B_i}.\overline{k}_{B_i}^*}} \quad (17)$$

where the $\overline{k}_{X_i}$ are the estimates of the corresponding component of $\mathbf{k}_X$, with X being A or B.
Coherence may be decomposed into multiplicative contributions including the backscattered signal-to-noise ratio, the spatial distribution of the illuminated scatterers, temporal variation between acquisitions and the polarization state (Papathanasiou, 2001). Figure 10. gives an example of an interferometric coherence image in composite colours (a low coherence is dark, a high coherence is bright).

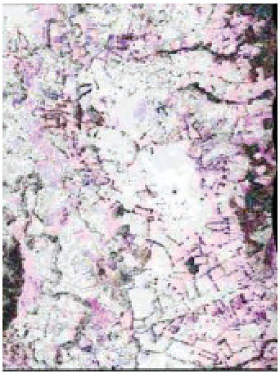


Fig. 10. Interferometric coherence image in composite colours: γ_1 ($hh_A - hh_B$) in red, γ_2 ($hv_A - hv_B$) in green and γ_3 ($vv_A - vv_B$) in blue. Image courtesy of DLR

9. Classification

9.1. Minimum Distance Classifier

This supervised and pixel-based classification method, applied on multi-spectral data assumes the availability of a training set with C known classes i in spectral band j with centres $c_{i,j}$ and standard deviation $\sigma_{i,j}$ in the feature space consisting of grey-values $p_j(m,n)$, where m and n are the pixel coordinates. Texture data may be added to the set of spectral bands. For each pixel, a minimum discounting distance $d(m,n)$ is computed as follows:

$$d(m,n) = \min_{i=1}^{C} \sqrt{\frac{1}{N} \sum_{j=1}^{N} \sigma_{i,j} \cdot (p_j(m,n) - c_{i,j})^2} \qquad (18)$$

where N is the number of bands. If $d(m,n)$ is smaller than or equal to the pre-set maximum distance d_{max}, the resulting pixel value $r(m,n)$ is set to the number of the winning class. Otherwise, the pixel is considered as belonging to an unknown class and its value $r(m,n)$ is set to 255. Distance discounting per band and per class using the standard deviation $\sigma_{i,j}$ has been introduced in (18) so that the higher the deviation is, the wider (less precise) the corresponding distance is. At the same time, a confidence $t(m,n)$ image is computed, given for pixel (m,n) by:

$$t(m,n) = p_{max} \cdot (1 - \frac{d(m,n)}{D_s}) \tag{19}$$

where p_{max} is the maximum grey-scale value (255), and D_s is the maximum distance for class s, with $s = r(m,n)$.

9.2. Classifier Based on Belief Functions

This tool classifies each band on a pixel basis and fuses the results through the belief functions framework. The theory of belief functions (Shafer, 1976) allows saying explicitly that two hypotheses cannot be distinguished. Then the two hypotheses can be merged into what is called a focal element, here a set of classes.

This classifier assigns a focal element to each pixel based on knowledge on how likely a pixel belongs to that focal element given its pixel values in the different channels. This likelihood is measured by what is called a mass.

The theory of belief functions does not require any specific method to compute the masses, provided the masses follow certain rules. For instance the higher the mass, the more likely the belonging to the focal element. The masses must be between 0 and 1. For a given pixel value and a given channel, the sum of all masses over all focal elements equals one.

In order to perform the classification, the classifier must take into consideration all the hypotheses and the evidence supporting them. A hypothesis is that the pixel belongs to a given focal elements. The belief functions framework offers several possible rules for this final decision.

The classifier can choose the hypothesis that is the most supported by evidence. This is called the maximum of belief. In order to avoid the cases where the chosen focal element consists of several classes leading to an ambiguous classification, it is possible to restrict the choice of focal elements to singletons, i.e. focal elements consisting of one class.

The classifier can also choose the hypothesis that is the less in contradiction with the available evidence. This is called the maximum of plausibility. Again the choice may be restricted to singletons in order to have an unambiguous classification.

A compromise between the maximum of belief and the maximum of plausibility can be found with the pignistic probabilities obtained by reallocating the mass of every non-singleton focal element uniformly over its members. Restricting the choice to singletons can be done here too.

In SMART, only the maximum of belief with singletons was computed and generated in order to simplify the use of the tool.

The belief functions framework is used to perform data fusion of the points of views of different experts. Here each band is an expert and the masses given as input are the expertise of each expert concerning the possible classification of each band.

The algorithm combines this information according to the belief functions model and computes the evidence for each hypothesis. More information on this classification method can be found in Chapter 4.

9.3. SAR Supervised Classifier with Multiple Logistic Regression

The supervised classification based on the multinomial logistic regression is a pixel-based method where all classes j are considered at the same time (Borghys et al, 2004a). The last class j^* is the so-called baseline class. As all classes are considered at the same time, the sum of the conditional probabilities of the different classes equals one in each pixel. For the non-baseline classes, the multinomial logistic function is given by:

$$p_{m,n}(c = j/\mathbf{F}) = \frac{e^{\beta_{0j} + \sum_i F_i(m,n)\beta_{ij}}}{1 + \sum_{k \neq j^*} e^{\beta_{0k} + \sum_i F_i(m,n)\beta_{ik}}} \tag{20}$$

with $c \neq j^*$ and where the sum is over all classes. For the baseline class j^*, it is given by

$$p_{m,n}(c = j^*/\mathbf{F}) = \frac{1}{1 + \sum_{k \neq j^*} e^{\beta_{0k} + \sum_i F_i(m,n)\beta_{ik}}} \tag{21}$$

Note that in case of dichotomous problems where a target class has to be distinguished from the background, the multinomial logistic regression is reduced to the simple logistic regression, which simplifies equations (20) and (21). Because of the complexity of the classes for the Glinska-Poljana test site, it was decided to develop a hierarchical, tree-based, classification (Borghys et al, 2004b). Figure 11. presents an overview of the classification tree used in SMART. At the first level, a logistic regression separates the group of "forests and hedges" from all other classes. Forests and hedges are separated from each other using again a logistic regression. Next, the other classes are separated with a multinomial regression. In this way, at each level, the full discriminative power of the features **F** is focused on a sub-problem of the classification.

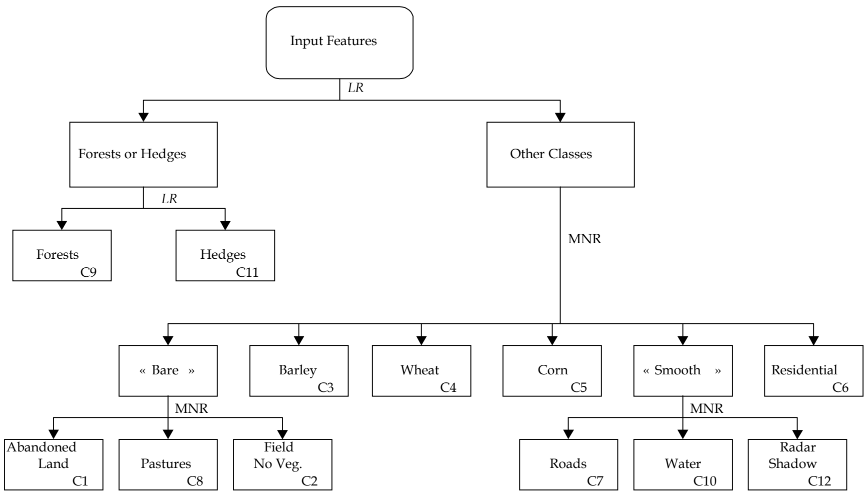


Fig. 11. SAR data classification tree in Glinska-Poljana.

The logistic (LR) and multinomial (MNR) regressions are applied to all pixels of the SAR image set, according to the tree described in Figure 11., and a "detection image" $p_{m,n}(c = j^*/\mathbf{F})$ for each class j (from C1 to C12) is obtained. The pixels in a detection image corresponding to a given class represent the conditional probability that the pixel belongs to that class given all features **F**. The detection images are combined in a classification process using majority voting, i.e. the class with the highest sum of conditional probabilities in a neighbourhood of each pixel is assigned to that pixel. This majority voting has to be performed at each level of the tree and the derived decision is used as a mask for the classification at the next level.

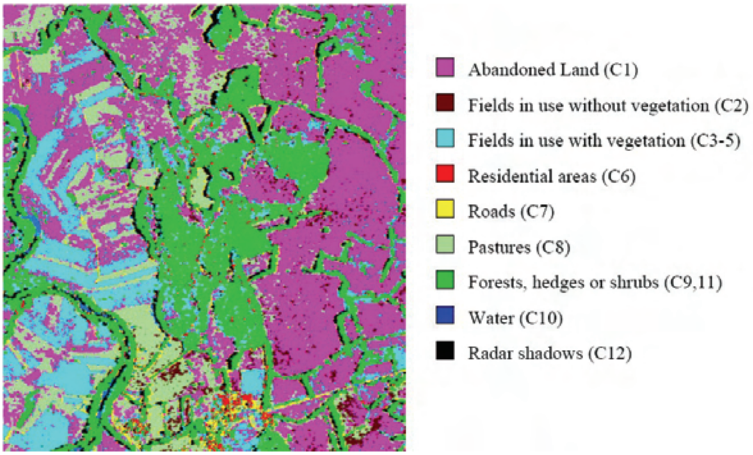


Fig. 12. SAR data hierarchical classification in Glinska-Poljana, using logistic and multinomial logistic regressions

Although this method gives conditional probabilities at each level, it is not possible to compare probabilities obtained at different tree levels. Figure 12. gives the results of the classification on the region of Glinska-Poljana.

9.4. Region-based Classifier

Region-based classification does not classify single pixels, but image objects extracted in a prior segmentation phase. A segmentation divides an image into homogeneous regions of contiguous pixels, used as building blocks and information carriers for subsequent classification. Beyond spectral information, regions contain additional attributes for classification, as shape, texture, and a set of relational/contextual features. In region growing procedures, the process starts with one-pixel objects, and uses local properties to create regions. Adjacent objects with the smallest heterogeneity growth are merged. To perform a supervised classification, features are defined and their values are computed for each region of a training set and a validation set, in order to train and validate the feature space, in which class centres and specific properties are recorded. In SMART, a supervised region-based fuzzy classification method has been used (Landsberg et al, 2006). The classification itself of the test data is performed in the feature space using fuzzy logic. A fuzzy classification method assigns an image object (region) to one class and defines at the same time the membership of this object to all considered classes. Class properties are defined using a fuzzy nearest neighbour algorithm or by combining fuzzy sets of object features, defined by membership functions.

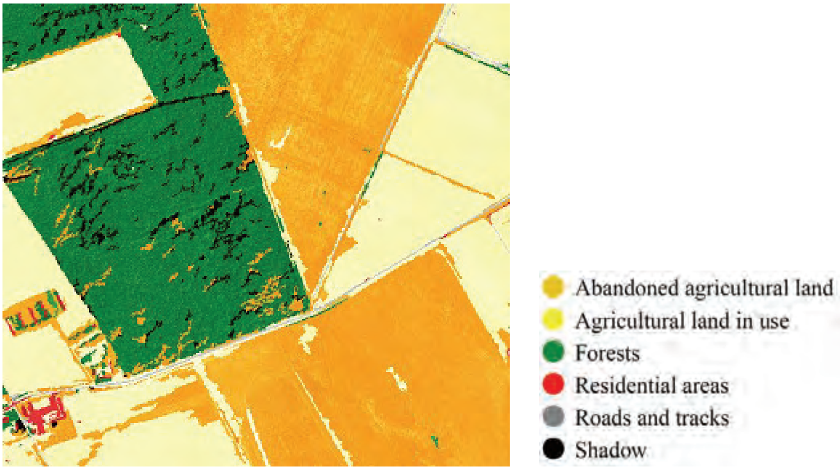


Fig. 13. Supervised fuzzy region-based classification results in Ceretinci

It has been decided to work on land use rather than on land cover, as it is mandatory in the context of mine action to discriminate used land from unused land. This imperative made the classification process a complex issue since internal variability is higher in land use than in land cover.

The feature set includes the mean values, standard deviations and shape features for each radiometric multi-spectral channel as well as for pseudo-channels created to increase the number of features available. These pseudo-channels include a NDVI channel produced from channels 7 and 5 of the multi-spectral sensor, two PCA channels made respectively with the largest and the second largest components of a Principal Component Analysis performed on all multi-spectral channels and 12 channels made with the 11 Haralick texture parameters (Haralick et al, 1973) and a second order statistics, all 12 computed from the two previous PCA channels. A subjective interactive method gave the best results to select the most discriminant features.

The classification process produces two images for each class. A first one gives the membership value of each region to that class and a second one the regions classified in that class. Figure 13. gives the classification results for an area in Ceretinci.

10. Change Detection

As far as change detection is concerned the challenge was to develop a new method that makes it possible to use data from different sensor types. A region-based fuzzy post-classification change detection method, similar to the classification method described in the previous Section, was developed in order to detect the land use changes in agricultural areas, and more particularly plots that were cultivated before the war and neglected after the war. This method has assets over traditional post-classification change detection methods. First, it uses a combination of historical Very High Resolution panchromatic (black and white) satellite data and of recent Very High Resolution multi-spectral aerial data. This possibility to use data from different sensor types for change detection opens new perspectives since historical VHR data are available mostly in the panchromatic mode. Second, it is based on a fuzzy approach: memberships to land use classes are used to map changes, but also to give a degree of confidence in the change detection results.

11. Data Fusion

The work on fusion was based on general considerations and theoretical work on possible fusion schemes, on main numerical methods as well as on the analysis of the characteristics of available data and pieces of knowledge. Based on this preliminary work, generic fusion tools were designed and implemented, mainly in the framework of belief function theory. In SMART, fusion aims at combining results provided by experts, here classifiers and anomaly detectors.

Numerous variants of belief function theories were designed and tested. Two of them appear as very promising, since they provide with good results and are very easy to adapt to other problems. The first one considers each classifier and anomaly detector as one information source. The classes of interest are the focal elements. The masses are discounted by a factor learned from the trace of the confusion matrix obtained for this classifier on the training regions and a mass is assigned to the whole set of discernment. The second one considers each class output by each classifier or anomaly detector as an information source. Focal elements for each source are derived from the line of the confusion matrix for this class, in order to account for possible confusions with other classes.

A simple fuzzy method provides with good results too, is faster, but remains somewhat specific. This method is based on the choice of the best classifiers or anomaly detectors for each class before combining them with a maximum operator (possibly with some weights). The decision is made according to a maximum rule. For each class, the best classifiers or anomaly detectors are those with the best diagonal element corresponding to this class in their confusion matrix.

A strong feature of the proposed methods is that additional knowledge can be included easily during the fusion and in the decision result. This feature allows for better results on the classes that are the most important ones for risk map construction, and for which knowledge is simple and straightforward (sure detection of roads, change detection, etc.).

A final spatial regularization step, based on the segmentation into homogeneous regions discussed in section 9.4, allows for obtaining less noisy classification results.

The overall results obtained at the end of this processing by all methods are better than those provided by each classifier or anomaly detector individually, and therefore constitute a useful input for risk map construction. The problem of fusion is discussed in more detail in Chapter 4.

12. Conclusions

This Chapter concentrates on the mine action technology problem and more specifically on the description of the processing algorithms used in the SMART project on area reduction. Nevertheless, the SMART approach has its limitations. The general knowledge used in SMART is strongly context-dependent. It has been currently derived from the study of three different test sites in Croatia chosen to be representative of South-East of Europe. In the case of another context a new field campaign is needed in order to derive and implement new general rules. Before using SMART the list of indicators must be re-evaluated and adapted. For instance it has been noted that the assumption that a cultivated field is not mined, although quite valid in Croatia, may not apply in other countries such as South Africa or Colombia. It must also be checked if the indicators can be identified on the data and if the new list is enough to reduce the suspected areas.

13. Acknowledgements

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4

Multi-sensor Data Fusion Based on Belief Functions and Possibility Theory: Close Range Antipersonnel Mine Detection and Remote Sensing Mined Area Reduction

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1. Introduction

Two main humanitarian mine action types may benefit from multi-sensor data fusion techniques: 1) close range antipersonnel (AP) mine detection and 2) mined area reduction. Data fusion for these two applications is presented here. Close range detection consists of detection of (sub-)surface anomalies that may be related to the presence of mines (e.g., detection of metals using a metal detector, or detection of temperature differences using an infrared camera) and/or detection of explosive materials. Area reduction consists in identifying the mine-free areas out of the mine-suspected areas.
For both close range detection and area reduction, efficient modeling and fusion of extracted features can improve the reliability and quality of single-sensor based processing (Acheroy, 2003). However, due to a huge variety of scenarios and conditions within a minefield (specific moisture, depth, burial angles) and between different minefields (types of mines, types of soil, minefield structure), a satisfactory performance of humanitarian mine action tools can only be obtained using multi-sensor and data fusion approaches (Keller et al., 2002; Milisavljević & Bloch, 2005). Furthermore, as the sensors used are typically detectors of different anomalies, combinations of these complementary pieces of information may improve the detection and classification results. Finally, in order to take into account the inter- and intra-minefield variability, uncertainty, ambiguity and partial knowledge, fuzzy set or possibility theory (Dubois & Prade, 1980) as well as belief functions (Smets, 1990b) within the framework of the Dempster-Shafer theory (Shafer, 1976) prove to be useful.
In case of close range detection, a detailed analysis of modeling and fusion of extracted features is presented and two fusion methods are discussed, one based on the belief functions and the other based on the possibility theory. They are illustrated using real data coming from three complementary sensors (metal detector, ground-penetrating radar and infrared camera), gathered within the Dutch project HOM-2000 (de Yong et al., 1999). These

results are obtained within two Belgian humanitarian demining projects, HUDEM and BEMAT. For mined area reduction, three approaches are shown, two of them based on the belief functions and one based on the fuzzy logic. They are also illustrated using real data of synthetic-aperture radar and multi-spectral sensors, collected within the EU project on space and airborne mined area reduction tools (SMART). In all cases, importance of collateral information (knowledge about types of mines, mine records, etc.) is demonstrated.

2. About Mine Detection and Mined Area Reduction

2.1 Close Range AP Mine Detection

Due to the high variety of types of mines and of conditions in which mines can be found, there is no single sensor used for humanitarian mine detection that can reach the necessarily high detection rate in all possible scenarios. Therefore, a way towards finding a solution is in taking the best from several complementary sensors. One of the most promising sensor combinations consists in an infrared camera (IR), an imaging metal detector (MD) and a ground-penetrating radar (GPR). We present here two approaches for combining these sensors, which can be easily adapted for other sensors and their combinations. These approaches are based on the belief function theory and on the possibility theory.

Most of the work done in the field of fusion of dissimilar mine detection sensors is based on statistical approaches (Cremer et al., 2001; Yee, 2001). Examples of alternative approaches are (Stanley et al., 2002) (neural networks) and (Auephanwiriyakul et al., 2002) (fuzzy fusion of classifiers). The statistical approaches lead to good results for a particular scenario, but they ignore or just briefly mention that several important problems have to be faced in this domain of application (Milisavljević & Acheroy, 1999), once more general solutions are looked for. Namely, the data are highly variable depending on the context and conditions. Besides, the data are not numerous enough to allow for a reliable statistical learning, and they do not give precise information on the type of mine (ambiguity between several types). Finally, it is not possible to model every object (neither mines nor objects that could be confused with them). In addition, a number of the fusion attempts in this domain of application, e.g. (den Breejen et al., 1999; Perrin, 2001), treat every alarm as a mine, and not as an object that could be a mine, but a false alarm as well.

In a previous work (Milisavljević & Bloch, 2003), a method based on the belief functions (Shafer, 1976; Smets & Kennes, 1994; Smets, 1994) has been proposed. In this chapter, we compare it with an alternative approach, based on the possibility theory, in order to take advantage of the flexibility in the choice of combination operators (Dubois & Prade, 1985). This is exploited here to account for the different characteristics of the sensors to be combined. To our knowledge, in the domain of humanitarian mine detection, there is no attempt to apply the two fusion theories in parallel or to compare them. In other domains, there are some works that compare the two approaches, such as (Dubois et al., 2001), where the belief function theory is opposed to the qualitative possibility theory and illustrated on a fictitious example of the assessment of the value of a candidate. On the contrary to that paper, we apply the quantitative possibility theory here.

2.2 Remote Sensing for Mined Area Reduction

AP mines affect at least 84 countries and 8 areas not internationally recognized as independent states (ICBL, 2005). Thanks to the Mine Ban Treaty, mine clearing operations have been organized in a more controlled and effective way, yet mine clearance remains a slow and resource demanding process. It is estimated that, on average, a deminer clears 10 m^2 during a working day using conventional tools such as metal detectors and prodders. Thus, humanitarian mine clearance operations must be understood and designed correctly, providing efficient aid to innocent people who may be severely injured by this dreadful pollution. The recommendations made during the Standing Committee on Mine Clearance, Mine Risk Education and Mine Action Technologies state that: 1) technologists should avoid building technologies based on assumed needs and should work interactively with end-users, 2) appropriate technologies could save human lives and increase mine action efficiency, and 3) nothing is more important than understanding the working environment (Acheroy, 2003; JMU). Besides the very long time needed to clear polluted terrain, actual demining campaigns show that the false alarm rate is very large, the threat of plastic mines (which cannot be detected by metal detectors) is not negligible and the variety of mine clearance scenarios is high, depending on the country, the region, the climate etc. These facts prove that the humanitarian mine detection is a very complex problem. In addition, the experience shows that it will be a long process to achieve a mine-free world, so the concept of a mine-free world is evolving softly toward the concept of a mine impact-free world, although a mine-free world remains the final goal of the Mine Ban Treaty. By this, the first priority of mine action becomes in allowing affected regions to reach their level of socio-economic standards. This new vision increases the importance of tools that facilitate prioritization and contribute to a rational and efficient distribution of the available resources. Several information management systems are developed and used. An example is the Information Management System for Mine Action – IMSMA (IMSMA, 1999), developed thanks to the Geneva International Centre for Humanitarian Demining (GICHD) and in use in more than 40 affected countries. Other examples are systems completing IMSMA, such as the EODIS system (Askelin, 1999) developed by SWEDEC in Sweden and the PARADIS system (Delhay et al., 2005) developed by the Royal Military Academy (RMA) in Belgium. Possible entries of such management systems are danger and risk assessment maps provided by the Space and airborne Mined Area Reduction Tools (SMART) project (SMART consortium, 2004; Acheroy, 2005), funded by the European Commission. The maps, obtained using data fusion, synthesize the knowledge gathered from the existing data. In the framework of SMART, the fusion module, detailed in this chapter, is a very important step, since it allows for taking the best from all available data, and of the large efforts made in the scientific community to design detectors and classifiers adapted to these data. It has proven to be a required step before constructing risk maps. This is an improvement in comparison to existing information management systems in this area. In particular, the proposed approach exploits all available data and knowledge and automatically adapts to the quality of the detectors and classifier outputs.

3. Belief Functions and Possibility Theory for Numerical Information Fusion

3.1 Belief Function Fusion – Overview

Belief function theory or Dempster-Shafer evidence theory (DS) (Shafer, 1976; Smets, 1990b) allows representing both imprecision and uncertainty, using plausibility and belief functions derived from a mass function. The mass of a proposition A is a part of the initial unitary amount of belief that supports that the solution is exactly in A. It is defined as a function m from 2^Θ into [0, 1], where Θ is the decision space, also called frame of discernment or full set. Usually the following constraints are imposed:

$$m(\emptyset) = 0, \tag{1}$$

$$\sum_{A \subseteq \Theta} m(A) = 1 \,. \tag{2}$$

In this formalism, any combination of possible decisions from the decision space can be quantified rather than considering only the singletons of Θ. This is one of the main advantages of the DS approach. Indeed, it leads to a very flexible and rich modeling, able to fit a very large class of situations, occurring in image fusion in particular. Examples of situations where DS theory may be successfully used include ignorance or partial ignorance, confusion between classes (in one or several sources of information), partial reliability, etc (van Cleynenbreugel et al., 1991; Mascle et al., 1997; Le Hégarat-Mascle et al., 1998; Tupin et al., 1999; Milisavljević & Bloch, 2003; Milisavljević & Bloch, 2005).

In the DS framework, masses assigned by different sources (e.g., classifiers) are combined by the orthogonal rule of Dempster (Shafer, 1976):

$$m_{ij}(S) = \sum_{\substack{k,l \\ A_k \cap B_l = S}} m_i(A_k) \cdot m_j(B_l) \tag{3}$$

where S is any subset of the full set, while m_i and m_j are masses assigned by measures i and j, and their focal elements are $A_1, A_2, \ldots, A_p$ and $B_1, B_2, \ldots, B_q$, respectively.

Dempster's rule is commutative and associative, meaning that it can be applied repeatedly, until all measures are combined, and that the result does not depend on the order used in the combination. After the combination in this unnormalized form (Smets, 1993), the mass that is assigned to the empty set:

$$m_{ij}(\emptyset) = \sum_{\substack{k,l \\ A_k \cap B_l = \emptyset}} m_i(A_k) \cdot m_j(B_l) \tag{4}$$

can be interpreted as a measure of conflict between the sources. It can be directly taken into account in the combination as a normalization factor. It is very important to consider this value for evaluating the quality of the combination: when it is high (in case of strong conflict), the normalized combination may not make sense and can lead to questionable decisions (Dubois & Prade, 1988). Several authors suggest not normalizing the combination result (e.g., Smets, 1993), which corresponds to Eq. 3.

This fusion operator has a conjunctive behavior. This means that all imprecision on the data has to be introduced explicitly at the modeling level, in particular in the choice of the focal elements. For instance, ambiguity between two classes in one source of information has to be modeled using a disjunction of hypotheses, so that conflict with other sources can be limited and ambiguity can be possibly solved during the combination.

From a mass function, we can derive a belief function:

$$\forall A \in 2^\Theta, Bel(A) = \sum_{B \subseteq A,\, B \neq \emptyset} m(B) \tag{5}$$

as well as a plausibility function:

$$\forall A \in 2^\Theta, Pls(A) = \sum_{B \cap A \neq \emptyset} m(B) \,. \tag{6}$$

After the combination, the final decision is usually taken in favor of a simple hypothesis using one of several rules (Denœux, 1995): e.g. the maximum of plausibility (generally over simple hypotheses), the maximum of belief, the pignistic decision rule (Smets, 1990a), etc.

For some applications, such as humanitarian demining, it may be necessary to give more importance to some classes (e.g., mines, since they must not be missed) at the decision level. Then maximum of plausibility can be used for the classes that should not be missed, and maximum of belief for the others (Milisavljević & Bloch, 2001), as shown in Subsection 4.4.

3.2 Fuzzy and Possibilistic Fusion – Overview

In the framework of fuzzy sets and possibility theory (Zadeh, 1965, Dubois & Prade, 1980), the modeling step consists in defining a membership function to each class or hypothesis in each source, or a possibility distribution over the set of hypotheses in each source.

Such models explicitly represent imprecision in the information, as well as possible ambiguity between classes or decisions.

For the combination step in the fusion process, the advantages of fuzzy sets and possibilities rely in the variety of combination operators, which may deal with heterogeneous information (Dubois & Prade, 1985; Yager, 1991). Among the main operators, we find t-norms, t-conorms , mean operators, symmetrical sums, and operators taking into account conflict between sources or reliability of the sources. We do not detail all operators in this chapter, but they can be easily found in the literature, with a synthesis in (Bloch, 1996).

We classify these operators with respect to their behavior (in terms of conjunctive, disjunctive, compromise (Dubois & Prade, 1985)), the possible control of this behavior, their properties and their decisiveness, which proved to be useful for several applications (Bloch, 1996). It should be noted that, unlike other data fusion theories (e.g., Bayesian or Dempster-Shafer combination), fuzzy sets provide a great flexibility in the choice of the operator, that can be adapted to any situation at hand. In particular nothing prevents using different operators for different hypotheses or different sources of information.

An advantage of this approach is that it is able to combine heterogeneous information, which is usually the case in multi-source fusion (as in both examples developed in the next sections), and to avoid to define a more or less arbitrary and questionable metric between pieces of information issued from these images, since each piece of information is converted in membership functions or possibility distributions over the same decision space.

Decision is usually taken from the maximum of membership or possibility values after the combination step. Constraints can be added to this decision, typically for checking for the reliability of the decision (is the obtained value high enough?) or for the discrimination power of the fusion (is the difference between the two highest values high enough?). Local spatial context can be used to reinforce or modify decisions (see the example in Section 5).

4. Close-range Mine Detection

4.1 Measures

From the data gathered by the sensors, a number of measures are extracted (Milisavljević & Bloch, 2003) and modeled using the two approaches. These measures concern:

- the area and the shape (elongation and ellipse fitting) of the object observed using the IR sensor,
- the size of the metallic area in MD data,
- the propagation velocity (thus the type of material), the burial depth of the object observed using GPR, and the ratio between object size and its scattering function.

Although the semantics are different, similar information can be modeled in both possibilistic and belief function models. The idea here is to design the possibility and mass functions as similarly as possible and to concentrate on the comparison at the combination step.

The main difference relies in the modeling of ambiguity. The semantics of possibility leads to model ambiguity between two hypotheses with the same degrees of possibilities for these two hypotheses (e.g., Eq. 7 and Eq. 12). On the contrary, the reasoning on the power set of hypotheses in the belief function theory leads to assigning a mass to the union of these two hypotheses (e.g., Eq. 9 and Eq. 14).

Another distinction concerns the ignorance. It is explicitly modeled in the belief function theory, through a mass on the whole set (to guarantee the normalization of the mass function over the power set), while it is only expressed implicitly in the possibilistic model, through the absence of normalization constraint.

IR measures: The possibility degrees derived from elongation and ellipse fitting measures are represented by π_{1I} and π_{2I}, respectively. Being related to shape regularity, they are defined for a regular-shaped mine (*MR*), an irregular-shaped mine (*MI*), a regular-shaped non-dangerous (i.e., friendly) object (*FR*) and an irregularly shaped friendly object (*FI*).

In the belief function framework, the full set is: $\Theta = \{MR, MI, FR, FI\}$. As elongation and ellipse fitting aim at distinguishing regular and irregular shapes, masses assigned by these two measures, m_{1I} and m_{2I}, are split between $MR \cup FR$, $MI \cup FI$ and Θ.

Regarding elongation, we calculate r_1 as the ratio between minimum and maximum distance of bordering pixels from the center of gravity (we work on thresholded images) and r_2 as the ratio of minor and major axis obtained from second moment calculation. Using these two ratios, the following possibility degrees are derived:

$$\pi_{1I}(MR) = \pi_{1I}(FR) = \min(r_1, r_2)\,, \tag{7}$$

$$\pi_{1I}(MI) = \pi_{1I}(FI) = 1 - \pi_{1I}(MR)\,. \tag{8}$$

In the framework of belief functions, for this measure, masses are defined as follows:

$$m_{1I}(MR \cup FR) = \min(r_1, r_2)\,, \tag{9}$$

$$m_{1I}(MI \cup FI) = |r_1 - r_2|\,, \tag{10}$$

and the full set takes the rest:

$$m_{1I}(\Theta) = 1 - \max(r_1, r_2)\,. \tag{11}$$

In case of ellipse fitting, let A_{oe} be the part of object area that belongs to the fitted ellipse as well, A_o the object area, and A_e the ellipse area. Then we define:

$$\pi_{2I}(MR) = \pi_{2I}(FR) = \max\left(0, \min\left\{\frac{A_{oe}-5}{A_o}, \frac{A_{oe}-5}{A_e}\right\}\right), \tag{12}$$

$$\pi_{2I}(MI) = \pi_{2I}(FI) = 1 - \pi_{2I}(MR)\,. \tag{13}$$

Masses for this measure are the following ones:

$$m_{2I}(MR \cup FR) = \max\left(0, \min\left\{\frac{A_{oe}-5}{A_o}, \frac{A_{oe}-5}{A_e}\right\}\right)\,, \tag{14}$$

$$m_{2I}(MI \cup FI) = \max\left\{\frac{A_e - A_{oe}}{A_e}, \frac{A_o - A_{oe}}{A_o}\right\}\,, \tag{15}$$

$$m_{2I}(\Theta) = 1 - m_{2I}(MR \cup FR) - m_{2I}(MI \cup FI) \,. \tag{16}$$

Note that in cases where it is sure that all mines have a regular shape, the possibility degrees of *MR* can be reassigned to mines of any shape (*M* = *MR*∪*MI*) while the possibility degrees of *MI* can be reassigned to friendly objects of any shape (*F* = *FR*∪*FI*). Similarly, masses given to *MR*∪*FR* can be reassigned to *M*, while masses given to *MI*∪*FI* can be reassigned to *F*.

The area directly provides a degree π_{3I} (*M*) of being a mine. Namely, since the range of possible AP mine sizes is approximately known, the degree of possibility of being a mine is derived as a function of the measured size:

$$\pi_{3I}(M) = \frac{a_I}{a_I + 0.1 \cdot a_{\mathrm{Im}in}} \cdot \exp \frac{-\left[a_I - 0.5 \cdot (a_{\mathrm{Im}in} + a_{\mathrm{Im}ax})\right]^2}{0.5 \cdot (a_{\mathrm{Im}ax} - a_{\mathrm{Im}in})^2} \,, \tag{17}$$

where a_I is the actual object area on the IR image, while the approximate range of expectable mine areas is between a_{Imin} and a_{Imax} (for AP mines, it is reasonable to set a_{Imin} = 15 cm^2 and a_{Imax} = 225 cm^2). On the contrary, friendly objects can be of any size, so the possibility degree is set to one whatever the value of the size:

$$\pi_{3I}(F) = 1 \,. \tag{18}$$

The area/size mass assignment based on the above reasoning is given by:

$$m_{3I}(\Theta) = \frac{a_I}{a_I + 0.1 \cdot a_{\mathrm{Im}in}} \cdot \exp \frac{-\left[a_I - 0.5 \cdot (a_{\mathrm{Im}in} + a_{\mathrm{Im}ax})\right]^2}{0.5 \cdot (a_{\mathrm{Im}ax} - a_{\mathrm{Im}in})^2} \,, \tag{19}$$

$$m_{3I}(FR \cup FI) = 1 - m_{3I}(\Theta) \,. \tag{20}$$

MD measures: In reality, MD data are usually saturated and data gathering resolution in the cross-scanning direction is typically very poor, so the MD information used consists of only one measure, which is the width of the region in the scanning direction, *w* [cm]. As friendly objects can contain metal of any size, we define:

$$\pi_{MD}(F) = 1 \,. \tag{21}$$

If there is some knowledge on the expected sizes of metal in mines (for AP mines, this range is typically between 5 cm and 15 cm), we can assign possibilities to mines as, e.g.:

$$\pi_{MD}(M) = \frac{w}{20} \cdot \left[1 - \exp(-0.2 \cdot w)\right] \cdot \exp\left(1 - \frac{w}{20}\right) . \tag{22}$$

The corresponding mass functions are:

$$m_{MD}(\Theta) = \frac{w}{20} \cdot \left[1 - \exp(-0.2 \cdot w)\right] \cdot \exp\left(1 - \frac{w}{20}\right) , \tag{23}$$

$$m_{MD}(FR \cup FI) = 1 - m_{MD}(\Theta) \,. \tag{24}$$

GPR measures: All three GPR measures provide information about mines.

In case of burial depth information (*D*), friendly objects can be found at any depth, while it is known that there is some maximum depth up to which AP mines can be expected, mainly due to their activation principles. However, due to soil perturbations, erosions etc., mines can, by time, go deeper or shallower than the depth at which they were initially buried. In any case, they can rarely be found buried below 25 cm ($D_{\max}$). Thus, for this GPR measure, possibility distributions π_{1G} for mines and friendly object can be modeled as follows:

$$\pi_{1G}(M) = \frac{1}{\cosh(D/D_{\max})^2} \,, \tag{25}$$

$$\pi_{1G}(F) = 1 \,. \tag{26}$$

In terms of belief functions, the masses for this measure are:

$$m_{1G}(\Theta) = \frac{1}{\cosh(D/D_{\max})^2}, \tag{27}$$

$$m_{1G}(FR \cup FI) = 1 - m_{1G}(\Theta). \tag{28}$$

Another GPR measure exploited here is the ratio between object size and its scattering function, *d/k*. Again, friendly objects can have any value of this measure, while for mines, there is a range of values that mines can have, and outside that range, the object is quite certainly not a mine:

$$\pi_{2G}(M) = \exp\left(-\frac{[(d/k) - m_d]^2}{2 \cdot p^2}\right), \tag{29}$$

$$\pi_{2G}(F) = 1, \tag{30}$$

where m_d is the *d/k* value at which the possibility distribution reaches its maximum value (here, m_d = 700, chosen based on prior information), and p is the width of the exponential function (here, p = 400).
Similarly, the mass assignments for this measure are:

$$m_{2G}(\Theta) = \exp\left(-\frac{[(d/k) - m_d]^2}{2 \cdot p^2}\right), \tag{31}$$

$$m_{2G}(FR \cup FI) = 1 - m_{2G}(\Theta). \tag{32}$$

Finally, propagation velocity, v, can provide information about object identity. Here, we extract depth information on a different way than in the case of the burial depth measure (Milisavljević et al., 2003) and we preserve the sign of the extracted depth. This information indicates whether a potential object is above the surface. If that is the case, the extracted v should be close to $c = 3 \cdot 10^8$ m/s, the propagation velocity in vacuum. Otherwise, if the sign indicates that the object is below the soil surface, the value of v should be around the values for the corresponding medium, e.g., from $5.5 \cdot 10^7$ m/s to $1.73 \cdot 10^8$ m/s in case of sand:

$$\pi_{3G}(M) = \exp\left(-\frac{(v - v_{\max})^2}{2 \cdot h^2}\right), \tag{33}$$

where $v_{\max}$ is the value of velocity which is the most typical for the medium (here, for sand, it is $0.5 \cdot (5.5 \cdot 10^7 + 1.73 \cdot 10^8) = 1.14 \cdot 10^8$ m/s, and for air, it is equal to c), and h is the width of the exponential function (here, $h = 6 \cdot 10^7$ m/s). Once again, friendly objects can have any value of the velocity:

$$\pi_{3G}(F) = 1. \tag{34}$$

The corresponding mass functions are:

$$m_{3G}(\Theta) = \exp\left(-\frac{(v - v_{\max})^2}{2 \cdot h^2}\right), \tag{35}$$

$$m_{3G}(FR \cup FI) = 1 - m_{3G}(\Theta). \tag{36}$$

4.2. Combination

The combination of possibility degrees, as well as of masses, is performed in two steps. The first one applies to all measures derived from one sensor. The second one combines results obtained in the first step for all three sensors.

In case of possibilities, only the combination rules related to mines are considered. The issue of combination rules for friendly objects is discussed in Subsection 4.4.

Let us first detail the first step for each sensor. For IR, since mines can be regular or irregular, the information about regularity on the level of each shape measure is combined using a disjunctive operator (here the max):

$$\pi_{1IM} = \max(\pi_{1I}(MR), \pi_{1I}(MI)), \quad (37)$$

$$\pi_{2IM} = \max(\pi_{2I}(MR), \pi_{2I}(MI)). \quad (38)$$

The choice of the maximum (smallest disjunction and idempotent operator) as a t-conorm is related to the fact that the measures cannot be considered as completely independent from each other. Thus, there is no reason to reinforce the measures by using a larger t-conorm, and the idempotent one is preferable in such situations. These two shape constraints should be both satisfied to have a high degree of possibility of being a mine, so they are combined in a conjunctive way (using a product). Finally, the object is possibly a mine if it has a size in the expected range or if it satisfies the shape constraint, hence the final combination for IR is:

$$\pi_I(M) = \pi_{3I}(M) + [1 - \pi_{3I}(M)] \cdot \pi_{1IM} \cdot \pi_{2IM}. \quad (39)$$

The conjunction in the second term guarantees that $\pi_I(M)$ is in [0,1].

In case of GPR, it is possible to have a mine if the object is at shallow depths and its dimensions resemble a mine and the extracted propagation velocity is appropriate for the medium. Thus, the combination of the obtained possibilities for mines is performed using a t-norm, expressing the conjunction of all criteria. Here the product t-norm is used:

$$\pi_G(M) = \pi_{1G}(M) \cdot \pi_{2G}(M) \cdot \pi_{3G}(M). \quad (40)$$

For MD, as there is just one measure used, there is no first combination step and the possibility degrees obtained using Eqs. 21 and 22 are directly used.

In case of possibilities, the second combination step is performed using the algebraic sum:

$$\begin{aligned}\pi(M) = \pi_I(M) + \pi_{MD}(M) + \pi_G(M) - \pi_I(M) \cdot \pi_{MD}(M) - \pi_I(M) \cdot \pi_G(M) - \\ - \pi_{MD}(M) \cdot \pi_G(M) + \pi_I(M) \cdot \pi_{MD}(M) \cdot \pi_G(M)\end{aligned}, \quad (41)$$

leading to a strong disjunction (Dubois & Prade, 1985; Bloch, 1996), as the final possibility should be high if at least one sensor provides a high possibility, reflecting the fact that it is better to assign a friendly object to the mine class than to miss a mine.

In the belief function framework, for IR and GPR, masses assigned by the measures of each of the two sensors are combined by Dempster’s rule in unnormalized form (Eq. 3). A general idea for using the unnormalized form of this rule instead of more usual, normalized form is to preserve conflict (Milisavljević & Bloch, 2001), i.e., mass assigned to the empty set, Eq. 4. Here, a high degree of conflict would indicate that either there are several objects and the sensors, as detectors of different physical phenomena, do not provide information on the same object, or some sources of information are not completely reliable. Our main interest is in the possibility that sensors do not refer to the same object, as the unreliability can be modeled and resolved through discounting factors (Milisavljević & Bloch, 2005). After combining masses per sensor, the fusion of sensors is performed, using Eq. 3 again. If the mass of the empty set after combination of sensors is high, they should be clustered as they do not sense the same object.

4.3 Comparison of the Combination Equations

For IR, based on Eqs. 6-20 and 39, it can be shown that

$$Pl_I(M) \le \pi_I(M) \,. \tag{42}$$

This is in accordance with the least commitment principle used in the possibilistic model, as usually done in this framework.

As far as MD is concerned, there is no difference since it provides only one measure.

In case of GPR, based on the comparison of Eqs. 25 and 27, Eqs. 29 and 31, as well as Eqs. 33 and 35, we can conclude that Eq. 40 can be rewritten as:

$$\pi_G(M) = m_{1G}(\Theta) \cdot m_{2G}(\Theta) m_{3G}(\Theta) \,. \tag{43}$$

Furthermore, the application of the Dempster's rule (Eq. 3) to the mass assignments of the three GPR measures results in the fused mass of the full set for this sensor:

$$m_G(\Theta) = m_{1G}(\Theta) \cdot m_{2G}(\Theta) m_{3G}(\Theta) \tag{44}$$

which leads to:

$$\pi_G(M) = m_G(\Theta) \,. \tag{45}$$

This means that the ignorance is modeled as a mass on Θ in the belief function framework, while it privileges the class that should not be missed (*M*) in the possibilistic framework (i.e., the ignorance will lead to safely decide in favor of mines).

4.4 Decision

As the final decision about the identity of the object should be left to the deminer not only because his life is in danger but also because of his experience, the fusion output is a suggested decision together with confidence degrees.

In case of possibilities, the final decision is obtained by thresholding the fusion result for *M* and providing the corresponding possibility degree as the confidence degree. As almost all possibility degrees obtained at the fusion output are either very low or very high, the selected regions having very low values of $\pi(M)$ (below 0.1) are classified as *F*, and the ones with very high values (above 0.7) are classified as *M*. Only a few regions exist at which the resulting possibility degree for *M* has an intermediary value and there, as mines must not be missed, the decision is *M*. In the following, this decision approach is referred to as *dec*1.

An alternative (*dec*2) for the final decision making is to derive the combination rule for *F* as well, compare the final values for *M* and *F* and derive an adequate decision rule. Due to operation principles of GPR and MD, the measures of these two sensors can only give information where mines are possibly not. As they are non-informative with respect to friendly objects, it is not useful to combine their possibility degrees for *F*. Thus, for deriving the final combination rule for *F*, $\pi(F)$, we can rely only on IR, i.e.:

$$\pi(F) = \pi_I(F) \,. \tag{46}$$

In case of IR, since friendly objects can be regular or irregular, we apply a disjunctive operator (the max) for each of the shape constraints. In order to be cautious when deciding *F*, we combine the two shape constraints and the area measure using a conjunctive operator. Taking into account Eq. 18, this reasoning results in:

$$\pi(F) = \max\left(\pi_{1I}(F_R), \pi_{1I}(F_I)\right) \cdot \max\left(\pi_{2I}(F_R), \pi_{2I}(F_I)\right). \tag{47}$$

Thus, in this alternative way to derive decisions, in regions where IR gives an alarm, the decision rule chooses *M* or *F* depending on which one of the two has a higher possibility value, given by Eqs. 41 and 58, respectively. In other regions, at which IR does not give an

alarm although at least one of the two other sensors gives an alarm, the decision is based on the fusion result for M, as in *dec*1.
In case of belief functions, as shown in (Milisavljević & Bloch, 2003), usual decision rules based on beliefs, plausibilities (Shafer, 1976) and pignistic probabilities (Smets, 1990a) do not give useful results because there are no focal elements containing mines alone (Milisavljević & Bloch, 2001). As a consequence, these usual decision rules would always favor friendly objects. The underlying reason is that the humanitarian demining sensors are anomaly detectors and not mine detectors. In such a sensitive application, no mistakes are allowed so in case of any ambiguity, much more importance should be given to mines. Because of that, in (Milisavljević & Bloch, 2003), guesses $G(A)$ are defined, where $A \in \{M, F, \varnothing\}$:

$$G(M) = \sum_{M \cap B \neq \varnothing} m(B) , \tag{48}$$

$$G(F) = \sum_{B \subseteq F, B \neq \varnothing} m(B) , \tag{49}$$

$$G(\varnothing) = m(\varnothing) . \tag{50}$$

In other words, the guess value of a mine is the sum of masses of all the focal elements containing mines, regardless their shape, and the guess of a friendly object is the sum of masses of all the focal elements containing nothing else but friendly objects of any shape, meaning that the guesses are a cautious way to estimate confidence degrees.
As the output of the belief function fusion module, the three possible outputs (M, F, conflict) are provided together with the guesses, for each of the sensors and for their combination.
For GPR, the focal elements are only F and Θ, so guesses for this sensor become simply:

$$G_G(M) = m_G(\Theta) , \tag{51}$$

$$G_G(F) = m_G(F) . \tag{52}$$

From Eqs. 45 and 51, we conclude that for GPR, the possibility degree of a mine is equal to the guess of a mine:

$$\pi_G(M) = G_G(M) . \tag{53}$$

Furthermore, Eqs. 6 and 48 show that the guess of a mine is equal to its plausibility, while Eqs. 5 and 49 show that the guess of a friendly object is equal to its belief. This means that the relation given by Eq. 42 shows, actually, that for IR:

$$G_I(M) \le \pi_I(M) . \tag{54}$$

4.5 Results

The proposed approach has been applied to a set of known objects, buried in sand, leading to 36 alarmed regions in total: 21 mines (M), 7 placed false alarms (PF, friendly objects) and 8 false alarms caused by clutter (FN, with no object).
The results of the possibilistic fusion are very promising, since all mines are classified correctly with the proposed approach, as can be seen in Table 1. The numbers given in the parenthesis indicate the number of regions selected in the preprocessing step for further analysis, i.e. measure extraction and classification. Regarding the combination operators, the results given in this table are based on the combination proposed in Subsection 4.2 (Eqs. 39-41). The second fusion step is important, since a decision taken after the first step provides only 18 mines for IR, 9 for MD and 13 for GPR. This illustrates the interest of combining heterogeneous sensors.

Classified correctly, possibility theory	Sensors			Fusion	
	IR	MD	GPR	dec1	dec2
M (total: 21)	18 (18)	9 (9)	13 (13)	21 (21)	21 (21)
PF (total: 7)	0 (4)	0 (4)	2 (6)	1 (7)	2 (7)
FN (total: 8)	0 (1)	0 (0)	6 (7)	6 (8)	6 (8)

Table 1. Correct classification results, possibilistic fusion

Classified correctly, belief functions	Sensors			Fusion
	IR	MD	GPR	
M (total: 21)	10 (18)	9 (9)	13 (13)	19 (21)
PF (total: 7)	3 (4)	0 (4)	1 (6)	2 (7)
FN (total: 8)	0 (1)	0 (0)	6 (7)	6 (8)

Table 2. Correct classification results, belief functions

The two decision rules, *dec*1 and *dec*2, give the same results for mines and friendly objects caused by clutter. In case of placed false alarms, 2 are correctly classified in case of *dec*2, which is a slight improvement with respect to *dec*1 and the same result as for the belief function fusion, shown in Table 2. It is not suprising that the placed false alarms are not so well detected by any of the methods, since our model is designed in order to favor the detection of mines. This is also the type of results expected from deminers. Regarding correct classification of mines, the results of the possibilistic fusion are slightly better than those obtained using the belief function method (19 mines detected, Table 2). This is due to the increased flexibility at the combination level. False alarms with no objects are correctly identified by the belief function method (6 out of 8), and it is the same result as for the two possibilistic decision rules. This result shows that a power of our methods is in decreasing the number of clutter-caused false alarms without decreasing the result of mine detection, thanks to knowledge inclusion.

All results have been obtained with the models proposed in Subsection 4.1, with the same parameters. Note that although the general shapes of the possibility distributions are important and have been designed based on prior knowledge, they do not need to be estimated very precisely, and the results are robust to small changes in these functions. What is important is that the functions are not crisp (no thresholding approach is used) and that the rank is preserved (e.g., an object with a measure value outside of the usual range should have a lower possibility degree than an object with a typical measure value). Two main reasons explain the experienced robustness: (i) these possibility distributions are used to model imprecise information, so they do not have to be precise themselves; (ii) each of them is combined in the fusion process (Subsection 4.2) with other pieces of information, which diminishes the importance and the influence of each of them.

Analysis regarding the robustness of the choice of the operator is also performed (within a class corresponding to the type of reasoning we want to achieve). Different operators within the same family have been tested, leading to the maximisation and minimisation of the possibility degrees of mines, thus being the safest and the least safe situations from the point of view of mine detection. The results obtained show that the model is robust indeed: all mines are detected in the second step, for all fusion schemes.

Differences between the results of Tables 1 and 2 can be formally explained as discussed in Subsection 4.3. For GPR, Eq. 53 explains why the results are the same for the two fusion approaches. In case of IR, Eq. 54 indicates that the possibilistic approach would favor mines more than the belief function approach, which is indeed the case here.

5. Area Reduction: the SMART Approach

5.1 Overview of the Approach

The aim of area reduction is to find which mine-suspected areas do not contain mines and this task is recognized as a mine action activity that should result in reduction in time and resources. Several well-known methods are in use to perform area reduction, especially using mechanical means. These expensive methods change and damage the environment and the ecosystem most of the time. To avoid this, some approaches have been developed that acquire the necessary information remotely, from air or space, using appropriate sensors associated with context information collected from the field and integrated in a geographical information system (GIS). The SMART project, funded by the European Commission/DG/INFSO, is among these approaches, and it is applied to Croatia. The goal of this project is to provide the human analyst with the SMART system, i.e. a GIS-based system augmented with dedicated tools and methods designed to use multispectral and radar data in order to assist in his interpretation of the possibly mined scene during the area reduction process. The usefulness of such image processing tools to help photo-interpretation is, at first place, in the possibility to process automatically a large amount of data and help a visual analysis (SMART consortium, 2004). The use of SMART includes a field survey and an archive analysis in order to collect knowledge about the site, a satellite data collection, a flight campaign to record the data and the exploitation of the SMART tools by an operator to detect indicators of presence or absence of mine-suspected areas. With the help of a data fusion module based on belief functions and fuzzy sets, the operator prepares thematic maps synthesizing all the knowledge gathered with these indicators. These maps of indicators can be transformed into risk maps showing how dangerous an area may be according to the location of known indicators and into priority maps indicating which areas are designed to help the mined area reduction process. Preliminary results obtained using SMART have shown a reduction rate of 25% (0.98 km^2 over analyzed 3.9 km^2) and an error rate of 0.1% for what SMART considers as not mined and is actually mined.

Fig. 1 illustrates the global SMART approach. This paper focuses on the fusion step, which provides an intermediary result in SMART, consisting of improved landcover classification maps, along with confidence values. Thus, it is a very useful result, exploited by the deminers together with the final result.

5.2. Data and Their Specificities in SMART

The available images include synthetic-aperture radar (SAR), multispectral, high resolution optical and satellite data. SAR data were collected with the E-SAR system of the German

Aerospace Centre (DLR) in fully polarimetric P- and L-band and in vv-polarization (waves are vertically transmitted

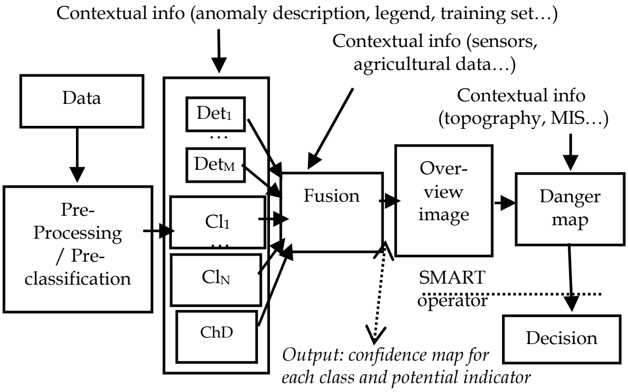

Fig. 1. The global SMART approach; Det – detector, Cl - classifier, M – number of detectors, N – number of classifiers, ChD – change detection, MIS - mine information system

and received) X- and C-band. Multispectral Daedalus data were collected with a spatial resolution of 1 m and in 12 channels, ranging from visible blue to thermal infrared. SAR and Daedalus data were geocoded. DLR also provided a complete set of RMK photographic aerial views recorded with a colored infrared film at a resolution of 3 cm. This non-geocoded data set is used as evidence to control the processing tools and for qualitative interpretation by photo-interpreters. Finally, geocoded KVR-1000 black-and-white satellite images with a resolution of 2 m, recorded before the war in Croatia, were purchased in order to assess the changes in the landscape due to the war.

The legend (expected classes in the images), derived based on the existing and gathered knowledge about the mined areas, is given in Table 3. Ground truth was provided as a set of regions (training regions and validation regions). In the fusion module, training regions are used for estimating the parameters of some of the proposed methods; validation regions are used for the evaluation of the results.

Table 4 summarizes the input of the fusion module.

A logistic regression classification was developed on SAR data at RMA (Borghys et al., 2004). The results consist of confidence images for each class, except for class 4, which is not detected by this approach. A classification into hedges, trees, shadows, and rivers from SAR data has been developed at DLR (Keller et al., 2002). The method relies on the satisfaction of several criteria. The number of satisfied criteria directly provides the confidence images for hedges and trees (after scaling on [0, 1]). Shadows and rivers, provided as binary images, are "discounted"(work done at RMA based on spectral characteristics of these types of landcover, and on existing landcover indices and meanings of Daedalus bands). Hedges and trees are then grouped to form class 6 using a maximum operator. Shadows and rivers are directly interpreted as classes 7 and 8.

Several classifiers have been developed for Daedalus:

- a supervised classification method based on minimum distance has been developed at RMA and a decision image is provided (Keller et al., 2002);

- a region-based classification was performed at Université Libre de Bruxelles (ULB) and confidence images interpreted as membership degrees to each class are provided;
- a belief function classification was developed at RMA and confidence images per class are provided (Keller et al., 2002).

Class no.	Legend
1	Abandoned agricultural land
2	Agricultural land in use
3	Asphalted roads
4	Rangeland
5	Residential areas
6	Trees and shrubs
7	Shadow
8	Water

Table 3. Expected classes in the images

Data type	Type of result
SAR	Classification with confidence images per class
SAR & Daedalus	Detection of hedges, trees, shadows, rivers, with confidence degrees, sometimes discounted
Daedalus	Supervised classification, result as a decision image
Daedalus	Region-based classification with confidence images per class
Daedalus	Belief function classification with confidence images per class
SAR & Daedalus	Binary detection of roads
SAR	River detection (binary)
Daedalus & KVR	Change detection (binary image)

Table 4. Summary of the input of the fusion module

Road detection was performed at ULB and RMA. Linear structures are provided. They are dilated to obtain roads with a width corresponding to the real width.
A tool for river detection previously developed at Ecole Nationale Supérieure des Télécommunications ENST (Tupin et al., 1999) was used too. It is based on a Markovian approach. This is not directly a result of SMART but it is interesting to show how such knowledge can be introduced in the fusion process.
Change detection was obtained at ULB, based on a comparison between older KVR images and images made during the project. It provides mainly information on abandoned regions (class 1). Again, this is an important knowledge that both improves the landcover classification and provides interesting results for the construction of danger map.
Other anomaly detection and classification tools developed in SMART were not used either in the fusion module or at all. For example, detectors of power poles, hilltops and strategic locations are not included in the legend. Thus, they are not considered as input data for the fusion process, but they are added in the final results (construction of danger maps).

5.3. Fusion Strategies in SMART

In all that follows, the computations are performed at pixel level. A final regularization step is then applied (see Section 5.4). Different fusion strategies have been developed (Bloch et al., 2007) and we present here three most promising ones.

Adding a global discounting factor (BF1): Here, we consider each classifier as one information source. The focal elements are the singletons and Θ. The definition of $m(\Theta)$ takes into account both the fact that some classes are not detected (thus it should be equal to 1 at points where 0 is obtained for all detected classes) as well as global errors. We propose to use a discounting factor α equal to the sum of the diagonal elements of the confusion matrix, divided by the cardinality of the training areas. This discounting is applied on all masses defined as in the previous approach. Then:

$$m(\Theta) = 1 - \alpha \,. \tag{55}$$

Note that this uses explicitly the confidence matrix, which should be computed on the training areas for each classifier or detector. It results that at each step of the fusion, the focal elements are always singletons and Θ. Decision rule can be maximum of belief, of mass or of pignistic probability (all being equivalent in this case).

This approach is very easy to implement and models in a simple way the fact that classifiers or detectors may not give any information on some classes and may be imperfect.

Use of confusion matrices for more specific discounting (BF2): Now each class of each classifier (or detector) is considered as a source and we take into account the behavior of the classifier with respect to the other classes, using the confusion matrices to define discounting for each class. From the confusion matrix computed from the decision made from one classifier and from training areas, we derive a kind of probability that the class is C_i given that the classifier says C_j as:

$$c(i,j) = \frac{conf(i,j)}{\sum_i conf(i,j)} \,, \tag{56}$$

where the values $conf(i,j)$ denote the coefficients of the confusion matrix. We can ignore the low values and normalize the others, in order to reduce the number of non-zero coefficients (thus the number of focal elements in the following). We used a threshold value of 0.05.

There are several ways to use this normalized confusion matrix, e.g. by setting $m(C_i)=c(i,j)$ for detected pixels in case of detectors and deriving a more complex method for classifiers. The most interesting way, applying to both classifiers and detectors in a similar way, is as follows. From $v(C_j)$ (denoting the result provided for class C_j by a classifier), we define:

$$m(C_i) = v(C_j)c(i,j) \tag{57}$$

for all classes C_i which are confused with C_j (which provides $\sum_i m(C_i) = v(C_j)$), and:

$$m(\Theta) = 1 - v(C_j) \,. \tag{58}$$

In comparison to the simplest method, instead of keeping a mass on C_i only (and Θ), this mass is spread over all classes possibly confused with C_i, thus better exploiting the richness of the information provided by a classifier.

Fuzzy fusion (FUZZY): In order to compare the previous methods with a fuzzy approach, we test a simple method, where we choose for each class the best classifiers, and combine them with a maximum operator (possibly with some weights). Then decision is made according to a maximum rule. The choice is made based on the confusion matrix for each

classifier or detector, by comparing the diagonal elements in all matrices for each class. In the illustrated example, the best detections, according to the confusion matrix of each classifier or detector are detailed in Subsection 5.5. They provide the inputs of the combination step, and a simple maximum operator performs well for this step.
This approach is very fast. It uses only a part of the information, which could also be a drawback if this part is not chosen appropriately. Some weights have to be tuned, which may need some user interaction in some cases. Although it may sound somewhat *ad hoc*, it is interesting to show what we can get by using the best parts of all classifiers.

5.4. Knowledge Introduction and Spatial Regularization

Knowledge inclusion is one of the main powers of our algorithms with respect to the commercial ones. This aspect has led to a lot of work in SMART, at different levels. Note that knowledge on the classifiers, their behaviors, etc. is already included in the previous steps. At this step, we use only the pieces of knowledge that directly provide information on the landcover classification. Other pieces of knowledge such as mine reports, etc. are not directly related to classes of interest, but rather to the dangerous areas, and are thus included in the danger map construction, which follows the fusion.
Several pieces of knowledge proved to be very useful at this step. They concern on the one hand some "sure" detection. Some detectors are available for roads and rivers, which provide areas or lines that surely belong to these classes. There is almost no confusion, but some parts can be missing. Then these detections can be imposed on the classification results. This is simply achieved by replacing the label of each pixel in the decision image by the label of the detected class if this pixel is actually detected. If not, its label is not changed.
As for roads, additional knowledge is used, namely on the width of the roads (based on observations done during the field missions). Since the detectors provide only lines, these are dilated by the appropriate size, taking into account both the actual road width and the resolution of the images.
Another type of knowledge is very useful: the detection of changes between images taken during the project and KVR images obtained earlier. The results of the change detection processing provide mainly information about class 1, since they exhibit the fields which were previously cultivated, and which are now abandoned. These results do not show all regions belonging to class 1, but the detected areas surely belong to that class.
Then a similar process can be applied as for the previous detectors.
With the proposed methods, it was difficult to obtain good results on class 2, while preserving the results on class 1 that is crucial since it corresponds to fields no longer in use hence potentially dangerous. Therefore we use the best detection of class 2 (extracted from region based classification on Daedalus) as an additional source of knowledge.
As shown in Subsection 5.5, this additional knowledge introduction leads to better results.
The last step is regularization. Indeed, it is very unlikely that isolated pixels of one class can appear in another class. Several local filters were tested, such as a majority filter, a median filter, or morphological filters, applied on the decision image. A Markovian regularization approach on local neighborhoods was tested too. The results are not significantly better.
A better approach is to use the segmentation into homogeneous regions provided by ULB.
In each of these regions, a majority voting is performed: we count the number of pixels in this region that are assigned to each class and the class with the largest cardinality is chosen for the whole region (all pixels of this region are relabeled and assigned to this class).

This type of regularization, which is performed at a regional level rather than at a local one, provides good results, as will be seen in the following.

5.5. Results of BF1, BF2 and FUZZY

Results shown here are obtained on the Glinska Poljana site in Croatia.
In case of BF1, for each classifier, the discounting factor α is calculated from the normalized sum of the diagonal elements of the confusion matrix obtained on the training areas (Table 5). After this type of fusion, a lot of confusion occurs between classes 1 and 2, but this is largely improved by knowledge inclusion, while noisy aspect is suppressed by regularization. In order to assess classification accuracy, we use user's accuracy (UA) and producer's accuracy (PA) measures that can be derived directly from confusion matrices. UA represents the probability that a given pixel will appear on the ground as it is classified. PA is the percentage of a given class that is correctly identified on the map. Table 6 shows some results for a few classes. Note that the most interesting classes for danger map building are 1, 2, 3 and 8, and that, regarding the purpose of the project, PA is important for classes 1 and 8, and UA for classes 2 and 3.

Team	Data type	Type of result	α
RMA	SAR	Classification with confidence images per class (except class 4)	0.41
DLR & RMA	SAR & Daedalus	Detection of hedges, trees, shadows, rivers, with confidence degrees for hedges and trees; rivers and shadows discounted based on Daedalus bands	0.11
RMA	Daedalus	Supervised classification, result as a decision image	0.46
ULB	Daedalus	Region based classification with confidence images per class	0.80
RMA	Daedalus	Belief function classification with confidence images per class	0.67

Table 5. Discounting factors for method BF1

Class	BC	BF1	BF2	FUZZY
1 (PA)	0.84	0.81	0.78	0.89
2 (UA)	0.87	0.86	0.81	0.95
3 (UA)	0.88	0.96	0.96	0.98
8 (PA)	0.96	0.97	0.99	0.99

Table 6. UA and PA for all three methods (after knowledge inclusion and spatial regularization) and the best classifier (BC) for each important class

In addition, the "best classifier" (BC) in Table 6 is not always the same one, but the result is the one provided by the classifier that is the best for a particular class.
In order for the reader to have a better visual idea about the images containing the results, Fig. 2 contains the raw image of Glinska Poljana in a visible channel of Daedalus.
After classification of this area using BF1 (basic version), we obtain the results given in Fig. 3 (left), while knowledge inclusion and spatial regularization applied to these results lead to Fig. 3 (right). The color code in all classification results is as follows: class 1 – orange; 2 – yellow; 3 – medium grey; 4 – light green; 5 – dark red; 6 – dark green; 7 – brown; 8 – blue.

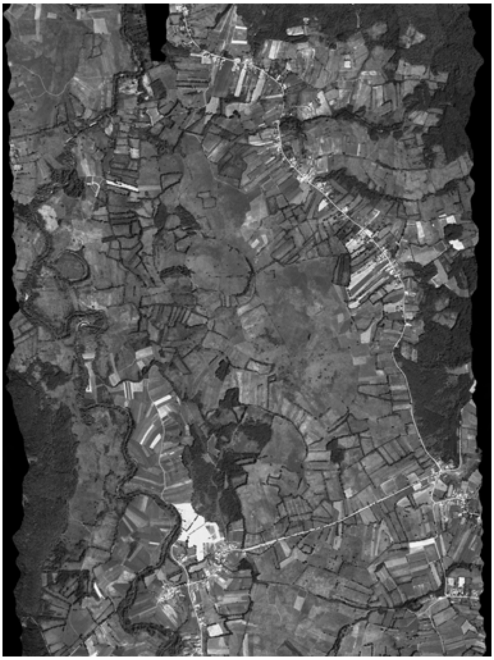

Fig. 2. Visible channel of Daedalus

The fusion module also provides confidence and stability images. The confidence image represents, at each pixel, the confidence degree of the decided class. The stability image is computed as the difference between the confidence in the decided class and confidence in the second most possible class. If the stability is high, this means that there is no doubt about the decision, and if it is low, the decision should be considered carefully. The confidence image and the stability image can be multiplied to provide a global image evaluating the quality of the classification in each point.
In the BF2 method, the confusion matrices for each classifier are normalized row by row, and the coefficients that are higher than 0.05 are used for discounting the corresponding classes. The results of the basic version of this type of fusion yield a poor detection of class 1 and a lot of confusion between this class and classes 2 and 7. In addition, class 4 is not detected and detection of class 3 is worse than with BF1. However, the results are largely improved by knowledge inclusion and confusions are strongly reduced. Finally, the noisy aspect is suppressed by the regularization, leading to an improved detection, in particular

for class 8. Results are given in Fig. 4 left (after knowledge inclusion and spatial regularization). UA and PA are given in Table 6.

For the fuzzy method, the following outputs of classifiers have been used for each class:

1: SAR logistic regression, region-based classification, belief function classification and change detection;

2: region-based classification and belief function classification;

3: region-based classification and road detection;

4: region-based classification, minimum distance classification and belief function classification;

5: region-based classification and belief function classification;

6: region-based classification and SAR trees and hedges detection;

7: SAR logistic regression, SAR shadow detection, minimum distance classification and belief function classification; the maximum is discounted by a factor 0.5, taking into account that this class is not really significant for further processing (shadows "hide" meaningful classes);

8: region-based classification, belief function classification and river detection.

The results of this fusion in its basic version are already very good, due to the fact that not all information provided by the classifiers is used, but only the best part of them. Further improvements are obtained by knowledge inclusion. After the regularization step, class 7 disappears, but this is not a problem since this class is not significant for further processing. Results of this method are shown in Fig. 4 right (after knowledge inclusion and spatial regularization). Table 6 contains PA and UA for this type of fusion too.

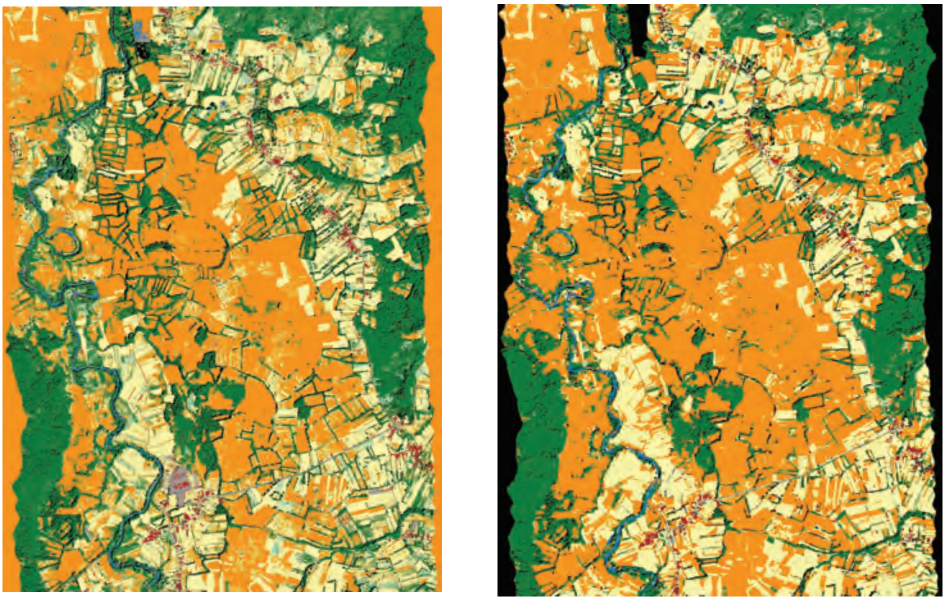

Fig. 3. BF1 results: basic (left), after knowledge inclusion and spatial regularization (right)

In order to get a synthetic view of the results obtained by the three methods, the normalized sums of the diagonal elements of the confusion matrices are shown in Table 7. The two methods based on belief functions provide similar global results, BF1 being somewhat better. The differences appear mainly when looking individually at each class. The

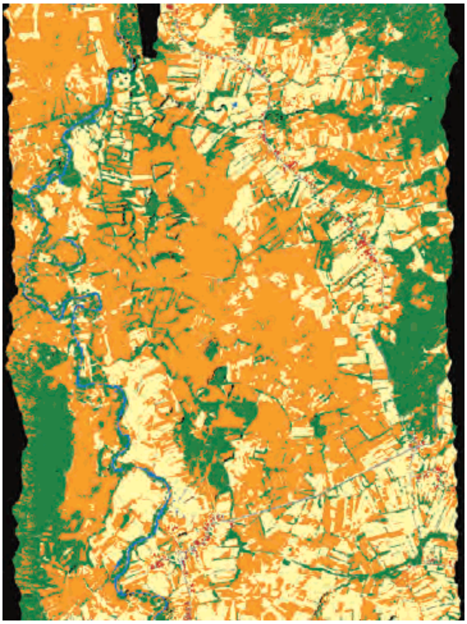
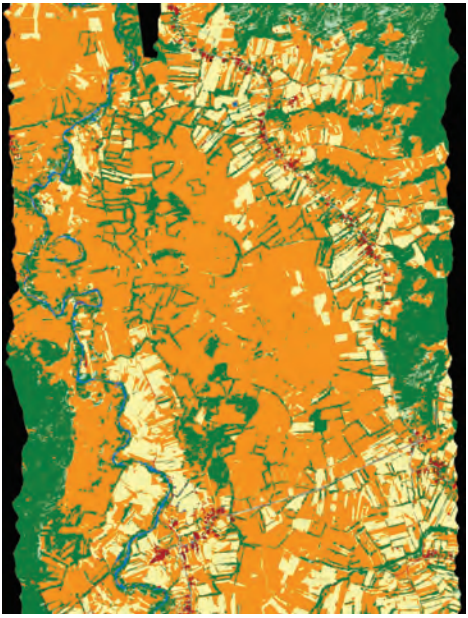

Fig. 4. Results with BF2 (left) and FUZZY (right), both after knowledge inclusion and spatial regularization

improvement achieved with knowledge inclusion is significant. Regularization provides an additional improvement. The final results are globally better than the ones obtained by each of the initial classifiers, as can be seen by comparing the values with those displayed in Table 5 (the best classifier provides a global accuracy of 0.80). The fuzzy method is the best in its basic version, since it already selects the best inputs, thus the improvement due to the next steps is not as important as for the belief function methods.

Method	Basic	Knowledge inclusion	Spatial regularization
BF1	0.70	0.81	0.85
BF2	0.65	0.78	0.81
Fuzzy	0.79	0.83	0.84

Table 7. Comparison of the normalized sum of diagonal elements of the confusion matrices for the three tested methods

5.7. Danger Maps and First Results of SMART Validation

The danger maps are synthetic documents designed to help the end users in their decision-making process regarding area reduction. They are created from results of all detection and classification tools and methods used in SMART (as well as some other sources such as fieldwork). These maps constitute the final output of the system and represent the basis for proposing areas for area reduction. Note that the results are for decision makers and that the reduction of a suspicious area is not an automatic process.

Four types of danger maps are developed in SMART (SMART consortium, 2004). The most useful continuous location maps, such as the one in Fig. 5, are obtained as a weighted sum of factors derived from the number of indicators of mine presence at each point (IMP), with a superimposition of vectors having a see-through inside, representing the number of indicators of mine absence (IMA) at each point.

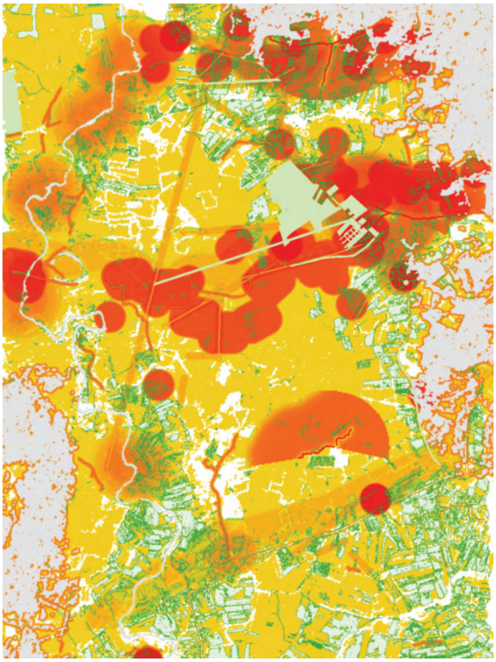

Fig. 5. Continuous location map (SMART consortium, 2004). Grey areas are outside of the scope of SMART, while no data exists for white areas. Demined areas are light green. IMAs are superimposed as parallel white and green lines. The degree of danger is on the scale from green (low) via yellow (intermediate) to red (high)

During the process of area reduction, the decision makers can refer to information relating to the IMA and the associated confidence values. The other key element is the information that concerns the IMP and the associated confidence values. As pointed out by the end users, this information can be of use for prioritizing the mine clearance operations.

Validation was done by blind tests at three sites in Croatia (Yvinec, 2005) having 3.9 km^2 in total: Glinska Poljana (0.63 km^2, fertile valley surrounded by hills), Pristeg (1.5 km^2, rocky, Mediterranean area) and Čeretinci (1.7 km^2, flat agricultural area). In each site clearing was performed after the flight campaign in order to have the true status of the mine presence, but this information was not available before the validation of produced danger maps. From these maps, a selection of areas proposed for area reduction was done, and areas considered as suspect were selected too. In average 25% of the mine-free area has been proposed for reduction: Glinska Poljana – 7.7%, Pristeg – 9.0% and Čeretinci – 47%. The error rate of 0.1% is relatively constant for all three sites. In addition to this technical evaluation, a panel of independent mine action experts working in Croatia has evaluated the SMART method and danger maps. They recognized SMART as a successful project that solved several crucial problems of the aerial survey of the suspected areas, especially by approved indicators of mine presence, efficient use of very different sensor techniques, data fusion and danger map functionalities. It has been found that it might be even more suited for risk assessment.

6. Conclusion

Several fusion methods for close range humanitarian mine detection and remote sensing mined area reduction are presented and compared. These methods are based on the belief functions as well as on the fuzzy/possibility theory.

Regarding close range mine detection, the differences at the combination step are mainly highlighted in this comparison. The modeling step is performed according to the semantics of each framework, but the designed functions are as similar as possible, so as to enhance the combination step. Different fusion operators are tested, depending on the information and its characteristics. An appropriate modeling of the data along with their combination in a possibilistic framework leads to a better differentiation between mines and friendly objects. The decision rule is designed to detect all mines, at the price of a few confusions with friendly objects. This is a requirement of this sensitive application domain (mines must not be missed). Still the number of false alarms remains limited in our results. The robustness of the choice of the operator is also tested, and all mines are detected for all fusion schemes. The proposed modeling is flexible enough to be easily adapted to the introduction of new pieces of information about the types of objects and their characteristics, as well as of new sensors.

As far as remote sensing mined area reduction is concerned, the concept of the whole method is described, developed within the SMART project, and most of the attention is given to the data fusion task. The proposed fusion approaches are to a large part original and constitute by themselves a result of the project. Results have been obtained on three test sites in Croatia, being representative of the South Eastern Europe, with the three most promising approaches, and as an example, fusion results for one of the sites are given here. Note that in order to apply the proposed methodology in another context, a new field campaign would be needed to derive and implement new general rules. We have shown how the results can be improved by introducing additional knowledge in the fusion process. A spatial regularization at a regional level further improves the results. At the end, the results are at least as good as the ones provided for each class by the best classifier for that class. Therefore they are globally better than any input classifier or detector. This shows the improvement brought by fusion.

The user has the possibility to be involved in the choice of the classifiers, in the choice of some of the parameters (in particular for the fuzzy fusion approach, some supervision is still

required in the choice of the parameters), and the programs are flexible enough to allow him to modify them at wish.
The work done here is useful in many other applications, even in quite different domains, and constitutes thus a large set of methods and tools for both research and applicative work. The developed schemes have a noticeable variety and richness and constitute a real improvement over existing tools.

7. Acknowledgement

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5

Resonance and Nonlinear Seismo-Acoustic Land Mine Detection

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1. Introduction

Since WWII acoustic echo-location method utilized in sonars has been one of the primary approaches for detecting underwater mines. However, earlier attempts to replicate sonar approach and its modifications for detection of landmines were not successful. For example, Caulfield, 1989, House & Pape, 1994, Don & Rogers, 1994 suggested the use of acoustic impulse reflection from soil. A buried object is detected by measuring a relative change in acoustic reflectivity of soil. However, compared to water, soil is an extremely inhomogeneous medium exhibiting wide variations in the physical properties: density, porosity, moisture content, etc. These variations often have a spatial scale comparable with the size of a mine creating respective variations in acoustic reflectivity regardless of presence of buried mines. Another significant drawback of these methods is their inability to discriminate mine from clatter with similar acoustic reflectivity (rocks, tree roots, etc.) The breakthrough in acoustic landmine detection had occurred with the discovery of landmine's resonance and nonlinear behaviors.

In 1999 Sabatier and Xiang reported the results of the first field test detecting live buried landmines using seismo-acoustic approach, proposed a decade earlier (according to the patent filing date) by Sabatier & Gilbert, 2000. Sabatier & Xiang used Laser Doppler Vibrometer (LDV) to measure vibration of soil excited with an airborne sound. Fig. 1 illustrates the detection approach and the resulting image of soil vibration above a buried mine. They observed noticeable deference (contrast) in soil vibration velocities measured above and off a buried mine. The contrast was observed for a variety of antitank (AT) mines in the relatively low frequency range of 50 to 300 Hz, which was quite puzzling at the time.

Simultaneously, Scott et al., 1998, initiated a laboratory testing of the detection scheme using seismic waves and radar vibrometer. Using sophisticated signal processing, the authors demonstrated that a buried object like a mine reflects a portion of seismic energy propagating along soil surface. They suggested to utilize this reflection effect for landmine detection.

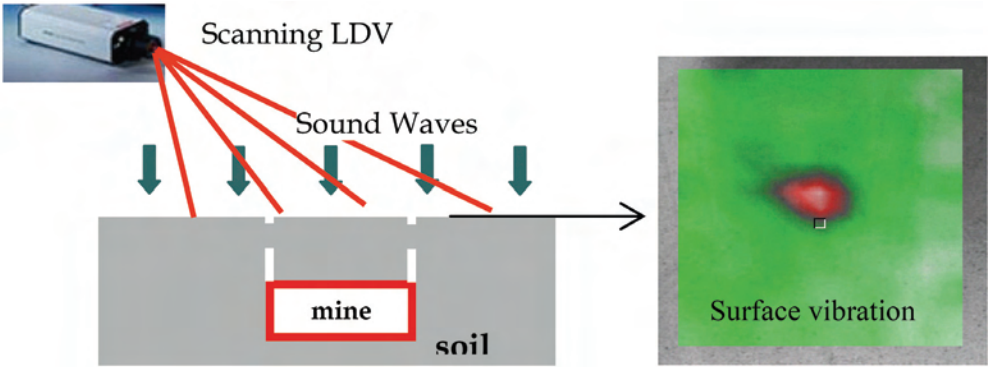

Fig. 1. Seismo-acoustic detection scheme (left) and typical vibration image of a buried mine

In the same year, Donskoy, 1998, reported first laboratory experiments demonstrating strong nonlinear dynamic behavior of buried landmines in the low frequency range below 1000 Hz. Using the same detection scheme shown in Fig. 1, Donskoy used dual harmonic excitation of soil applying airborne acoustic as well as directly coupled seismic waves and measuring nonlinear vibrations (harmonics, sum and difference frequencies) of soil above the buried mine. He noticed that the nonlinear effect is frequency dependent indicating some resonance behavior. In the following year, Donskoy, 1999, proposed a simple mass-spring model of a coupled soil-mine system explaining its resonance and nonlinear dynamics. According to this model, the combination of masses and springs (representing soil and mine dynamic stiffnesses and inertia) creates a resonance vibration response, while the nonlinearity is explained by lack of the tensile stress at the interface between a mine top surface and soil. The nonlinear mass-spring model was later refined to account for mine's own resonances and the shear stiffness of the soil column, Donskoy, et al. 2001; 2002. Further refinements included quadratic and cubic nonlinearities, Donskoy, et al., 2005 and multiple mine resonances, Zagrai, et al, 2005.

Along with the development of the nonlinear mass-spring model, the discovery of the mine's resonances was one of the key steps in understanding and developing seismo-acoustic landmine detection techniques. In 2000, our team at Stevens Institute of Technology conducted dynamic impedance measurements of over 50 live antitank (AT) and antipersonnel (AP) mines. This collection, shown in part in Fig.2, included metal, plastic, and wooden mines manufactured in different countries in Europe and Asia, as well as in the United Stated.

Fig. 2. Collection of live mines and experimental setup for dynamic impedance measurements of mines at U.S.Army testing ground

Remarkably, almost all tested mines exhibited well defined resonances with Q-factors ranging from 5 to 25 in quite narrow frequency bands: 200 Hz – 400 Hz for AT mines and 250Hz – 520 Hz for AP mines. Using this data and the model, it was possible to explain various phenomena observed during the laboratory and field measurements: high on/off mine vibration contrast (detection contrast) in the narrow frequency band observed by Sabatier & Xiang, 1999; mine's resonance responce to seismic waves, Schroeder & Scott, 2001; variation of detection frequencies and contrast level with burial depth, Sabatier, et al., 2002, Fenneman, et al ., 2003, Zagrai, et al., 2004; low detection contrast for non-mine objects such as rocks, Donskoy, et al., 2001, Schroeder & Scott, 2001; effects of moisture, temperature, and soil consolidation, Donskoy, et al., 2002.

In parallel to investigation of the mine-soil resonance behavior, our team at SIT conducted an extensive study of the nonlinear dynamics of the coupled soil-mine system. These studies, supported by numerous laboratory and field tests, demonstrated high potential of the nonlinear technique for landmine detection (Donskoy, et.al. 2002, 2005, Korman & Sabatier, 2004). Specifically, the nonlinear technique demonstrated very high (up to 40dB) detection contrast and low false alarm rate due to low clutter sensitivity.

Following this introduction, we describe major results obtained and methodology developed by the SIT team.

2. Resonance Vibrations of Land Mines

Seismo-acoustic detection of buried landmines explores the dynamic mechanical behavior of mines coupled with soil. Therefore, knowing mine's dynamic properties would be a natural first step toward understanding the mechanism of the detection, building its physical model, and developing effective detection algorithms.

In August 2000, at the U.S.Army testing site, we conducted first comprehensive measurements of variety of live mines: mines with explosive charges but without fuses. Overall over 50 mines were tested including metal, plastic and wooden AT and AP mines manufactured throughout the world. These tests involved the evaluation of mine's mechanical impedance in the frequency range 30 – 800 Hz by measuring the acoustic pressure, exerted on mine, and the resulting vibration velocity of the mine top surface. Each tested mine was placed on 2x2x2 cu. ft. concrete foundation flush buried in the ground. External force (airborne acoustic pressure) was applied with a loudspeaker suspended above the mine. We used sinusoidal signal linearly swept from 30 to 800 Hz. The acoustic pressure, P, was measured with a microphone positioned a few mm above the mine top. The mine's vibration velocity, V, was simultaneously measured just beneath the microphone using a non-contact Laser-Doppler Vibrometer. Data from the microphone and the LDV were fed into a two-channel data acquisition system which calculated and recorded magnitudes of the mine dynamic impedance (per unit area) as function of frequency, ω; $Z_m(\omega) = P(\omega)/V(\omega)$. The measurements were taken for two representative mines of the same kind and demonstrated good data repeatability. Fig. 3 presents the recorded impedances of some plastic and metal AT and AP mines. The minimum value of the impedance corresponds to the resonance frequency.

As evident from Fig.3, AT and AP mines exhibit the resonance behaviour. In fact, almost all tested mines have at least one clearly defined resonance, Table 1:

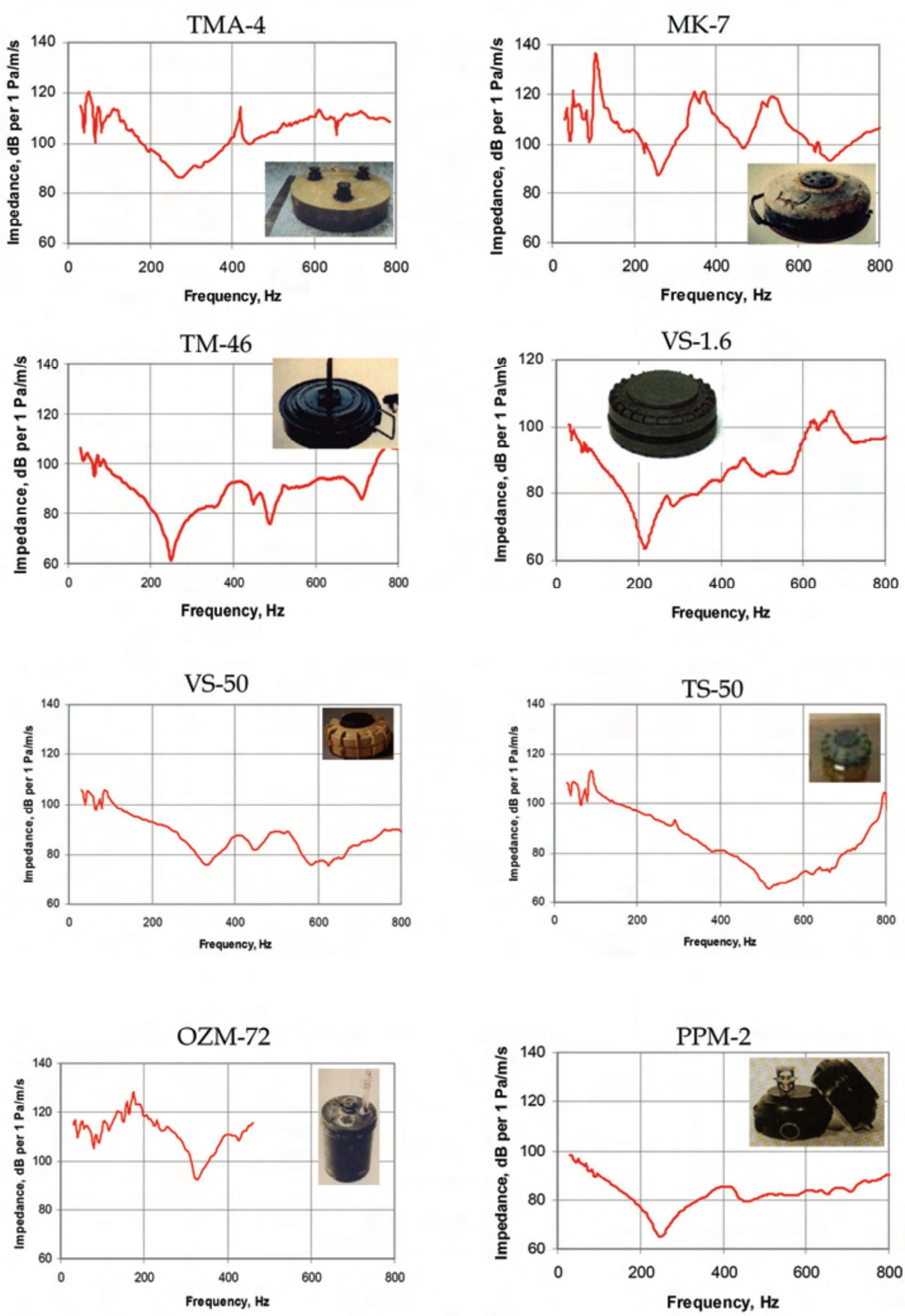

Fig. 3. Representative impedances of AT mines (TMA-4, MK-7, TM-46, VS-1.6) and AP mines (VS-50, TS-50, OZM-72, PPM-2)

Mine type	First Resonance frequency f_0 (Hz)	Dynamic stiffness K_m*10^{-7} (Pa/m)	Dynamic mass M_m (kg/m^2)	Damping constant R_m ($kg/s*m^2$)	Description
TS-50	520	10	9	4000	AP Plastic
VS-50	330	6	13	3300	AP Plastic
PONZ-2	380	50	85	26000	AP Plastic
PPM-2	320	4	10	4000	AP Plastic
OZM-72	330	80	190	18000	AP Metal
VS-1.6	220	2.5	12	1700	AT Plastic
TMA-5	190	0.2	1.4	300	AT Plastic
SH-55	280	2.5	8	3000	AT Plastic
VS-HCT-2	465	2.8	3.3	500	AT Plastic
TM-62P3	200	7	45	9000	AT Plastic
PTMIBA-3	260	2.5	10	1300	AT Plastic
TMA-4	250	17	65	20000	AT Metal
TM-46	250	4	16	1200	AT Metal
AT-72	200	2	14	1800	AT Wood

Table 1. Dynamic parameters of live mines

Considering a mine as an oscillator, its impedance in the vicinity of the first (lowest) resonance can be expressed through oscillator's dynamic parameters (per unit area): inertia or mass, M_m , stiffness, K_m , and damping, R_m , as following

$$z_m(\omega) = R_m + j(\omega M_m - K_m/\omega) . \qquad (1)$$

Using curve fitting of the calculated impedance (1) into the measured impedance curve, we estimate the dynamic parameters of each mine for their lowest resonance. These values are also shown in Table 1.

What is the physical nature of these resonances? Depending on mine's structure, there are two major types of resonances: piston and flexural (bending) resonances of mines' upper diaphragms. Some mines, such as VS-2.2, VS-1.6, SH-55, TS-50, VS-50, and some others have a very softly supported disk-shaped pressure plate (piston). For such mines, the support is much softer than the rigidity of the plate, so the plate vibrates as a whole (as a piston) up and down or wobble from side to side or from one side only without deformation, Fig.4. These images obtained with a scanning LDV show the vibration velocity distribution at the top of the mine. The color indicates the magnitude of the velocity: red is high and green is low. Each mode is associated with the particular resonance frequency, as shown for the mine VS-50.

Many mines have a top cover rigidly connected to their side casings as it can be seen on the pictures of mines TMA-4, TM-46, MK-7, OZM-72 (Fig.3). These covers can be considered as dynamically flexible diaphragms with the respective flexural resonating modes, example of which is depicted in Fig.5 for AT mine TMA-2.

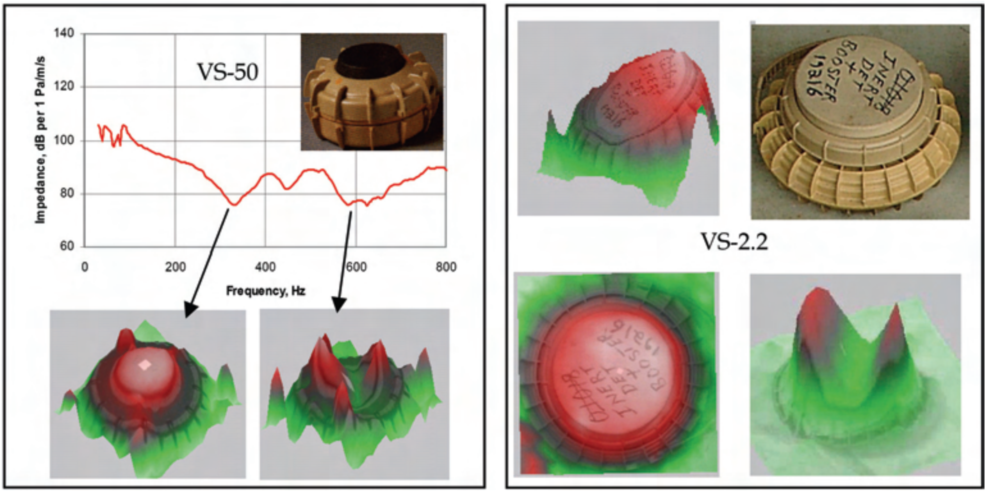

Fig. 4. Piston modes of vibration of AP mine VS-50 (left) and AT mine VS2.2 (right)

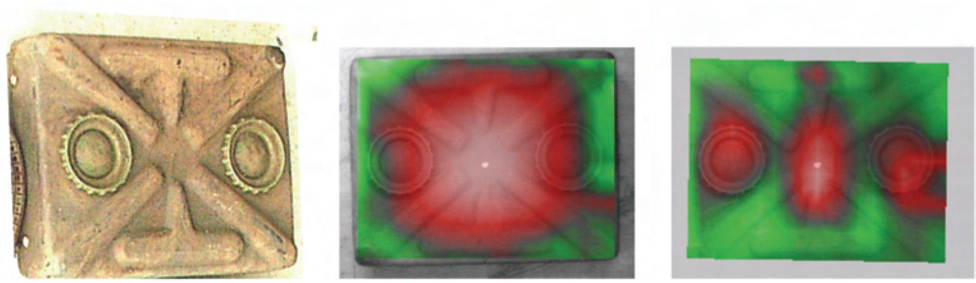
Fig. 5. Flexural modes of vibration of AT mine TMA-2 with the respective resonance frequencies 190 Hz and 490 Hz

As an example, we estimate the first flexural resonance frequency for a metal AT mine, similar to TM-46. We simplify its upper diaphragm as a clamped circular plate. The first flexural resonance frequency of this plate can be evaluated using the following formula, Skudrzyk, 1968:

$$f_0 \cong \frac{\pi h}{2R^2}\sqrt{\frac{E}{12(1-\upsilon^2)\rho}}, \qquad (2)$$

where h and R are the thickness and the radius of the plate respectively and E, ν, ρ are the material parameters of the plate (Young's modulus, Poisson's ratio, and density). Thus, for 1 mm thick and 0.1 m radius steel plate, the resonance frequency is app. 240 Hz, which is a quite accurate estimate of the measured resonance frequency 250Hz for this mine.

It should be pointed out that mines exhibit not just one but multiple resonances. Although for many mines the first resonance has the lowest impedance, the higher frequency modes may also contribute to a measured soil-mine vibration response.

3. Lump-element Linear Model of Coupled Soil-mine System

One of the critical elements in understanding, developing, and implementing the mine detection technique is an adequate physical model describing dynamic behavior of the soil-mine system. The appropriate model helps to develop optimum detection algorithms and evaluate detection capabilities of the technique applied to various mine types, burial depths, and soil conditions.

The first step in developing a physical model of a dynamic system starts with a comparison of the wavelength and characteristic geometric sizes of the system. If the wavelength is shorter than the characteristic sizes, the wave approach should be used. In the opposite situation, the lump-element approach is more appropriate. In the case of a soil-mine system, the use of the lump-element (mass-spring-dashpot) approach is justified as long as low frequency waves are used: i.e. the wavelengths are greater than the size of a mine and its burial depth (characteristic sizes). The typical sizes of anti-personnel (AP) mines are in the range of 5 – 10 cm and their burial depths are up to 5 cm. The typical sizes of anti-tank (AT) mines are in the range of 20 – 30 cm and their burial depths are up to 20 cm. Wavelengths in soil depend on soil characteristics. Typically, the wavelengths are greater than 30 cm in the frequency range of hundreds of Hz: the range where the most successful practical results were obtained.

When soil is excited with acoustic or seismic waves, it vibrates directly above a buried mine with a greater amplitude than the surrounding soil. It is, in fact, one of the primary detection criteria. This suggests that some important (for detection) dynamic effects are taking place within a soil column supported by a low impedance mine (as shown in the previous section). Obviously, the mine influences the dynamics of the supported soil column; therefore, soil and mine must be treated as a dynamically coupled soil-mine system.

We start constructing the model using the Free Body Diagram (FBD) of the body of interest: mine and soil column on the top of it. Because we are interested in a perpendicular to soil surface (normal) component of vibration, in the model we account only for a normal component of the externally exerted force (normal stress σ_{zz}). The effect of the cut off from the FBD surrounding soil is represented with the shear stress, τ_{nz}, applied to the soil column around its side (cut off) surface, as shown in Fig.6.

Next, we construct a mechanical diagram (Fig.7) of the obtained FBD. The mine (rather the mine's top diaphragm responsive to the soil column vibration) is represented by its mass (inertia), M_m, compression stiffness, K_m, and damping, R_m. Similarly, dynamic properties of the soil column are described by soil inertia, M_S, compression stiffness, K_{S2}, and damping associated with the soil compression, R_{S2}. The resisting shear stress, τ_{nz}, is proportional to the soil shear modulus and shear strain and could be represented by soil shear resistance (stiffness), K_{S1}. We also add an additional damping, R_{S1}, associated with soil shear deformation.

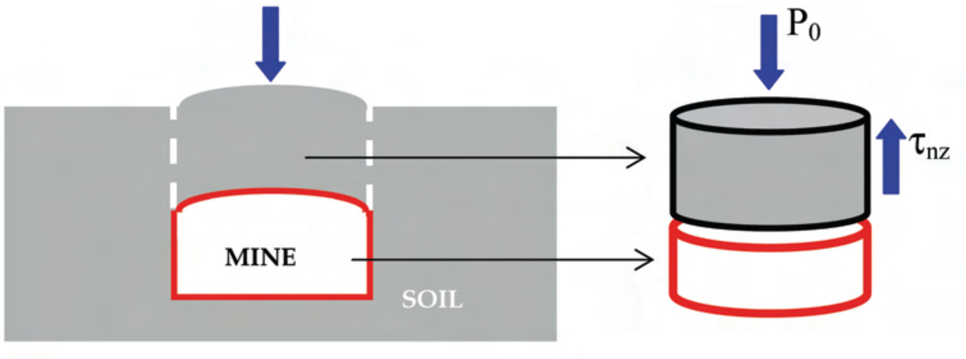

Fig. 6. Free Body Diagram (right) of vibrating mine and soil column on top of it

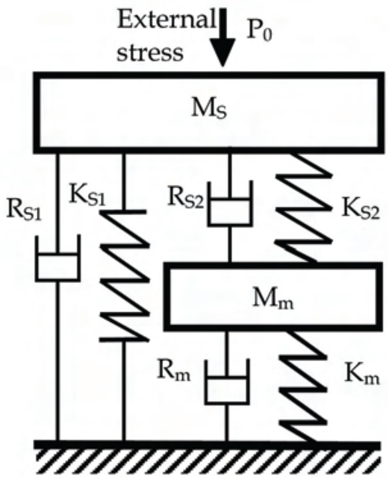

Fig.7. Linear mass-spring model of coupled soil-mine system

The introduced soil parameters are depth-dependent. The following formulas can be used to evaluate these parameters:

$$M_S \cong \rho AH \,, \tag{3}$$

where H is the burial depth, A is the effective area of the upper compliant diaphragm of the mine, and ρ is the density of the soil. The shear and compression stiffnesses, K_{S1} and K_{S2}, of the soil can be evaluated from the soil effective shear modulus, *G*, and compressibility, *B*, (Mitchell, 1993) by evaluating total shear and compressive forces acting on the vibrating soil column above the compliant mine diaphragm. For evaluation purpose we use a uniform cylindrical soil column on the top of a circular mine diaphragm having radius R. The column is under the normal stress, σ_{zz}, and its side surface is under the shear stress, τ_{nz}.

Spring stiffnesses are defined as a ratio of an exerted external force (stress) to the resulting deformation:

$$K_{S2} = (P_0A)/\Delta_n, \quad K_{S1} = (\tau_{nz}S)/\Delta_s, \tag{4}$$

where $S = 2\pi RH$ is the side area of the column, $A = \pi R^2$ is the area of the column foundation, $\Delta_n = \varepsilon H$ and $\Delta_s = \gamma(\lambda_S/4)$ are normal and shear deformations, respectively, and λ_S is the shear wavelength. Here the deformations are defined using respective normal and shear strains, ε and γ, multiplied by respective characteristic lengths. In dynamic (wave) problems, the characteristic lengths could be estimated as a quarter of the wavelengths: compression (P-wave) wavelength for the normal deformation and shear (S-wave) wavelength for the shear deformation. In the outlined problem, however, the height of the column, H, is much less than the wavelength of the P-wave, so H is used as a characteristic length for the normal deformation. Substituting the defined deformations into the Eq.(4) and taking into account the stress-strain relationships for the normal and shear deformations, the effective soil column stiffnesses can be evaluated as

$$K_{S2} \cong A/BH, \quad K_{S1} \cong (8\pi/\lambda_S)\, GRH, \tag{5}$$

The soil damping factors, R_{S1} and R_{S2}, are both proportional to the depth, H. (In a later study by Zagrai, et.al., 2005, the dependence for K_{S1} was modified to be proportional to H^3). The actual values of the damping coefficients could vary in a wide range depending on a soil type and conditions.

Analysis of this system is easy to perform using an equivalent electrical diagram in which external force (stress), P_0, is equivalent to voltage generator; masses, stiffnesses, and damping parameters are represented by inductances, M, capacitances, 1/K, and resistances, R, as shown in the Fig.8.

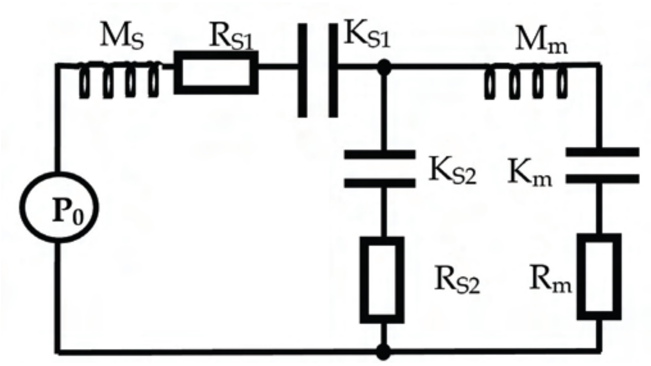

Fig.8. Equivalent electrical diagram of the mine-soil mechanical system

Using this equivalent circuit, it is easy to derive the equation for the input impedance of the soil-mine system:

$$z(\omega) = P(\omega)/V(\omega) = z_{S1} + z_\Sigma\,, \tag{6}$$

where

$$z_\Sigma = z_{S2}\, z_m / (z_{S2} + z_m), \quad z_{S1} = R_{S1} + j(\omega M_S - K_{S1}/\omega), \quad z_{S2} = R_{s2} - jK_{S2}/\omega\ , \tag{6a}$$

and z_m is defined by the Eq.(1).

The described model is one-dimentional or single degree of freedom (SDOF). It is simple, yet very effective and easy to analyze. It explains the linear detection contrast as well as many other experimental observations, such as frequency, phase, and amplitude dependencies of the measured soil vibration as a function of various mine and soil parameters.

This SDOF model could be expanded into two-dimensional one, as it is done in Zagrai, et al, 2005, and to include the nonlinear behavior of mines, Donskoy, et al., 2002; 2005.

4. Linear Detection Contrast and its Dependence on Mine and Soil Parameters

Linear detection of buried landmines is based on measuring the ratio or difference (using dB scale) between the soil surface normal vibration velocities above and off buried mine: the linear detection contrast. This approach was initially developed and actively pursued by Sabatier and his team at the University of Mississippi (Sabatier & Xiang, 1999 and many other following publications). During their first field test with live mines, the highest detection contrast was observed in the quite narrow frequency band of 50 Hz to 300 Hz. Their theory at the time was that the detection is due to difference in porosity between highly porous soil and non-porous mines. This theory, however, could not explain the observed strong frequency dependence of the detection contrast.

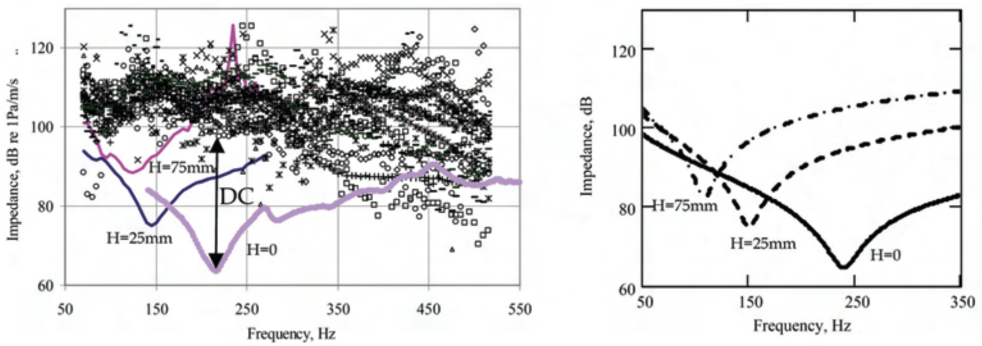

Fig. 9. Measured (left) and calculated (right) impedances of AT mine VS1.6 buried at 0, 25, and 75mm depths. Left figure also shows soil impedances measured at 23 off-mine locations at the same site. The difference between mine and soil impedances (double-sided arrow on the left) is the detection contrast (DC)

The developed lump-element model along with the evaluation of the mine's dynamic parameters provided not just qualitative, but quantitative explanation of this and other experimental observations. The model shows that the vibration response of the soil above buried mines will be resonance-like with the central (resonance) frequency determined by

the mine and soil dynamic parameters introduced in the model. Fig.8 (left) shows the impedances of soil measured at 23 off-mine locations (dotted lines) and impedances on the top and above an AT mine VS1.6 at the depths of 0 mm (flash buried), 25 mm, and 75 mm (solid lines). It demonstrates that the detection contrast is resonance-like, its maximum is depth dependant, and it diminishes with the depth. All of these are predicted by the model, Fig.9 (right).
The model explains many other field observations. For example, zero linear detection contrast (no detection) for mines buried in frozen soil, in which the shear stiffness, $K_{S2,}$ is very high. As can be seen from the model diagrams depicted in Fig.6 or Fig.7, high value of the shear stiffness dominates the total impedance of the system overwhelming the mine's contribution. Similarly, an increase in shear stiffness of consolidating soil explains the diminishing contrast for mines buried for a long period of time.
Furthermore, the analysis of the model shows that the soil shear stiffness, K_{S1}, is one of the key parameters determining the detection contrast: the higher is the stiffness, the lower is the contrast.

4.1 Effect of Soil Shear Stiffness on the Detection Contrast

A range of factors influences the detection contrast including the soil mechanical loading, its inhomogeneity, the distribution of moisture in the soil, vegetation, weathering, etc. As a result, the soil layer above the buried mine considerably affects the system dynamic response, the detection contrast, and its resonance frequency. At greater depths, the contrast is diminishing (Fig. 9) leading to poor detection and discrimination.
Understanding physical mechanisms that contribute to the reduction in soil vibration amplitude above buried mine is crucially important, since the amplitude is a key parameter used for detection. Certainly, dissipation of the elastic energy in a soil column above the mine plays an important role. However, the dissipation along can't explain the reduction of the detection contrast with time (for the same undisturbed mine) as soil consolidates. The dissipation can't account for significant contrast reduction for deeper buried mines.
Based on the model analysis, we suggest that increasing shear stiffness of soil contributes to reduction of the vibration amplitude above the buried mine. This effect is illustrated in Fig. 10, showing calculated admittances (inverse impedances) for the AT mine VS-1.6. The solid line in the figure is the admittance of the flush-buried mine (zero depth) obtained by using the experimental data from the Table 1. The dotted line represents the admittance of the mine buried at 1 cm, where $K_{S1}=2{\cdot}10^6$ Pa/m. Then, without modifying other parameters in the model, we calculated admittances for the higher shear stiffness: $K_{S1}=7{\cdot}10^7$ Pa/m (dashed line) and $K_{S1}=1.2\cdot10^8$ Pa/m (dashed-dotted line). As it could be seen from the figure, the vibration amplitude of the mine buried in the stiffer soil decreased substantially without any change in damping.

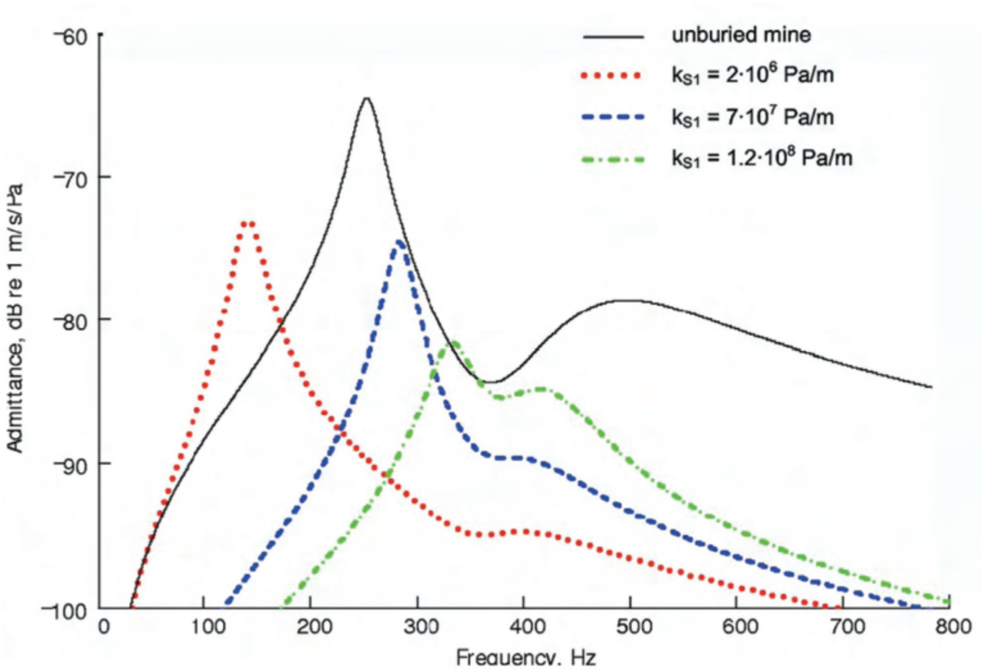

Fig. 10. Calculated admittances of the AT mine VS-1.6 illustrating the reduction of the vibration amplitude due to soil shear stiffening (Zagrai, et.al., 2005)

The soil column shear stiffness variations could be caused by different factors such as grain size distribution, compaction, consolidation, vegetation, freezing, moisture content, etc. Mine burial depth is also a significant factor affecting the total shear stiffness of the soil column above a mine, as shown in Zagrai, et al., 2005.

4.2 Effect of Burial Depth on the Soil-mine Resonance Frequency

The maximum detection contrast for most mines coincides with the first resonance of the coupled soil-mine system, as followed from the solution (6) in which soil parameters are depth-dependent. Using the depth dependencies defined by formulas (3) and (5) it can be shown that the increase in the burial depth, H, leads to downward resonance frequency shift along with the reduction of the contrast. However, experimental investigations, Sabatier, et.al., 2002, Fenneman, et.al ., 2003, Zagrai, et.al., 2004, revealed that at certain depths the soil-mine system resonance exhibits an unexpected upward frequency shift suggesting a more complex dependence of soil parameters with depth.

Fig.11 demonstrates soil-mine resonance frequency dependence on the burial depth, Zagrai, et.al. 2004. Here the resonance frequency decreases initially and then, at a certain burial depth, it starts to increase.

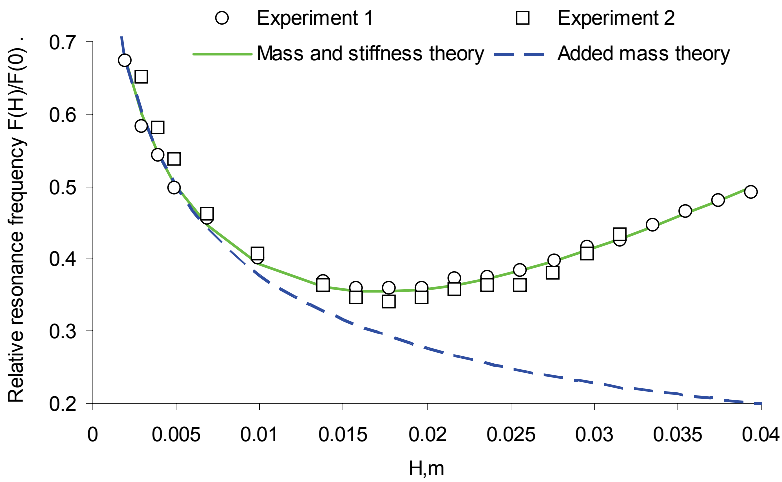

Fig. 11. Soil-mine relative resonance frequency versus burial depth, H. The relative frequency is a ratio between the resonance frequency at particular burial depth and the resonance frequency of the flush-buried mine, i.e. at zero depth

The downward shift of the resonance frequency with increase of the burial depth can be explained by the added mass of soil column (dashed line). However, the upward shift at greater depths needs an additional explanation.

The resonance frequency increase indicates that the system is stiffening with depth. We considered two possible explanations of this phenomenon. The first one deals with stiffening of the mine casing due to nonlinear stress-strain relationship for the casing. In other words, an additional soil load modifies stiffness of the casing and, respectively, stiffness of the whole soil-mine system. This explanation, however, could only hold for exceedingly high stresses which unlikely to occur under given experimental conditions. To estimate the effect of casing stiffening due to some additional mass, we conducted an experiment in which concentrated weights were placed on the casing and the impedance frequency response was measured using non-contact LDV and a microphone. The test revealed only the decrease of the resonance frequency consistent with the added mass effect. Therefore, we suggest that the upward frequency shift is due to increase of the soil shear stiffness, as elaborated by Zagrai, et al, 2005. According to this study, $K_{S1} \sim H^3$ rather than H, as was initially prescribed by Eq.(5).

4.3 Effect of Soil Moisture

Soil moisture content variation is a common factor in open fields. It was observed that vibrations of a mine buried in wet or dry soil could be considerably different. Fig.12 demonstrates vibration responses measured above a mine buried in wet and dry sand. In this test the mine initially was buried in wet sand and than the sand naturally dried, so the dry sand response was measured for the same undisturbed soil-mine setup. These measurements show that the soil moisture has a pronounced effect: it shifts the resonance frequency and changes the resonance amplitude, effectively changing the detection contrast.

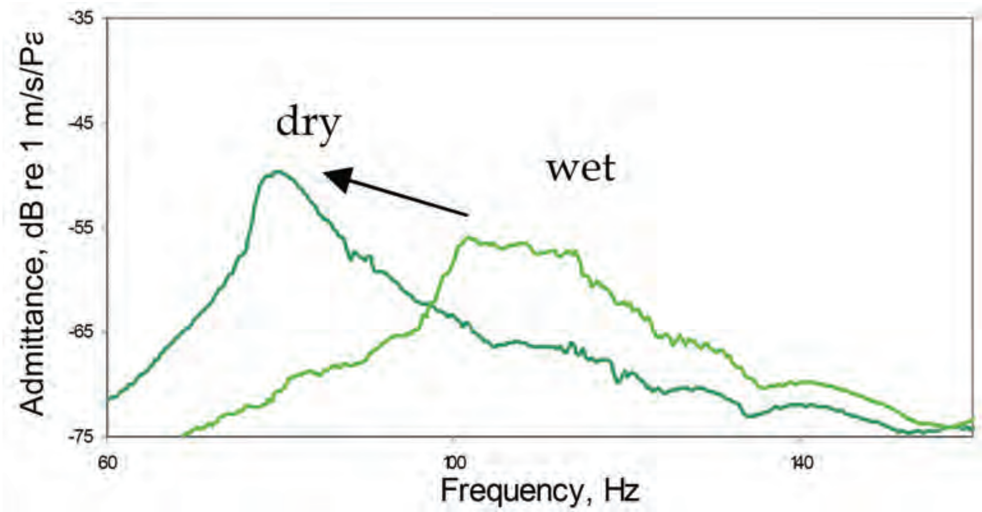

Fig.12. Effect of soil moisture on the resonance vibration of mine simulant buried at 25 mm

In order to understand and quantify the moisture effect, we conducted a laboratory test in which the plastic mine simulant was buried under gradually increasing sand depths subjected to the controlled level of water saturation. The soil water content, WC, was calculated utilizing a gravimetric method as following:

$WC=W_{water}/(W_{soil}+W_{water})\cdot 100\%$,

where W_{soil} and W_{water} are respective weights of the soil and water. Initially, we repeated the experiment with the layers of dry sand similar to described in the previous section. A relative frequency shift of the resonance frequency $F(WC=0\%)/F_0$ (here F_0 is the resonance frequency of flush-buried mine) due to increasing burial depths, H, was measured and result is presented in Fig. 13 with solid dots line. Then, the test was repeated for different moisture contents ranging from 2.5% to 15%. Moisture was uniformly distributed throughout the sand column and was kept constant for each test run. Experimental results depicted in Fig. 13 show that moisture significantly affects the dynamic resonance of the buried mine, especially at the greater depths.

It is interesting to note that the significant upward frequency shift occurs for the relatively small moisture content, and does not change for the higher moisture levels. This observation coupled with our previous conclusion that the upward frequency shift is due to soil shear stiffness increase, lead us to believe that the introduction of moisture results in soil consolidation. Consolidated soil has appreciably higher shear stiffness. As the test reveals, even relatively small water content creates appreciable consolidation (stiffening) effect shifting the resonance frequency upward and reducing the vibration velocity (Fig.12). Further increase of the water content adds little to already consolidated soil resulting in an insignificant frequency shift. These effects were recently confirmed by Horoshenkov & Mohamed, (2006).

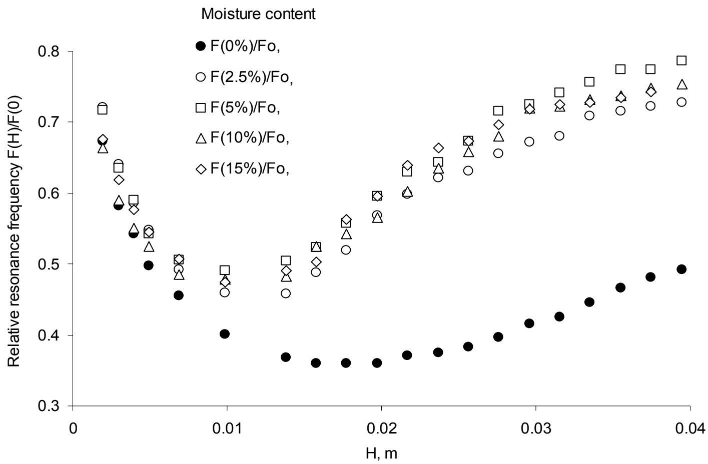

Fig.13. Effect of moisture and burial depth on soil-mine resonance frequency

5. Nonlinear Dynamics of Soil-mine System

Along with the resonance dynamics, buried mines exhibit highly nonlinear behavior, amplified by the resonance. If the system is excited by two harmonic signals, the nonlinearity manifests itself through generation of the nonlinear frequencies: harmonics, combination, and intermodulation frequencies, as depicted in Fig.14. The nonlinear frequencies were successfully employed for the detection of buried landmines (Donskoy, 1998 and the following publications). The detection scheme is similar to that shown in Fig.1. Here the acoustic or seismic waves contain two frequencies swept across the frequency band, typically 50 – 500 Hz. Scanning LDV measures the response at the nonlinear frequencies outputting the nonlinear vibration image of the buried mine. Among the advantages of the nonlinear detection approach are high detection contrast and low false alarm rate even for small plastic AP mines.

We believe that the major reason for the strong nonlinearity is the lack of bonding at the soil-mine interface. The stress-strain dependence at the interface is quite different during the compressive and tensile phases of vibration: under tensile stress, separation of soil grains may occur at the soil-mine interface whereas under compressive stress a mine and the soil are always in contact. This asymmetric response leads to noticeable nonlinear effects such as the generation of harmonics and signals with combination and intermodulation frequencies.

There are two possible mechanisms for separation at the interface. In the first one, the level of applied vibrational force (stress) is higher than the weight of the soil column. In this case, the soil will “jump or bounce” on the top of the mine leading to a very strong nonlinearity. This mechanism, however, should occur rarely considering the practical levels of vibrational excitation. Indeed, in most of the field tests we conducted, the soil surface acceleration was below the gravitational acceleration implying that the vibrational force was smaller than the weight of the soil above the mine. Nevertheless, noticeable nonlinear effects were still observed suggesting that there should be another mechanism of “separation”.

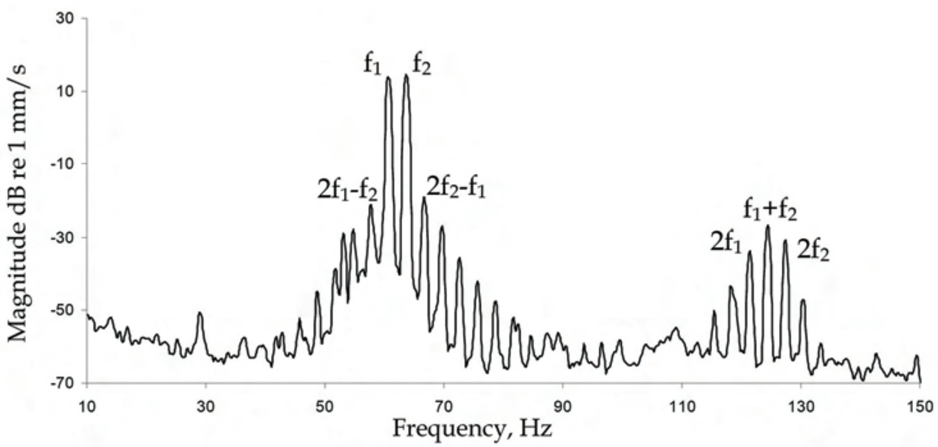

Fig. 14. Vibration spectrum measured above buried in sand plastic mine simulant. Here f_1 & f_2 are the fundamental (excitation) frequencies and f_1+f_2, $2f_{1,2}$, $2f_2-f_1$, $2f_1-f_2$ are the nonlinear (sum, harmonic, and intermodulation) frequencies

Since both soil and mine are mechanical systems, each with their own inertia and stiffness, their respective phases of oscillation depend on the relative contributions of inertia and stiffness. If stiffness is the dominant contributor to the system’s mechanical impedance, then the system will oscillate in phase with the applied external force. At higher frequencies, however, the inertial contribution becomes dominant and the system oscillates in the opposite phase with respect to the external force. Therefore, the mine and soil may oscillate with the opposite phases depending on relative values of their mechanical impedances. This leads to the soil separation at the interface. When this mechanism is dominant, the separation is taken place even at relatively low levels of the exerted dynamic force.

In addition to the interface nonlinearity, soil itself can contribute to the overall nonlinear dynamics of the soil-mine system, as suggested by Korman & Sabatier, 2004. However, in the foregoing discussion, we will focus only on the interface nonlinearity, following Donskoy, et al., 2004.

5.1 Nonlinear lump-element model of soil-mine system

The interface nonlinearity can be described using a generic form of Hooke’s law:

$$P_m = \xi \cdot \left(K_m + K_m^{nl}(\xi)\right), \tag{7}$$

where ξ is the deformation, K_m is the mine linear stiffness coefficient, $K_m^{nl}(\xi)$ describes the nonlinear stiffness at mine interface, and P_m is the normal stress (pressure) applied to the interface. Accounting for the introduced nonlinear stiffness, the mechanical mass-spring-dashpot diagram, shown in Fig. 7, can be respectively modified by introducing an additional nonlinear spring, Fig. 15.

The mathematical analogy between mechanical and electrical systems provides exceptional flexibility and convenience in the analysis of complex dynamical systems. Using this analogy (Skudrzyk, 1968) we can conveniently represent the mechanical parameters in terms of elements of the electrical circuit depicted in Fig. 8. The introduction of the nonlinear spring is shown as an additional capacitance in Fig.16. The advantage of this approach is that the analysis of the nonlinear mechanical system is significantly simplified by applying the perturbation technique and considering linear impedance solutions for the equivalent electrical circuits corresponding to each step of perturbation, yielding liner and nonlinear solutions.

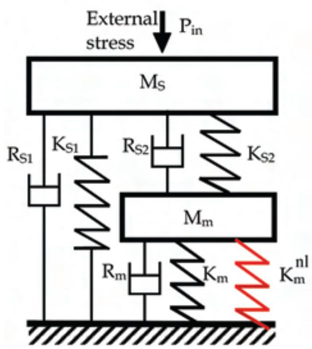

Fig. 15. Non-linear mass-spring model of soil-mine system

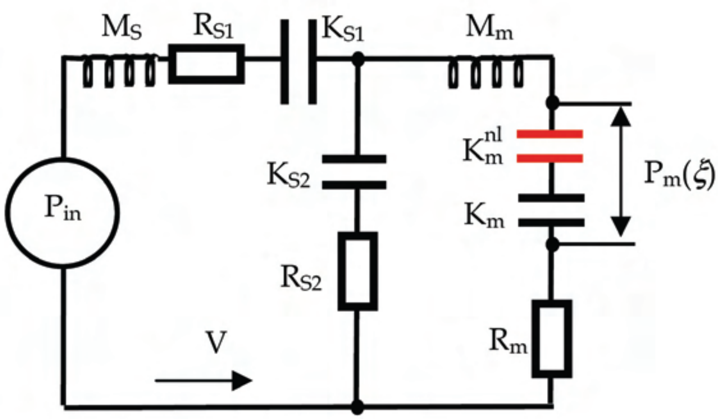

Fig. 16. Equivalent electrical diagram of the nonlinear mine-soil mechanical system

The nonlinear nature of the acoustic interaction at the soil-mine interface is accounted for by the dependence of stiffness on deformation, ξ , in Hooke's law, Eq. (7). For small deformations, the nonlinear contribution can be approximated using the 1st and 2nd terms in Taylor's expansion, i.e. $K_m^{nl}(\xi) \approx K_m\left(\alpha\xi + \beta^2\xi^2\right)$. Substitution of this approximation into Eq.(7) yeilds

$$P_m(\xi) = K_m\xi\,[1 + \alpha\xi + (\beta\xi)^2]. \tag{8}$$

The coefficients α and β characterize, respectively, the quadratic and cubic nonlinearities of the soil-mine interface. The first, second, and third terms on the right-hand side of Eq.(8) are equal when $\xi = 1/\alpha = 1/\beta$ which is the case of very strong nonlinearity. In practice, the nonlinearity is usually weak, so we assume:

$$\alpha\xi << 1 \quad \text{and}\ \beta\xi << 1 \ . \tag{9}$$

In classical nonlinear acoustics, the quadratic term in the nonlinear form of Hooke's law, as a rule, dominates over the cubic term and the effects of the latter are usually neglected, unless there is strong hysteretic or other non-classical nonlinearity.

We are not discounting the hysteretic and relaxation nature of the soil dynamics. In fact, such nonlinearity is common for grainy media and could contribute to the nonlinearity of the soil-mine system, as pointed out by Korman & Sabatier, 2004. Regardless of its nature, the cubic nonlinearity could have appreciable effects in a resonance system, such as soil-mine. If the probing signal has excitation frequencies ω_1 and ω_2 close to the system's resonance frequency, the nonlinear response due to the cubic nonlinearity manifests itself at the intermodulation (IM) frequencies $2\omega_1$-ω_2 and $2\omega_2$-ω_1 (the term IM is widely used in electronic and RF engineering to describe similar cubic nonlinear effects). If these intermodulation frequencies lie within the system's resonance they are effectively amplified by the resonance. In contrast, the quadratic nonlinear response observed at frequencies ω_1-ω_2, $\omega_1+\omega_2$, $2\omega_1$, $2\omega_2$ is not amplified since these frequencies are outside of the resonance frequency band. As a result, even if the contribution of the cubic nonlinearity in Eq. (8) is weak, the response of the system at frequencies $2\omega_1$-ω_2 and $2\omega_2$-ω_1 could be comparable or even exceeding the response associated with the quadratic nonlinearity.

5.2 Quadratic and Intermodulation Nonlinear Solutions

The analytical solution of a "weakly" nonlinear system represented in Fig.16 is derived using the perturbation method (Donskoy, et.al., 2004). Skipping the derivations, here we present the final solution for the nonlinear vibration velocity responces of the mine-soil system under the bi-harmonic excitation:

$$P_{in}(t) = P_{01}e^{i\omega_1 t} + P_{02}e^{i\omega_2 t} + cc. \quad , \tag{10}$$

where P_{01} and P_{02} are complex amplitudes of the applied acoustic normal stress at the respective frequencies ω_1 and ω_2 .

The quadratic nonlinearity manifests itself at sum, $\omega_1+\omega_2$, and difference, ω_1-ω_2, frequencies. The sum frequency solution for the vibration velocity, V_Σ , is the following (the similar solution is for the difference frequency):

$$V_\Sigma = \frac{2\alpha K_m}{\omega_1\omega_2} V_1 V_2 \frac{z_\Sigma(\omega_1) z_\Sigma(\omega_2)}{z_m(\omega_1) z_m(\omega_2)} \frac{1}{z_1(\omega_\Sigma)} \quad , \tag{11}$$

where $V_{1,2} = P_{01,02}/z_0(\omega_{1,2})$ are the linear solutions determined by the Eq.(6) and z_Σ is defined by the Eq.6a. Other notations used in this page are

$$z_1 = z_{S1} + z_m (1 + z_{S1} / z_{S2}) , \; z_2 = z_m + z_{S2} (1 + z_{S2} / z_{S1}) \, . \tag{12}$$

Here z_m is defined by Eq.(1) and z_{S1} , z_{S2} are by Eq.(6a).
Next, we present the intermodulation solution: vibration velocities V_{im1} and V_{im2} for the frequencies $\omega_{im1} = 2\omega_1 - \omega_2$ and $\omega_{im2} = 2\omega_2 - \omega_1$, respectively. Note that both the quadratic and the cubic terms in Eq.(9) contribute to the intermodulation solution:

$$V_{im1} = V_{im1}^{Q} + V_{im1}^{C} \, . \tag{13}$$

Here V_{im1}^{Q} is the contribution of the quadratic nonlinearity and V_{im1}^{C} that of the cubic nonlinearity:

$$V_{im1}^{Q} = -\frac{2\alpha^2 K_m^2 V_1^2 V_2^*}{\omega_1^2 \omega_2} \left(\frac{z_\Sigma(\omega_1)}{z_m(\omega_1)}\right)^2 \left(\frac{z_\Sigma(\omega_2)}{z_m(\omega_2)}\right)^* \frac{1}{z_1(\omega_{im1})} \left(\frac{1}{\omega_\Delta z_2(\omega_\Delta)} + \frac{1}{2\omega_1 z_2(2\omega_1)}\right), \tag{14}$$

$$V_{im1}^{C} = j\frac{3\beta^2 K_m V_1^2 V_2^*}{\omega_1^2 \omega_2} \left(\frac{z_\Sigma(\omega_1)}{z_m(\omega_1)}\right)^2 \left(\frac{z_\Sigma(\omega_2)}{z_m(\omega_2)}\right)^* \frac{1}{z_1(\omega_{im1})} , \tag{15}$$

where $\omega_\Delta = \omega_1 - \omega_2$, and $(\ldots)^*$ denotes the complex conjugate. The solution (13)-(15) is obtained for the intermodulation frequency ω_{im1}. In the expression for the intermodulation response at ω_{im2}, indices 1 and 2 in (13)-(15) should be interchanged.

It should be mentioned that in addition to the intermodulation (IM) response described by Eqs. (13) – (15), many other combination frequency components, such as $3\omega_1$, $3\omega_2$, $2\omega_1+\omega_2$, $2\omega_2+\omega_1$, etc., are obtainable in the 2nd order of perturbation. We devote particular attention to the IM components because of their aforementioned resonance amplification.

5.3 Case Study: the Nonlinear Solution for AT Mine VS-1.6

In this example we use solutions (11) – (15) to calculate a nonlinear vibration responce of a plastic AT mine VS-1.6 buried at 25mm depth. The mine dynamic parameters are defined in the Table 1. Soil parameters depend on many factors and vary over a rather wide range. Fitting the calculated linear solutions, V_1, into the measured in the field responces of AT mine VS-1.6 buried in gravel (Fig.11 in Donskoy, et al., 2004), we estimated parameters of the gravel soil as follows: $K_{S1}=2.4\cdot10^7$ Pa/m, $R_{S1}=3.9\cdot10^3$ kg/(m^{2}s), $M_S=40$ kg/m^2, $K_{S2}=10^8$ Pa/m, $R_{S2}=4\cdot10^3$ kg/(m^{2}s). All parameters are per unit area.
Fig.17 illustrates the results of calculations for the linear and nonlinear responses as a function of the probing signal frequency, $f_1=\omega_1/2\pi$. The linear response was obtained by setting the amplitude of the probing signal in Eq.(10) equal to $P_{01}=P_{02}=$ 0.3 Pa. This value

corresponds to the amplitude of the acoustic pressure at the soil surface, which, according to field measurements, produces a soil surface velocity of $V_1 \approx V_2 \approx 5.7 \cdot 10^{-5}$m/s at the soil-mine resonance frequency $f_0 \approx 150$ Hz (mine is buried at 25 mm depth). This result is presented in Fig.17 with a solid line and denoted as $\omega = \omega_{1,2}$. As it can be seen from the linear response, the resonance frequency bandwidth at –6 dB level is approximately Δf = 20 Hz. In order to observe the resonance amplification of the intermodulation frequencies, Δf should be greater than the difference between the frequencies of the probing signal (5), i.e. $\Delta f > \delta f = f_2 - f_1$ and for this reason we have chosen δf = 5 Hz.

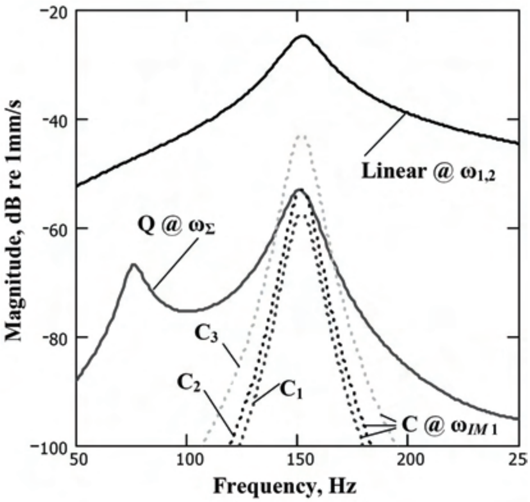

Fig. 17. Linear $V_1(\omega_1)$, Q-nonlinear $V_\Sigma(\omega_\Sigma)$ and IM nonlinear, $V_{im1}(\omega_{m1})$ responses of the soil-mine system plotted versus frequency ω_1. The intermodulation components are represented as follows: C_1 for $\beta = 0\ \mu m^{-1}$; C_2 for $\beta = 1\ \mu m^{-1}$; C_3 for $\beta = 2\ \mu m^{-1}$

The quadratic nonlinear response (Q-curve in Fig. 17) features two distinctive maximums. The first, weaker in amplitude, occurs when the sum frequency ω_Σ coincides with the soil-mine resonance frequency ω_0 (in this case the probing signal frequencies are near half of the resonance frequency; $\omega_1 \approx \omega_2 \approx \omega_0/2$). As the probing frequencies coinsides with the system resonance; $\omega_1 \approx \omega_2 \approx \omega_0$, the Q-response has the second strong maximum. The sum frequency in this case is $\omega_\Sigma \approx 2\omega_0$. For the chosen nonlinear parameter $\alpha = 1\ \mu m^{-1}$, the amplitude of the vibration velocity V_Σ reaches maximum value of -54 dB re 1mm/s which is in good agreement with the field measurements.

The IM nonlinear response, V_{im1}, is depicted in Fig.17 with the family of dotted curves (C-curves). Maximum values are within the mine resonance band and the slopes rapidly decrease outside of the resonance. Each C-curve is obtained for the specific value of the cubic nonlinear parameter $\beta(C_1) = 0$, $\beta(C_2) = 1\ \mu m^{-1}$, and $\beta(C_3) = 2\ \mu m^{-1}$. Curve C_1 shows the quadratic nonlinear contribution V_{im1}^{Q}. The dominance of the curves C_2 and C_3 over C_1 demonstrates that the IM response is mostly defined by the cubic nonlinear contribution V_{im1}^{C}. Interestingly, for the parameter $\beta(C_2) = 1\ \mu m^{-1}$, V_{im1} is of the same order of magnitude as V_Σ and for $\beta(C_3) = 2\ \mu m^{-1}$ the IM response even exceeds the maximum value of the quadratic nonlinear response V_Σ.

5.4 Nonlinear Detection Contrast

Similar to the linear detection contrast, the nonlinear contrast is the ratio (linear scale) or difference (dB scale) between nonlinear vibration velocities of the soil above and off buried mine. Essentially, it is the detection contrast that determines the detectability of a buried landmine. With a background level (or, in other words, velocities measured at off mine locations) of approximately –(40÷50) dB re 1 mm/s (Sabatier &Xiang, 1999), typical values of the detection contrast for linear detection is in the range of ~ 10÷20 dB. The nonlinear background level is ~ –80 dB re 1 mm/s (Donskoy, et.al., 2002), so the nonlinear detection contrast is in the range of ~ 30÷40 dB. This is an order of magnitude greater than the linear detection scheme could offer. This indicates that the nonlinear detection has the potential of being very sensitive.

Immediate use of the nonlinear contrast gain, however, is constrained by the relatively high noise floor of commercially available scanning LDVs. For example, the Polytec scanning LDV used in our field tests has a noise level of ~ -60 dB re 1 mm/s thereby limiting the nonlinear contrast to ~10÷20 dB only. At the same time, a single point LDV (from Polytec as well) with lower noise levels allowed for the measurements of background nonlinearity at –80 dB, thus, bringing up the nonlinear contrast to the predicted value of 40 dB.

5.5 False Target Nonlinear Response

Aside from the high detection contrast, nonlinear detection offers very low sensitivity to clutters: rocks, tree roots, solid metal pieces, such as shrapnel, etc. This is because the clutter is much less dynamically compliant than mines. Compliance of mines and their resonance nature lead to the separation and other nonlinear effects (hysteresis, slow dynamics) at the soil-mine interface.

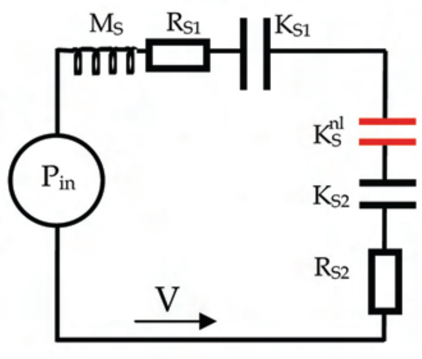

Fig. 18. Equivalent electrical diagram of the nonlinear soil column above a high impedance (false) target

A distinctively different situation occurs when a stiff (high impedance) target, such as a stone or a piece of metal, is buried into the soil. A stiff target always oscillates in-phase with the soil preventing separation at the interface. The deformations of the stiff target are much smaller than those of compliant mine, so any other nonlinear phenomena at the soil-stiff target interface are also much smaller. Therefore, in case of a high impedance (false) target, the nonlinear response is due to inherent nonlinearity of a soil column above the target.

In order to estimate this nonlinear response, the equivalent electrical diagram of the soil-mine system should be modified by eliminating the elements that are responsible for mine parameters and by including a soil nonlinear spring K_S^{nl}, Fig.18. Using this diagram, it is not difficult to show that linear and quadratic nonlinear responses are governed by the following relationships:

$$V_{1,2} = P_{01,\,02}/z_S(\omega_{1,2})\,, \tag{16}$$

$$V_\Sigma = 2\alpha_S K_S V_1 V_2/[\omega_1\, \omega_2\, z_S(\omega_\Sigma)]\,, \tag{17}$$

where $z_S = z_{S1} + z_{S2}$ is a complex soil impedance, $K_S = K_{S1} + K_{S2}$ is a total soil stiffness and α_S corresponds to the quadratic nonlinear parameter of the soil. Here we consider only quadratic nonlinearity. In order to be noticeable, the IM response requires strong resonance amplification, which is not apparent in this system.

To be consistent with the field test and previous estimates for an AT mine, we consider gravel soil with the same dynamic parameters as used in § 5.3 : K_{S1}=2.4·10^7 Pa/m, R_{S1}=3.9·10^3 kg/(m^{2}s), M_S=40 kg/m^2, K_{S2}=10^8 Pa/m, R_{S2}=4·10^3 kg/(m^{2}s). We will use the value of the nonlinear parameter α_S = 0.03 μm^{-1} as estimated for gravel soil (Donskoy, et.al.,2004). We also assume that soil vibration velocities, V_1 and V_2, above buried false target are the same as on top of buried AT mine VS-1.6 (§ 5.3) , i.e. $V_1 = V_2 = 5.7\cdot10^{-5}$m/s at the frequency 150 Hz. This means that the mine and the false target exhibit the same linear detection contrast. Substituting the above values into Eq.(17) we get V_Σ(false target) = -71 dB re 1mm/s which is 17 dB below vibration level for the mine VS-1.6 as estimated in § 5.3. That is, even if the mine and the false target are unrecognizable using linear detection generating false alarm, the nonlinear detection offers 17 dB difference effectively eliminating the false alarm.

In reality, the nonlinear response from a false target will be even less than this estimate because for the same incident pressure P_0, vibration velocities above stiff targets will be less than above mines. This brings the response from the false target well below the nonlinear background level of app. -75 ÷ - 80 dB re 1mm/s (Donskoy, et.al., 2004) which is conducive with the field measurements. In our field tests, various false targets, such as shown in Fig. 19, buried at different depths in gravel soil were not recognizable from the background effectively providing zero false alarms.

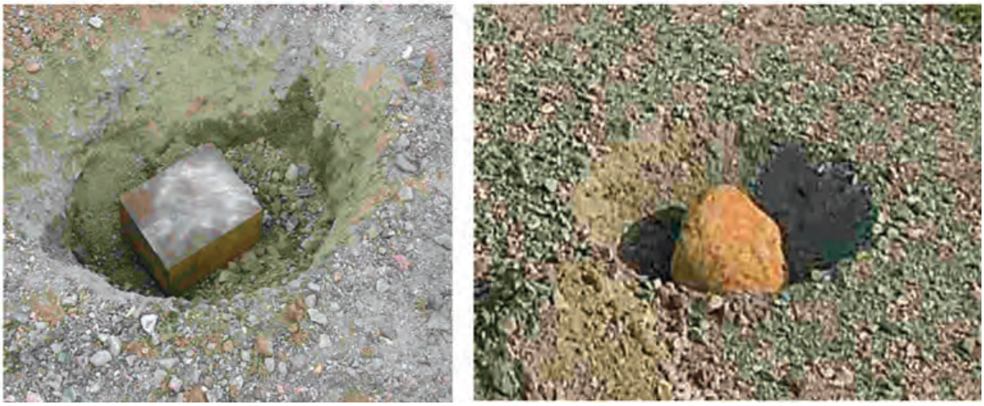

Fig. 19. Non-compliant false targets (steel block and stone) buried in gravel soil at depth 25 mm and 55 mm. Their nonlinear responses did not exceed the background level resulting in zero detection contrast

6. Field validation of the Nonlinear Detection Technique

Numerous field tests with live mines were conducted at the U.S. Army's outdoor test facilities during 2001 through 2004. The facilities offered an opportunity to perform measurements under a broad variety of conditions: several soil types and numerous types of live mines buried at different depths. The major objective of the tests was the experimental validation of the developed nonlinear seismo-acoustic detection technique, including hypotheses and model testing, collecting data for mine and soil parameters, developing and testing data collection procedures, signal processing algorithms, hardware and software. Aside from the impedance measurements, we primarily concentrated on the nonlinear detection technique. These measurements were taken in gravel and sandy soil off and above live but not armed AT and AP mines buried at different depths up to 20 cm for AT mines and up to 5 cm for AP mines.

6.1 Experimental Setup

The measurement system used in the field studies is shown in Fig. 20. Fig. 21 presents the schematic diagram of the setup. The system consists of two platforms: (a) a test cart which carries field instrumentation: speakers, scanning and single point LDVs, microphone, and may also accommodate a magnetostrictive shaker for seismic excitation; and (b) a vehicle with signal generators, power amplifiers, data acquisition and processing systems, and user interface.

The test cart carries six speakers arranged in a hexagonal pyramid to insonify the soil within the pyramid footprint. The resulting soil vibration velocity, $V(\omega)$, is measured by the single-point or scanning LDV. The system also allows for real time measuring and computing the soil impedance, $z_0 = P(\omega)/V(\omega)$, where $P(\omega)$ is the applied acoustic pressure measured with a microphone positioned near the soil surface.

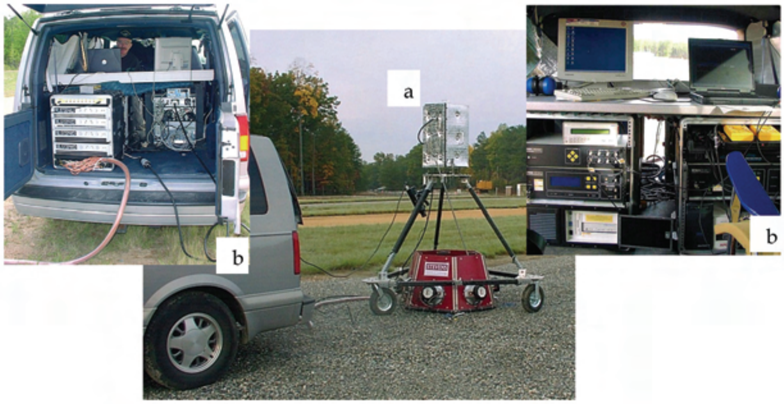

Fig. 20. Field test system

We used two harmonic excitation signals with frequencies (f_1, f_2) close enough so that $\delta f = f_2 - f_1 \leq 20$ Hz. 20 Hz is a typical resonance bandwidth of AT mines, so the above condition allows for enhancing the intermodulation effect as both frequencies fit into the resonance band. During the tests, these frequencies were simultaneously swept in a wide frequency range (typically 50-1000Hz) to yield both linear and nonlinear vibration responses. The sweep rate for both frequencies was the same, so δf was always the same for the entire sweep.
The intermodulation effect was studied at the fixed frequencies fitted to the resonance frequency band of a particular mine. LDV noise floor precluded us from obtaining the intermodulation frequency response outside the resonance.
This setup also allowed for scanning the soil surface to obtain the linear and nonlinear spatial distribution (images) of vibration velocities above buried mine, such as shown in Fig.1. The resultant velocity profiles (in multiple frequency bands) enable imaging of the buried mines with the prescribed scanning resolution (in the order of a cm) and the determination of the detection contrasts.

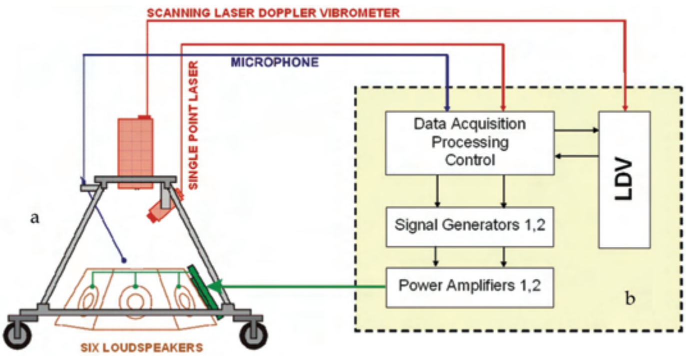

Fig. 21. Diagram of the setup

6.2. Linear and Nonlinear Correlation Imaging

Step-frequency sweeping (initially used in earlier experiments) at every grid point during the soil surface scan requires significant time. For example, each frequency step may last 100ms to achieve 10Hz resolution; therefore sweeping through 500Hz band with 10 Hz resolution requires N = 50 steps with the total time of 5 sec. Scanning 1 sq.m. of area with 4 cm resolution yields 625 point, so the total scan time will be 625x5sec = 3125sec, or 52 min which is unacceptably long.

In order to speedup the scanning time we developed a very efficient and fast correlation imaging algorithm which provides N time faster, simultaneously linear and nonlinear, imaging in a wide frequency band, yet preserving a spectral content, so the images could be reconstructed in multiple frequency sub-bands.

The developed approach uses two chirp (linearly continuously swept) signals, $P_1(t)$ and $P_2(t)$ with start (initial) frequencies f_1 and f_2 and the same sweep rate, so at every moment of time there is $\delta f = f_2 - f_1$ frequency shift between these two signals:

$$P_{1,2}(t) = P_{01,02}\cos[2\pi f_{1,2}\,(1 + \Delta F\, t/f_{1,2}T)\, t]\,, \tag{18}$$

where ΔF is the total frequency band of the sweep, and T is the duration of the sweep.

LDV receives linear and nonlinear vibration signals:

$$V_{1,2}(t) = V_{01,02}\cos[2\pi f_{1,2}\,(1 + \Delta F\, t/f_{1,2}T)\, t]\,, \tag{19}$$

$$V_{\Sigma}(t) = V_{0\Sigma}\cos[2\pi(f_1 + f_2)\, t + 2\Delta F\, t^2/T)]\,. \tag{20}$$

Next we compute convolution for both linear and nonlinear signals using linear and nonlinear convolution bases, respectively:

$$u_{1,2}(t) = \cos[2\pi f_{1,2}\,(1 + \Delta F\, t/f_{1,2}T)\, t] \quad \text{and} \quad g_{\Sigma}(t) = u_1(t) \times u_2(t)\,. \tag{21}$$

For every scan grid point we output the maximum value of the computed convolutions for the linear and nonlinear responses:

$$K_1 = \max\left[\int_{t1}^{t2} u_1(t+\tau)V_1(\tau)d\tau\right] \quad , \quad K_{\Sigma} = \max\left[\int_{t1}^{t2} g_{\Sigma}(t+\tau)V_{\Sigma}(\tau)d\tau\right]\,. \tag{22}$$

Here the time interval [$t1$, $t2$] determines the corresponding frequency band in which the convolution is calculated. Thus, the full frequency band ΔF is defined by the interval [0, T]. Using different time intervals, K_1 and K_{Σ} could be calculated for multiple sub-band to find the one with the maximum detection contrast. Fig. 22 illustrates the frequency sub-band division and resulting images. As expected, the best contrast (best image) is obtained for the sub-band which coincides with the soil-mine resonance.

In the field, the precise resonance frequency of the soil-mine system is not known because it depends on the depth and soil parameters, therefore the sub-division procedure is essential for reliable and sensitive detection.

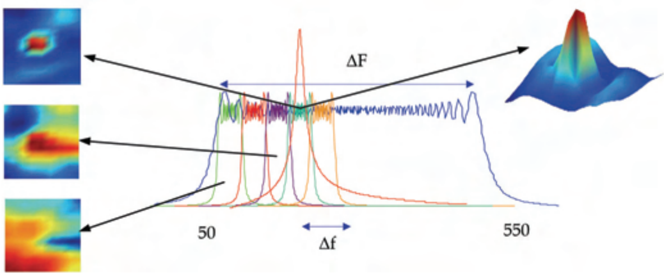

Fig. 22. Illustration of the frequency sub-band division and the resulting correlation images of AP mine VS-50 buried at 25 mm depth. Here ΔF is the total frequency band occupied by the chirp signal and Δf is the sub-band. Red resonance line illustrates the soil-mine resonance response

The linear and nonlinear detection contrasts for the correlation imaging is defined similarly to the vibration velocity detection contrast; i.e. the linear detection contrast LDC = K_1(on mine)/ K_1(off mine) and the nonlinear detection contrast NDC = K_Σ(on mine)/ K_Σ(off mine). The developed correlation imaging algorithm includes an optimization analysis to obtain the best detection contrast choosing the optimum duration and bandwidth of the chirp signals.

6.3. Examples of the Nonlinear Detection of Buried AT and AP Mines

Some of the field test results have already been presented throughout this chapter as an illustration of the developed detection technique, model, and algorithms. Many more examples of linear and nonlinear detection are described in numerous publications referred in this chapter. Fig.23 and Fig.24 show two more examples illustrating nonlinear detection of live mines obtained with the correlation imaging algorithm.

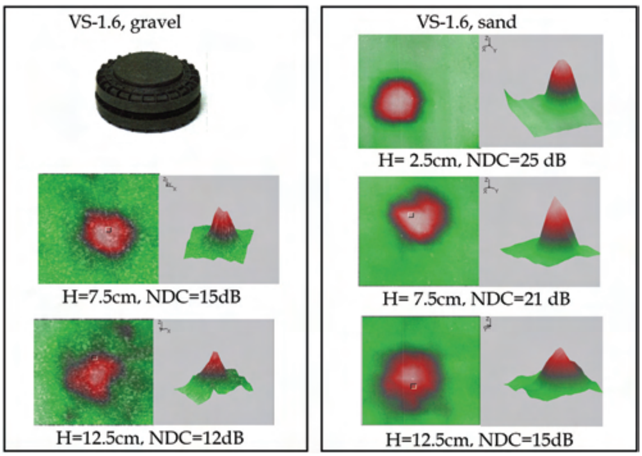

Fig. 23. Nonlinear images and respective nonlinear detection contrasts (NDC) for AT mine VS-1.6 buried at different depths in gravel and sandy soils

As we pointed out previously, NDC in these tests was limited by the noise floor of off-the-shelf scanning LDV rather than the background nonlinearity of soil. Still, the measured contrast is quite impressive, especially for a small plastic mine such as VS-50.

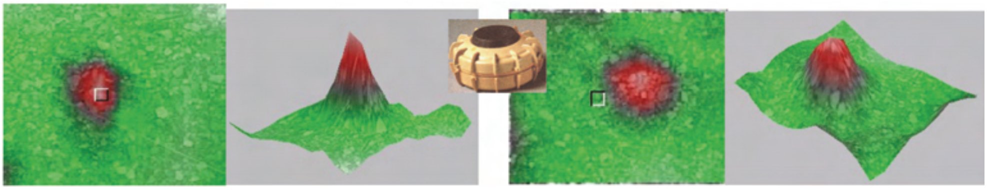

Fig. 24. Nonlinear images of AP mine VS-50 buried in gravel at 12 mm (left), NDC =19dB, and 25 mm (right), NDC =16dB

7. Conclusion

We have presented an overview of our team's (at Stevens Institute of Technology) contribution in development of resonance and nonlinear Seismo-Acoustic Mine Detection (SAMD) techniques. Among our major accomplishments are the discovery and quantitative characterization of mine resonances; the discovery of a very strong nonlinear dynamics of the buried mines manifesting itself through the combination and intermodulation frequencies; the development of a physical model describing the linear and nonlinear dynamics of the soil-mine systems; the development and field validation of the nonlinear detection technique including data collection and processing algorithms. The developed model analytically describes linear and nonlinear responses of the coupled soil-mine system providing an improved understanding of the effects of the soil and mine parameters on detection performance, explaining and predicting many laboratory and field experimental observations of soil-mine vibration responses.

Since 1988, SAMD has matured from just ideas and a few laboratory experiments into a well understood and highly promising technique proven during numerous field tests with real (live) mines. The primary advantages of resonance and nonlinear techniques as compared to conventional electromagnetic methods, such as metal detectors and GPRs, are very low false alarms and a high detection contrast for buried AT and AP mines, especially for non-metal mines. The main drawback is that SAMD is relatively slow as compared to electromagnetic methods. As it currently stands, these capabilities make SAMD an excellent confirmatory detection method: after the electromagnetic detection systems provide fast scan of the large area identifying suspicious locations, SAMD scans only the suspected areas confirming or rejecting the alarms.

SAMD is still an evolving technology and many improvements and implementation could be developed making SAMD faster, more robust, and affordable, especially for humanitarian demining. Thus, there are ongoing efforts to develop SAMD-dedicated sensors and sensor systems, such as an array of contact accelerometers (Martin, et.al., 2005), a multi-beam LDV (Lal, et.al., 2003), and a seismic and acoustic vibration imaging (SAVi) recently initiated by DARPA (www.darpa.mil/sto/underground/savi.html). Other developmental efforts involve various advance signal processing approaches, the use of directional acoustic sources, fusion of SAMD with electromagnetic methods, etc. All of these and other related technological advances eventually will bring SAMD onto the landmine fields as a capable and robust detection tool.

8. Acknowledgements

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6

GPR Environmental-Based Landmine Automatic Detection

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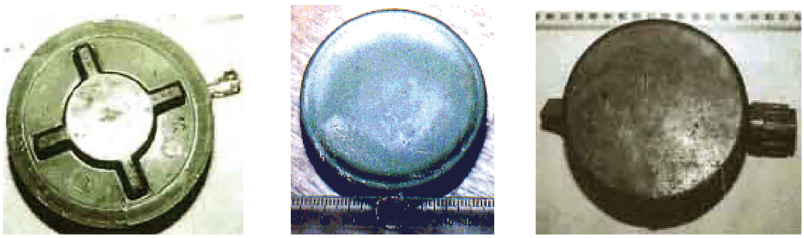
1. Introduction

According to the United Nations, as of the year 2000 there were 70 million landmines planted in a third of the world's nations affecting global causality rate of up to 20,000/year, (Anderson, 2002). That is why landmine detection has attracted much attention by many research teams around the world during the last two decades; among them is our research team in Nagoya University. Anti-personnel (AP) mine ranges from 5 to 15 cm in size; they can be metal, plastic, or wood. AP mines are normally buried at shallow depth; detonated by very low pressure, and designated to kill or maim people. PMN2, Type72 and PMN are examples, Fig. 1. In real world clearance activities, AP mine suspect areas are divided into 1 m grid squares, and each square meter is probed with a bayonet or plastic rod. Probing is done at an oblique angle to the ground so that the rod will encounter the side of a land mine and not trip the fuse. No need to say, this work is very dangerous and proceeds very slow, (Siegel, 2002). The need for a safer and more fast humanitarian demining action by replacing a manual sensing task by vehicle sensing task have motivated our research team to introduce a low-ground-pressure tires detection vehicle, (Hasegawa et al, 2004-A). The unmanned vehicle that can move in mine field without detonating a group of AP mines will be presented in this chapter.

One of the big challenges in demining process is detection. If a mine is detected, deminers can explode, mark or move it to a pit for later detonation or defusing. Conventional mine detection, by a metal detector, is often difficult for two reasons. First, mines are increasingly being made of plastics, minimizing the more easily detectable metal components. Second, mined areas are often equipped with metal scraps creating a high false alarm rate. Because of the difficulty encountered in detecting the tiny amounts of metal in a plastic landmine with a metal detector, technology development has been extended to other sensors. Ground penetrating radar (GPR) used for about 70 years for a variety of geophysical subsurface imaging applications including utility mapping and hazardous waste container has been actively applied to the problem of land mine detection for nearly the last two decades of research. It provides sensing objects underground based on dielectric properties. It senses the reflected electromagnetic wave by a buried object. It is expected that GPR be a good alternative sensor and/or an important support sensor when fused with a metal detector for landmine detection. However, one major source of error in GPR data is the reflection from the surface of the ground, (Daniels, 2004). The problem becomes much more difficult for an undulating ground-surface. As a general objective of signal processing as applied to GPR is to present an image that can be easily interpreted by the operator, it is important to adapt the signal processing technique for an undulating surface scanning. In this chapter, ground-surface-adaptive scanning and signal processing for ground-surface-adaptive scanning, (Hasegawa et al, 2004-B), applying a vector GPR, (Fukuda et al, 2006; Fukuda et al, 2007), will be presented.

A metal detector is one of the most major sensors applied for current humanitarian demining. It is simple and cost effective. It is also reliable to find an anti-personal mine (APM) in a shallow subsurface. However it suffers from the high false alarm rate, (about 99.95%), as it senses all metal objects including metal fragments in the field other than land mines. On the other hand, ground penetrating radar provides, (after processing), images for objects underground based on dielectric properties. However it senses a land mine object as well as any other object as it senses dielectric discontinuities in metallic and/or non-metallic objects. Fusion of GPR with MD is expected to minimize the false alarm rate significantly. In this chapter, fusion of both MD and GPR for APM detection in a shallow subsurface is presented. A “feature in-decision out” fuzzy sensor fusion algorithm for GPR and MD is introduced, (Zyada et al, 2006-A). The inputs to the fuzzy fusion system are features extracted from both GPR and MD measurements. The output from the fuzzy fusion system is a decision if there is a land mine and at what depth it would be. Fuzzy fusion rules are extracted from training data through a fuzzy learning algorithm. Experimental test results are presented to demonstrate the validity of the proposed fuzzy fusion algorithm and hence its influence in minimizing the false alarm rate for mine detection, (Zyada et al, 2007).



(a) (b) (c)

Fig. 1. Anti-personnel landmine samples: (a) PMN2; (b) Type72; (c) PMN.

This chapter is organized as follows: Section 2 introduces a low-pressure-tire vehicle capable of moving inside a mine field without detonating a group of antipersonnel landmines. This vehicle is applied as a sensor manipulator. Section 3 presents the enhancement of landmine images through signal processing of a scanned undulating surface applying a vector frequency modulated continuous wave (FMCW) GPR. Section 4 presents the fuzzy fusion algorithm of GPR with MD for antipersonnel landmine automatic detection. Learning fuzzy fusion rules as well as experimental evaluation of the learnt fusion rule base, is also presented. Section 5 presents conclusions and projected work.

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2. Low-pressure-tire Vehicle

General demining method is exploring with a probe or with a metal detector by an operator, (Shimoi, 2002; Genève international centre, 2004). However, it is not few cases that the workers suffer damage during the demining process. Then, robot-based demining in place of human-based demining has been investigated by many researchers. Most of them move in the minefield evading the landmine (Nonami, 2002; Kato, 2001). Complex mechanism and big cost is needed for building an evading robot. In contrast, a simple and low cost system is needed in affected areas. In this section, a mine detection vehicle which can enter a minefield and detect landmines directly without detonating landmines is introduced.

2.1 In-minefield Vehicle

By this sub-title, it is meant that the vehicle can enter a mine field without detonating its landmines. In order to enter a mine field, this system uses low landing pressure tires. Stiffness of these tires is much lower than that of ordinal ones, so that the area contacting the ground is very large and the load on the tire is distributed over the area. Access Vehicle is made of a commercial available leisure cart. This vehicle equips 4 low landing pressure tires and electric motors for driving. Figure 2 shows its appearance. Access vehicle carries battery as power supply in order to work without any cable. It also carries 2 laptop PCs for the purpose of motor and GPR control. These PCs are used to receive commands from operator via wireless LAN (IEEE802.11b) . On the other hand, Operator's Instrument consists of a laptop PC and a laser total station for position measurement. Operator's Instrument communicates with access vehicle using PC, and acquires position of the Access Vehicle by the total station. Data from sensor are stored to a PC on Access Vehicle temporally, transmitted to Operator's Instrument timely, and recorded with position of vehicle to Information Management System, (Hasegawa et al, 2004-B). Utilizing a commercial available cart as a frame shortens the time period of development and reduces cost. Access vehicle's total weight including sensor and sensor manipulator is about 90 kgs, so load on each tire is about 22.5 kg. Low landing pressure tires for this vehicle are made by Roleez Wheels, Inc. in U.S.A.

2.2 Subsurface Forces

To check the validity of the access vehicle for entering a minefield without detonating landmines, a group of experiments have been executed. A force sensor is buried under the ground surface for a range of 0~20 cm. Subsurface forces as well as the detonating pressure force for a group of anti-personal landmines are shown in Fig. 3. These values are average stress, load divided by the area of force sensor. Maximum pressure amounts to 0.063 [kg/cm2]. This result means that landing pressure of this vehicle is less than that of small landmines such as Type-72 (0.19 [kgf/cm2]) and PMN2 (0.26 [kgf/cm2]), but almost the same as PMN (0.064 [kgf/cm2]), and bigger than PMA-1 (0.031 [kgf/cm2]). Considering these landmines' small ignition force (3kgf, 5kgf), PMN or PMA-1 anti personnel landmine have large areas to receive force so it is very hard to apply low landing pressure vehicle to a minefield which contains these kinds of landmines. Clearly, even though this vehicle has a contact pressure smaller than many anti-personnel land mines ignition pressure, it cannot enter the minefield which contains some types such as PMA-1 and PMN. The vehicle is currently under developing its tires to distribute force to larger area. Furthermore equipping two tires on one axle would raise its safety coefficient.

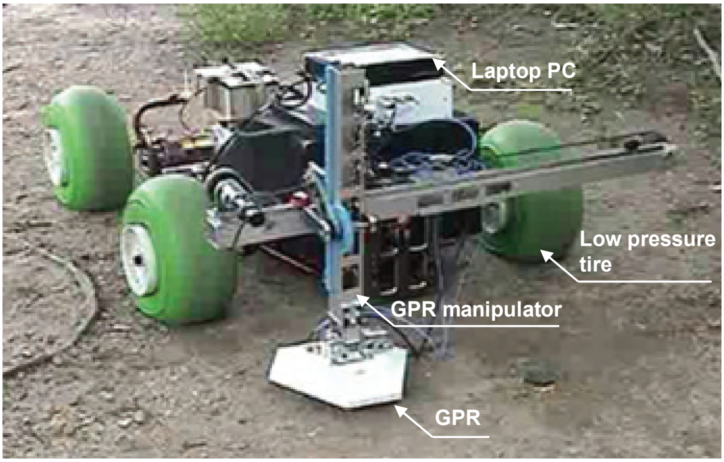


Fig. 2. Low-pressure-tire vehicle

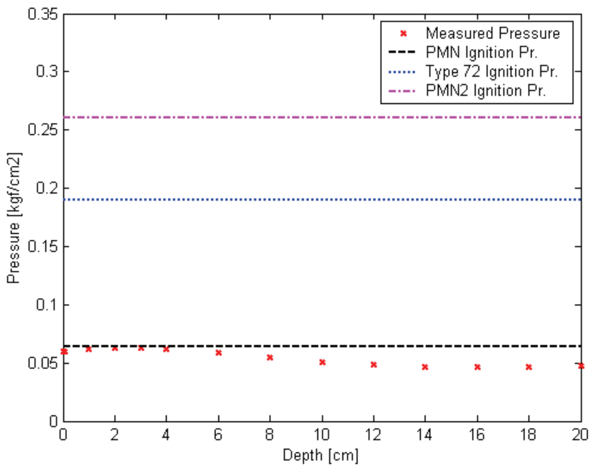


Fig. 3. Sub-surface pressure and ignition pressure for a group of anti-personnel mines

3. Environmental-adaptive GPR Manipulation and Signal Processing

Ground Penetrating Radar (GPR) is expected to be a good alternative sensor or support device of metal detector for humanitarian demining. GPR system measures the response time of reflected electromagnetic wave caused by buried objects, and it is originally used for archeological digging, detection of underground pipe and detection of lack in reinforced concrete. Though GPR performance is expected to be high for land-mine detection, there are

many problems encountered in the sening process. Among them, (1) decrement of an electromagnetic wave becomes large, and performance turns worse by a water content of the soil; (2) reliability of detection result deteriorates when operation is conducted with non-homogeneous soil; (3) if there are irregularities or a slant in a ground surface, they are projected onto an image of the underground. As a result, it becomes difficult to distinguish a shallow underground object. For the first problem, it can be overcomed by choosing the electromagnetic wave frequency that is hard to be absorbed by soil water content; fusion with a metal detector is effective for solving the second problem. However, because the last problem cannot be solved by fusion with metal detector beyond the maximum depth at which a metal detector can sense, it cannot be overcomed. Trying to solve the third problem, the enhancement of mine detection, applying a vector type ground penetrating radar (Kimura et al., 1992 ; Murasawa et al.., 1992), that is adaptively scanning the ground surface, (Fukuda et al, 2003; Hasegawa et al, 2004-B), is presented.
In this section, an environmental-adaptive GPR manipulation and signal processing is presented. First, the applied ground penetrating radar sensor and concept of geography adaptive scanning are introduced. Then, image enhancement based on signal processing for geography adaptive scanning applying FMCW GPR and imaging results are introduced.

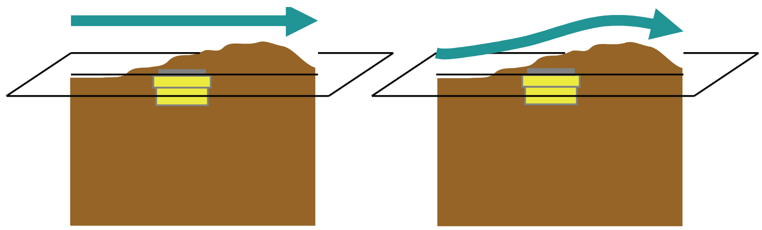
3.1 Ground Penetrating Radar (GPR) Sensor

A three-element vector stepped-frequency ground penetrating radar (GPR) system, Fig. 4, developed by Mitsui Engineering and Ship Building Company, (Japan), is applied in this study. It is an ultra-wide bandwidth vector type GPR. Its frequency bandwidth is 7.8125 MHz – 2.0 GHz. Its frequency is changed in 256 steps.

Fig. 4. Ground Penetrating Radar (GPR) system

3.2 Concept of Geography Adaptive Scanning

Ground surface reflects most power of an electromagnetic wave transmitted by GPR antenna because of the big difference of permittivity of the atmospheric layer with respect to ground surface. It is important to eliminate the ground surface effect. Elimination of ground surface effect is done by letting the antenna trace the ground configuration. The concept of geography adaptive scanning is shown in Fig. 5. The ground configuration is measured by a laser range finder, as will be presented later in this section.



(a) (b)

Fig. 5. Scanning methods: (a) Flat scanning; (b) Geometric adaptive scanning

3.3 GPR Images Enhancement for Geography Adaptive Scanning

It is known that frequency modulated continuous wave FMCW radar systems have been used in preference to AM systems where the targets of interest are shallow and frequencies above 1 MHz can be used, (Daniels, 2004). Since a GPR response signal is reflection intensity versus time, image reconstruction is required for easier extraction of mine suspects, for both easier interpretation and automatic detection, (Yilmaz, 1987). For this purpose, many signal processing methods have been proposed and applied to GPR imaging, but most of them have only considered a measuring system which maneuvers an antenna flatly regardless of geography. In this section, the signal processing technique applicable to geography adaptive antenna applying a vector GPR is summarized. GPR signal processing includes two main steps to obtain image spatial distribution. These steps are: suppression of reflection from ground surface and and migration.

3.3.1 Suppression of reflection from ground surface

A local average subtraction is applied for better clutter suppression. The local average subtracted signal $\phi_i'(t)$ is given by $\phi_i'(t) = \phi_i(t) - \bar{\phi}_i(t)$ where $\phi_i(t)$ is the raw data and $\bar{\phi}_i(t)$ is local average signal at sensing point i; $\bar{\phi}_i(t) = \frac{1}{n_i}\sum_{k \in K_i} \phi_k(t)$ where K_i is a set of sensing points in the neighborhood of sensing point i and n_i is the number of members of K_i.

A time series signal is obtained through Inverse Fast Fourier Transformation. Given the frequency domain signal $\psi_v(\mathrm{x}, \mathrm{y}, \mathrm{z}, {}^{\mathrm{B}}_{\mathrm{S}}\mathrm{R}, \mathrm{m}, \mathrm{f})$ measured by the wide range stepped frequency radar, we can get the time domain signal through Inverse Fourier Transform

$$\begin{aligned} \phi_v(x, y, z, {}^{B}_{S}R, m, t) &= \mathrm{IFT_f}\{\psi_v(\mathrm{x}, \mathrm{y}, \mathrm{z}, {}^{\mathrm{B}}_{\mathrm{S}}\mathrm{R}, \mathrm{m}, \mathrm{f})\} \\ &= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \psi_v(\mathrm{x}, \mathrm{y}, \mathrm{z}, {}^{\mathrm{B}}_{\mathrm{S}}\mathrm{R}, \mathrm{m}, \mathrm{f}) e^{j2\pi ft} df \end{aligned} \quad (1)$$

where $\phi_v\left(x, y, z, {}_S^B R, m, t\right)$ is the reflected wave; $[x, y, z]^T$ is the centre position of antenna; ${}_S^B R$ is the rotation matrix of center of sensor head; m is polarization mode; t is the time between emitting and receiving; z is the ground surface function, $z = z_g(x, y)$, (obtained through measurements); x, y are its arguments.

A 3-D GPR spatial signal is reconstructed from the time signal. Kirchhoff migration is adopted to reconstruct the spatial distribution of subsurface reflectivity from a set of time series signals acquired on the ground surface by three-element vector radar.

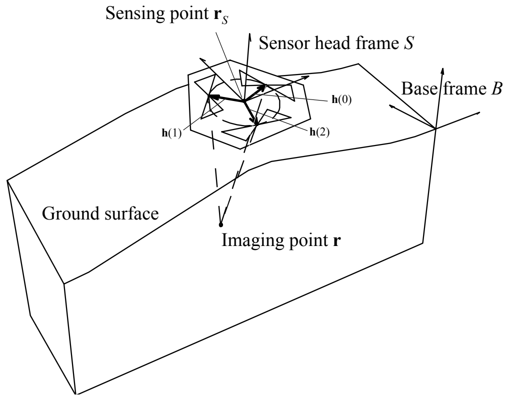


Fig. 6. Alignment of an antenna and imaging point

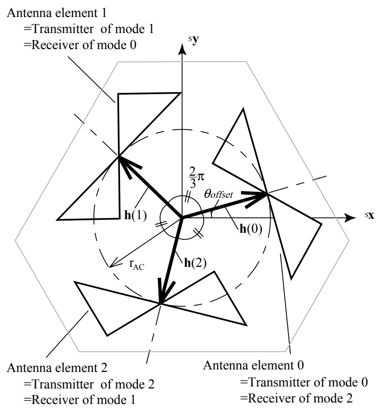


Fig. 7. Layout of antenna elements

3.3.2 Migration

Migration is a method to reconstruct the spatial distribution of subsurface reflectivity from a set of time-series signals acquired on the ground surface. This method has been studied in seismology (Yilmaz, 1987), and applied to GPR in some cases, (Feng and Sato, 2004).

Several kinds of migration are known, such as diffraction stacking, Kirchhoff migration, f-k migration, FD migration, and reverse time migration. Kirchhoff migration has been chosen here because it is easy to be implemented and to give physical meanings, (Schneider, 1978). The migration process will be summarized here. Figure 6 shows coordinate system of GPR. Here, position of focused point under ground is indicated as $P = [x, y, z]^T$, and center position of three antennas at measurement point is indicated as $P_S = [x_S, y_S, z_g(x_S, y_S)]^T$. Then, reflection rate $\sigma(x, y, z)$ is expressed as:

$$\sigma(x,y,z) = \sum_{m=0}^{m=2} \iint_{-\infty}^{\infty} \frac{\cos\theta}{r^2} \phi_v(x_S, y_S, m, t_P) dx_S dy_S \tag{2}$$

where, $r = \|P_S - P\|$; $\cos\theta = n_g(x_S, y_S) \cdot (P_S - P)/r$; $n_g(x_S, y_S)$ is the unit vector of ground surface; t_P is the traveling time of electromagnetic wave and expressed as $t_P = (\|P_T - P\| + \|P_R - P\|)/v$; v is the propagation velocity of electromagnetic wave; $P_T = P_T + {}^B_S R(P_S) {}^S h(i_T(m))$; $P_R = P_R + {}^B_S R(P_S) {}^S h(i_R(m))$; $i_R(m)$ is index of receiver antenna; $i_T(m)$ is index of transmitting antenna; m is the mode as shown in Fig. 7. ${}^B_S R(P_S)$ is rotation matrix of center of antennas frame $\{S\}$ with respect to the base frame. $\{B\}$; ${}^S h(i_R(m))$: position of i antennas element viewed from $\{S\}$.

$$ {}^S h(i_R(m)) = \begin{bmatrix} r_{AC} \cos(\frac{2\pi}{3} i + \theta_{offset}) \\ r_{AC} \sin(\frac{2\pi}{3} i + \theta_{offset}) \\ 0 \end{bmatrix} \tag{3}$$

3.4 Imaging Results

The validity of signal processing for geography adaptive scanning was investigated through experiments. A buried object as applied for this evaluation is a plastic case of the shape of Type 72 landmine, Fig. 8. Dry sand with 3% water content inside a tank with its surface is formed with inclined plane. Its surface data measured by a laser range finder is shown in Fig. 9. The ground surface is flatly and adaptively scanned as shown in Fig. 5. The results of flat and geography adaptive scans after signal processing are shown in Fig. 10. As shown in Fig. 10(a), effect of ground surface remains and the shape of landmine deforms according to it. On the other hand, when scanned adaptively to ground surface, disturbance according to ground surface hardly remained and the target-clutter ratio enhances, especially for shallow buried object, Fig. 10(b). The effect of polar modes is shown in Fig. 12 and the effectiveness of the synthesized modes for 3-antenna radar is shown Fig. 12d. Appearance of adaptive scanning experiment is shown in Fig. 11.

Fig. 8. Buried object: plastic case of a landmine shape

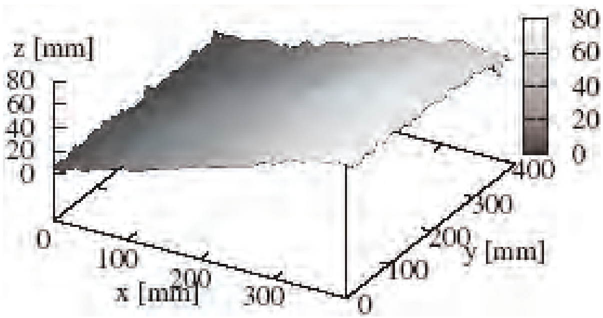
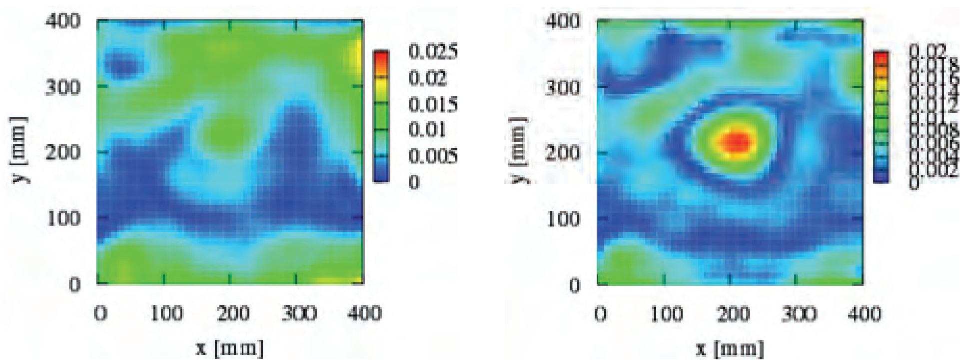


Fig. 9. Shape of ground surface



(a) (b)

Fig. 10. C-scan results applying: (a)Flat scanning; (b)Geometric adaptive scanning

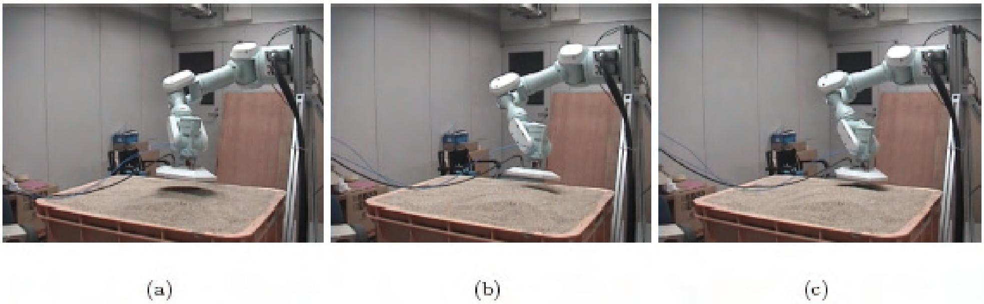


Fig. 11. Appearance of adaptive scanning experiment

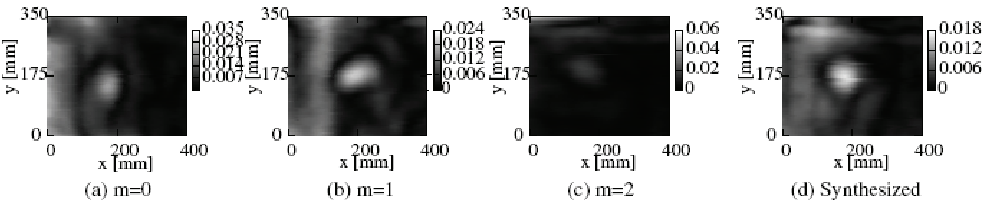


Fig. 12. C-scan views processed with various polar modes

4. GPR-MD Fuzzy Fusion

In this section, an automatic sensor-fusion based detection algorithm of an anti-personnel land mine is presented. A “feature in-decision out” fuzzy sensor fusion algorithm for a ground penetrating radar, (GPR), and a metal detector, (MD), for anti-personnel landmine detection is introduced. The inputs to the fuzzy fusion system are features extracted from both GPR and MD measurements. The output from the fuzzy fusion system is a decision if there is a land mine and at what depth it would be. Fuzzy fusion rules are extracted from training data through a fuzzy learning algorithm. Experimental test results are presented to demonstrate the validity of the proposed fuzzy fusion algorithm and hence its influence in minimizing the false alarm rate for humanitarian demining.

4.1 Experimental System

A six-degree of freedom serial manipulator of type PA10-7C, manufactured by Mitsubishi Heavy Industries, Japan, is applied as a sensor manipulator for GPR-MD sensor fusion. Manipulator based scanning facilitates a regular step scanning better than a manual based scanning, which leads to better signal processing results. Another advantage is the safety achieved by automatic scanning as an operator can do his task from a remote place. PA10 manipulator holding a metal detector is shown in Fig. 13. Avoiding the manipulator singularity points, it was possible to design the same path for both GPR and MD sensors. The test field is a tank full of dry and homogeneous river sand, as shown in Fig. 13. Its water content is 4.0 %, (relative permittivity of about 3.29). EM wave absorber covers all the sidewalls and the bottom of the tank to suppress the tank walls reflection during GPR measurements. A dummy land mine of type PMN2 is the applied one for demonstrating the methodology of this study, Fig. 14. It has the same dielectric constant and the same metal content as the real one. Its diameter and height is 122 and 54 mm, respectively. The field is relatively flat and both the GPR antenna and MD sensing head scanned in a path parallel to the surface with a gap between the sensor head and the ground of 10 mm. During the experiments, the scanning area is 400x500 mm^2. The manipulator movement is in 20 mm steps in both Y-Z directions comprising a grid of 21x26 measurement points by both GPR and MD. The scanning path is as shown in Fig. 15.

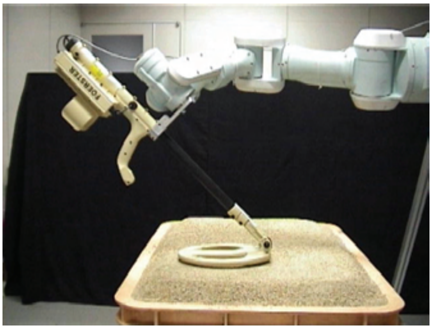


Fig. 13. Metal detector manipulation

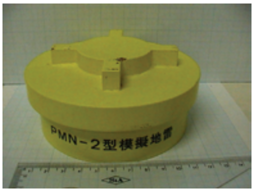


Fig. 14. Dummy PMN2 landmine

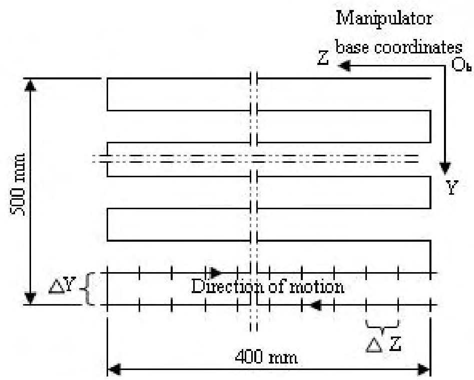


Fig. 15. Scanning path

4.2 Features Extraction

The inputs to fusion algorithm are GPR and MD features while the output is a decision if there is a landmine or not and at what depth it would be. In this subsection, extraction of GPR as well as MD features from the processed data is presented.

4.2.1 GPR Features Extraction

The migrated GPR data, (section 3), gives 3-D reconstructed image, from which horizontal slice image (C-scan), can be extracted. A horizontal slice of reconstructed signal amplitude for a buried PMN2 dummy land mine at a depth of 20 mm is shown in Fig. 16. We use the maximum amplitude from all the different horizontal slices as a feature of GPR measurements. The amplitude as well as position is extracted from the 3-D reconstructed image. It should be noted that A-scan, Fig. 17, for a buried object will have peaks at a depth different from that for a pure ground. As shown in Fig. 17, the reflection intensity of a dummy landmine has two peaks near the surface and at another depth underground, (about 7.0 cm), while that for a pure mine field, (without a landmine), has only one peak at the surface. A peak of reflection intensity underground is an indication of a buried object.

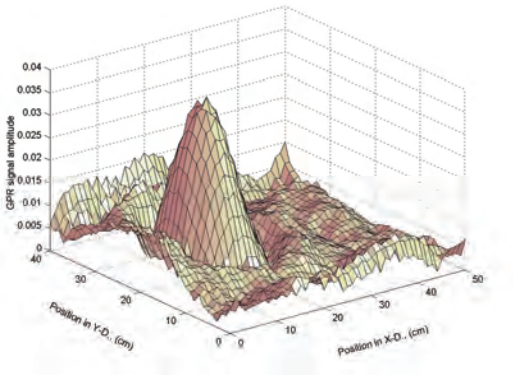


Fig. 16. C-scan of the reconstructed signal amplitude of a dummy PMN2 landmine, (buried at depth 2.0 cm)

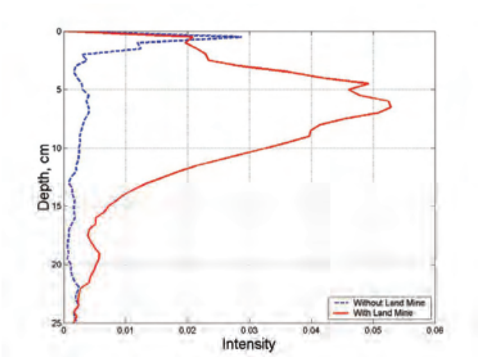


Fig. 17. A-scan of the mine field with and without a landmine

4.2.2 MD Features Extraction

A dual frequency metal detector of type MINEX 2FD 4.500, Fig. 13, manufactured by Forster, (Germany), is applied. The operating principle is based on continuous wave technique, comprising a transmitter coil and two symmetrical receiver coils in a gradient arrangement. The transmitter coil sends one signal continuously at two frequencies. As a result of the induction effect in a conducting object and its return effect on the coil system, the coil impedance changes. This change is evaluated and returned in the form of an acoustic signal. In the current measurement system, the output signal is acquired through a direct wiring interface.

The captured MD time-domain signal is transformed into frequency domain then the peak around the working frequency is captured. For a scanned surface, the output signal is like that shown in Fig. 18. The object position is exactly at the position of changing the sign of amplitudes from positive to negative. We reform this signal to the cumulative sum in X-D, Fig. 19, so as to make it easier in deciding the position of scanned object which is directly at the peak cumulative sum. We take this cumulative sum as an MD feature, (Zyada et al, 2006-A). Cumulative sum, CS_i at point i, is defined as:

$$CS_i = \sum_{y=1}^{y=i} I_{x,y}\Big|_{x=1,\ldots,x_{\max}} \quad (4)$$

It is the summation of the intensity, $I_{x,y}$ from the initial point $(y=1)$ to the current point $(y=i)$ in y direction. That is to be repeated for all values of x. The cumulative sum of the measured signal according to the definition of equation (2) is shown in Fig. 19. The peak amplitude in Fig. 19 as well as its position can be easily extracted. This maximum amplitude is applied as MD-feature of a landmine.

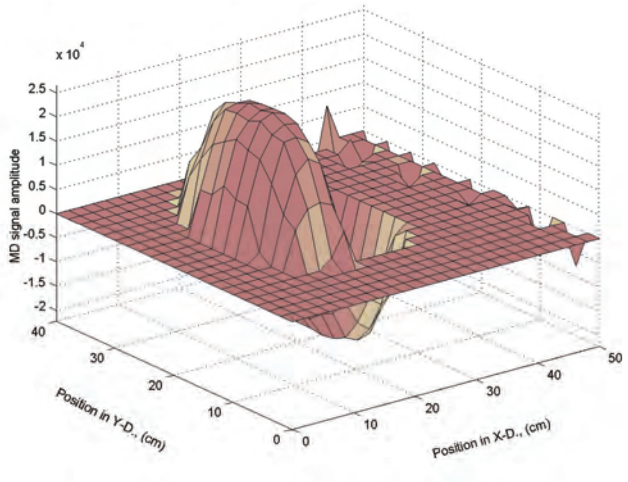


Fig. 18. Metal detector signal amplitude

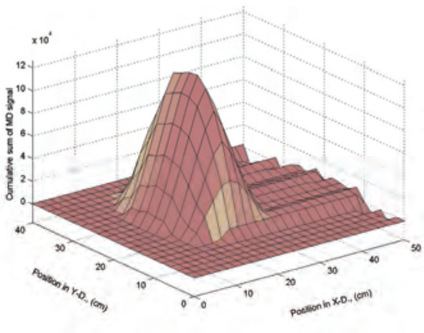


Fig. 19. Cumulative sum of metal detector signal amplitude

4.3 Fuzzy Fusion Rules Learning

We use a fuzzy rule base for fusion of both GPR and MD sensors for humanitarian landmine detection. The learning algorithm applies Wang-Mendel method, [10], for fuzzy rule learning from experimental data.

4.3.1 Learning Fuzzy Rules from Experimental Data

The chosen algorithm for our study, to learn rules from experimental data, is a simplified fuzzy algorithm. It presents three characteristics that make it a good choice in view of our objectives: simplicity, simple one-pass to extract the rules, and flexibility with fast computational time to operate in a demining system. Also, it is possible to collect the learnt rules from numerical data as well as heuristic rules in the same frame of work which may be needed in future development of the current work. This learning algorithm is developed and applied to different applications, (Zyada et al, 2002; Branco and Dente, (1998; 2000-A; 2000-B)).

Fuzzy rules are first learnt from examples then the number of associated membership functions for every variable is optimized for the all learnt rules. The best group of rules expressing data is then selected based on the overall average rules truth degree. In the following, we describe the main steps and a simple example to illustrate the method of extracting fuzzy rule base with two inputs and one output:

Step 1: Choose the Variables and Divide the Input and Output Spaces into Fuzzy Regions: Choose the variables that better characterize the system. The input variables and the output will compose, respectively, the condition and the conclusion of the rule parts. Assume that the domain intervals of variables (x_1, x_2) and y are $[x_1^-, x_1^+]$, $[x_2^-, x_2^+]$ and $[y^-, y^+]$, respectively, where "domain interval" of a variable means that most probably this variable will lie in this interval. Divide each domain interval into an odd number of regions. This number of regions may be different from one variable to another. Assign each region a fuzzy membership function. Use symmetric triangular membership functions whose one of its vertices lies at the center of the region with a membership value of unity and the other two vertices lie at the centers of the two neighboring regions with membership values of zeros as shown in Fig. 20. Other shapes of membership functions are possible. However authors of the current work applied the stated and examined triangular membership functions proposed by Wang-Mendel, (Wang and Mendel, 1992).

Step 2: Generating Fuzzy Rules from Numerical Data:

From the training set, take the kith numerical data pair

$$(x_1^{(k)}, x_2^{(k)}) \rightarrow y^{(k)} \tag{5}$$

For each input value, $(x_1^{(k)}, x_2^{(k)})$, and corresponding output one, $y^{(k)}$, calculate their respective membership grades in the attributed fuzzy sets. Hence it is constructed for each variable a raw vector denoted by $\vec{m}(x_1^{(k)}), \vec{m}(x_2^{(k)})$ for the inputs and $\vec{m}(y^{(k)})$ for the output, with a number of elements equal to the fuzzy sets attributed in step 1.

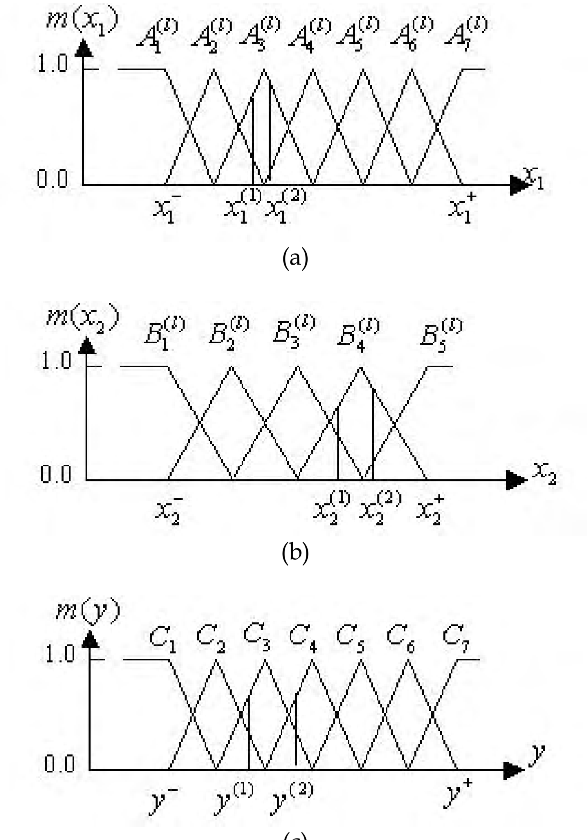


Fig. 20. Divisions of the input and output spaces into fuzzy regions and the corresponding membership functions, (a) $m(x_1)$, (b) $m(x_2)$, (c) $m(y)$

Choose for each variable their highest membership degree from the grades in the respective vectors, $\vec{m}(x_1^{(k)}), \vec{m}(x_2^{(k)})$ and $\vec{m}(y^{(k)})$. The selected grades are $[\vec{m}(x_1^{(k)})]_{\max}$,

$[\vec{m}(x_2^{(k)})]_{\max}$ and $[\vec{m}(y^{(k)})]_{\max}$. Now, a rule from the kith training pair is obtained. The fuzzy sets attributed for the condition and conclusion parts of this rule are, respectively, the sets A_j, B_j and C_j in which the inputs $(x_1^{(k)}, x_2^{(k)})$ and the output $y^{(k)}$ had maximal membership grades.

Step 3: Assign a Truth Degree to Each Rule:
A truth degree is assigned to each extracted rule as indicated in the following equation. The degree is defined as the product of the highest membership degree of each vector calculated in step 2.

$$\mu(R(k)) = [\vec{m}(x_1^{(k)})]_{\max} \cdot [\vec{m}(x_2^{(k)})]_{\max} \cdot [\vec{m}(y^{(k)})]_{\max}. \tag{6}$$

When two rules have the same fuzzy set in the IF part but a different fuzzy set in THEN part, the rules are called to be in conflict. To resolve this problem, it is accepted only that rule with highest truth degree. At last for this step, if it is not the end of the training data set, the algorithm goes again to the beginning of step 2 to pick up the next data pair.

For completeness, we introduce here an example describing how the learning algorithm in the above three steps operates. We consider for this example a simple case of a system with two input variables (x_1, x_2) and one output variable (y). The variables are partitioned by a number of symmetric triangular membership functions as shown in Fig. 20. Seven fuzzy sets were associated with variable x_1, five fuzzy sets to x_2 and seven fuzzy sets to y.
Suppose a first data pair $(x_1^{(1)}, x_2^{(1)}) \rightarrow y^{(1)}$ collected from the system, which is indicated in Fig. 9. For each input value, compute its membership degree in fuzzy sets A_j or B_j associated to its variable, and do the same for the output variable in its C_j. This procedure results in the following three vectors:

$$\begin{aligned}
\vec{m}_1(x_1^{(1)}) &= [A_1 \ \ A_2 \ \ A_3 \ \ A_4 \ \ A_5 \ \ A_6 \ \ A_7], \\
&= [0.0 \ 0.2 \ 0.8 \ 0.0 \ \ 0.0 \ 0.0 \ \ 0.0] \\
\vec{m}_2(x_2^{(1)}) &= [B_1 \ \ B_2 \ \ B_3 \ \ B_4 \ \ B_5], \\
&= [0.0 \ 0.0 \ 0.4 \ 0.6 \ \ 0.0] \\
\vec{m}(y^{(1)}) &= [C_1 \ \ C_2 \ \ C_3 \ \ C_4 \ \ C_5 \ \ C_6 \ \ C_7], \\
&= [0.0 \ 0.4 \ 0.6 \ 0.0 \ \ 0.0 \ 0.0 \ \ 0.0]
\end{aligned} \tag{7}$$

Next, choose in each vector of the above three vectors, the fuzzy set with maximum membership degree, resulting in

$$[\vec{m}_1(x_1^{(1)})]_{\max} = \max\{\vec{m}_1(x_1^{(1)})\} \rightarrow 0.8 \rightarrow A_3,$$
$$[\vec{m}_2(x_2^{(1)})]_{\max} = \max\{\vec{m}_2(x_2^{(1)})\} \rightarrow 0.6 \rightarrow B_4,$$
$$[\vec{m}(y^{(1)})]_{\max} = \max\{\vec{m}(y^{(1)})\} \rightarrow 0.6 \rightarrow C_3.$$

From this procedure, the first rule, from the first data pair, (k=1) is extracted, being

$$R_l(1): \text{ IF } (x_1 \text{ is } A_3 \text{ and } x_2 \text{ is } B_4) \quad \text{THEN } y \text{ is } C_3 \tag{8}$$

A truth degree is attributed to this rule, which is computed by multiplying the membership degrees. That is

$$\mu(R_l(1)) = (0.8)(0.6)(0.6) = 0.288. \tag{9}$$

Suppose now a second data pair $(x_1^{(2)}, x_2^{(2)}) \rightarrow y^{(2)}$, indicated in Fig. 9 too, is to be acquired. If we calculate their vectors and their respective maximum membership degrees, the new data pair has the same input fuzzy sets as the rule extracted from the first data pair, although producing an output fuzzy set different from that extracted from the first data pair. In this case we choose the one with maximal degree.

$$\begin{aligned} \vec{m}_1(x_1^{(2)}) &= [A_1 \;\; A_2 \;\; A_3 \;\; A_4 \;\; A_5 \;\; A_6 \;\; A_7], \\ &= [0 \quad 0 \;\; 0.85 \;\; 0.15 \;\; 0 \quad 0 \quad 0] \\ \vec{m}(y^{(2)}) &= [C_1 \;\; C_2 \;\; C_3 \;\; C_4 \;\; C_5 \;\; C_6 \;\; C_7], \\ &= [0 \quad 0 \quad 0.4 \;\; 0.6 \quad 0 \quad 0 \quad 0] \\ [\vec{m}_1(x_1^{(2)})]_{\max} &= \max\{\vec{m}_1(x_1^{(2)})\} \rightarrow 0.85 \rightarrow A_3, \\ [\vec{m}_2(x_2^{(2)})]_{\max} &= \max\{\vec{m}_2(x_2^{(2)})\} \rightarrow 0.8 \rightarrow B_4, \\ [\vec{m}(y^{(2)})]_{\max} &= \max\{\vec{m}(y^{(2)})\} \rightarrow 0.6 \rightarrow C_4. \end{aligned} \tag{10}$$

$$\mu(R_l(2)) = (0.85)(0.8)(0.6) = 0.408. \tag{11}$$

So we choose this rule in place of the above rule so that it will be

$$R_l(1): \text{ IF } (x_1 \text{ is } A_3 \text{ and } x_2 \text{ is } B_4) \quad \text{THEN } y \text{ is } C_4 \tag{12}$$

Step 4: Refining the Selection of Associated Membership Functions Set Numbers
Calculate the average truth degree of all extracted rules as:

$$\mu_{av} = \sum_{i=1}^{n} \mu(R(i))/n \tag{13}$$

where n is the number of extracted rules.
We change the number of fuzzy sets associated with each input and output variable and repeat the above steps for every possible combination for prescribed numbers of associated fuzzy sets for every variable. The group which gives maximum average μ_{av} is chosen. The learning algorithm with its 4 steps can be summarized as shown in the flow chart of Fig. 21. If we view this four step procedure as a block, then the inputs to this block are examples and the output is the best group of fuzzy rules expressing these examples with their associated membership functions, (Zyada et al, 2006-A).

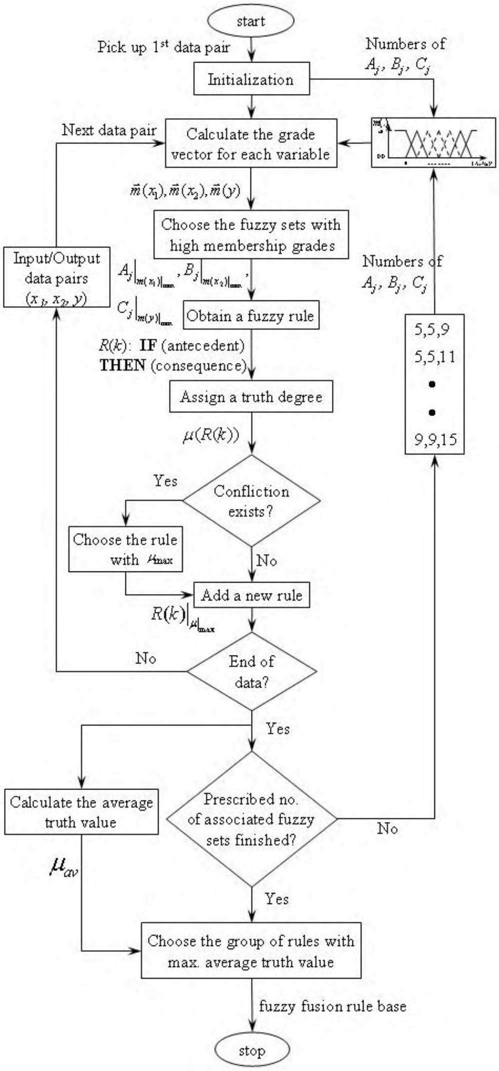


Fig. 21. Learning algorithm flow chart

4.3.2 Learning Fuzzy Rules for GPR-MD Fusion

For the system described in section II, the scanning path is designed as shown in Fig. 15. The manipulator scanned the object, dummy PMN2 landmine, while it is buried at different depths. The depth is changed from 0.0 to 70.0 mm in steps of 10 mm. The depth is measured from the ground surface to the upper face of the dummy land mine. The depth is limited to the maximum depth at which a land mine could be sensed by a metal detector, (70 mm in our case). The gap between the sensor head, (both GPR and MD), and the ground surface is kept constant at 10 mm during all experiments. The sensors positioning variables are treated as crisp not as fuzzy variables in the current work. The data is acquired for both GPR and MD scanning. The signal for both sensors is processed as described in section III. The output of processing is the values of GPR and MD features at different depths. These values are input to the learning algorithm described in the first part of this section, as shown in Fig. 22.

	IF Part		THEN Part
No.	MD Feature	GPR Feature	
1	A1	B1	C7
2	A3	B3	C6
3	A3	B4	C5
4	A5	B6	C4
5	A2	B7	C3
6	A1	B8	C2
7	A3	B9	C1

Table 1. Learnt fuzzy fusion rules

The output is a group of fuzzy rules that best express these GPR and MD features. The output fuzzy rules are shown in Table 1, [18], where A's, B's and C's fuzzy sets are changing from low to high, (i.e. A1 is smaller than A2, B1 is smaller than B2, C1 is smaller C2, and so on). Because of the limited number of training data, the learnt fuzzy rules are few for association. A solution for this problem is to increase the number of training data through interpolation. We applied linear interpolation for the extracted features and re-applied the learning algorithm of Fig. 22. The result is a better number of fuzzy rules suitable for rules association as shown in Table 2.

GPR Variable

MD Variable	A1	A2	A3	A4	A5	A6	A7
B1			C9				
B2			C8	C7	C7	C7	
B3			C5	C6	C6	C6	C6
B4	C3	C3	C4				
B5	C2	C1					

Table 2. Learnt fuzzy fusion rules after interpolation

4.4 Experimental Evaluation

The A decision making system, Fig. 23, is proposed for evaluating the learnt fuzzy fusion rules. The inputs of the decision making system are the extracted features for both MD and GPR, the features positions as well as the learnt fuzzy fusion rules. A tested object should fulfill three conditions to be decided as a land mine: 1) position of features of both GPR and MD should be near from each other. MD feature position, (MD_Pos), to be near from GPR feature position, GPR_Pos, is defined as the following crisp expression with a specific offset.

$$MD\_Pos - Offset \le GPR\_Pos \le MD\_Pos + Offset \qquad (14)$$

In the decision making algorithm, the offset is chosen to be the land mine radius, 2) the object should be detected a landmine suspect by a GPR. It means that GPR feature should be associated in the learnt fuzzy rule base, 3) the object should be detected as a land mine suspect by MD too. The MD feature should be associated within the fuzzy rule base.
In the following, three experimental tests and their results for evaluating the proposed fuzzy rule-based fusion system are presented.

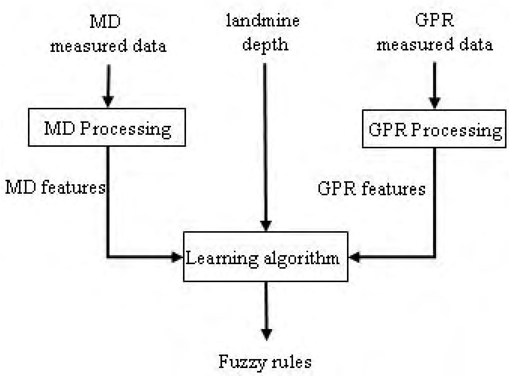


Fig. 22. Fuzzy rules learning algorithm for MD and GPR sensors fusion

4.4.1 Tests

Three tests are carried out with different objects. The first object is the dummy land mine, Fig. 14, at a depth different from that specified in the training phase. The second object is a plastic case, Fig. 8, having the same shape of a land mine in which a metal object, (bolt), is inserted. The third object is a metal bolt only. The three objects can be sensed by both metal detector and ground penetrating radar. Each object is scanned by both MD and GPR. Data is processed and the features as well as their positions are obtained. The features, their positions, learnt fusion rules for a specific tested object are input to fuzzy decision making system, Fig. 23. The positions of landmine suspect features are checked first. If they were near from each other according to definition of (12), the decision making system proceed for fuzzy fusion. The features are fuzzified with the same membership functions obtained in the learning phase. The fuzzified values are compared with the final learnt fusion rules of Table 2 through an implemented MATLAB program. It is based on input fuzzy sets association, (Yen, 1999). If there is an association then there is a PMN2 landmine and its depth is the output fuzzy rule. If there is no association for any of the features, it means that the object is not the specified PMN2 landmine.

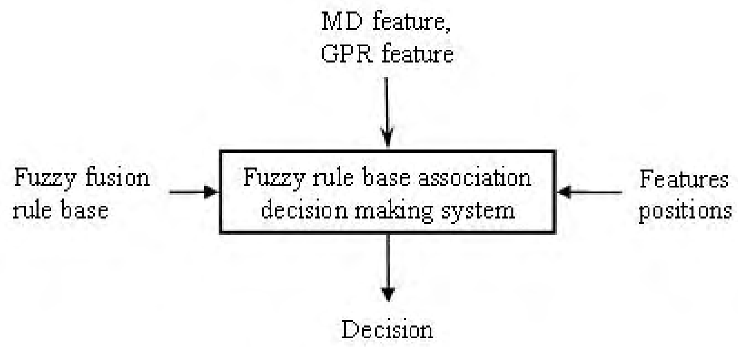


Fig. 23. Decision making system

4.4.2 Performance

The The proposed algorithm could easily classify the first object, (the dummy land mine), and expect its depth to be around 2.3 cm (its surface was actually at a depth of 2.5 cm). The second object, (a case with an inserted metal bolt), as well as the third object, (a metal bolt only), could be classified as a non-land mine object. The second object was detected as a land mine suspect with GPR but not a land mine suspect with MD. There was no association of the MD feature. Also, the third object was not detected as a landmine suspect with either MD or GPR. There was no association of both MD feature and GPR feature. The fulfillment of the decision making conditions as well as the final decision are shown in Table 3, where "O" means the condition is fulfilled and "X" means the condition is not fulfilled.
The decision of the second and third object would be difficult if it to be done by a deminer from GPR images and/or MD sounds (or images). It should be noted here that even though the MD feature of the 2nd object, Table 3, was not fulfilled by the decision making system, MD will give a sound, (or image). Also, even though the GPR feature of the 3rd object, Table 3, was not fulfilled by the decision making system, it will give an image. The features were not fulfilled because their values were outside the range leant during the learning phase. Based on that, the proposed automatic detection algorithm will decrease the false alarm rate significantly. One limitation of the algorithm is that it is based on the association of the input fuzzy rules, (i.e.: if the input fuzzy rules are outside the learnt rules, the algorithm will not give decision). That is the need to modify the decision making to be based on implication in place of association, (Yen, 1999). One more limitation is that the positions of GPR and MD features are treated as crisp variables because a PA10 manipulator, (with its high positioning accuracy), is applied for sensor manipulation. However in a real field, if a mobile vehicle like that presented in section 2, is applied for sensor manipulation, the features' positions are preferably treated as fuzzy variables as well. Fuzzy fusion development will include geography adaptive scanning based fusion in the future.

No.	Object	Features position fulfillment	MD feature fulfillment	GPR feature fulfillment	Decision
1	Dummy land mine	O	O	O	A land mine at an expected depth
2	Plastic case + a metal bolt	O	X	O	Not a land mine
3	A metal bolt	O	X	X	Not a land mine

Table 3. Decision making system results

5. Conclusions

In this chapter, GPR environmental-based landmine automatic detection is presented. The contribution of the presented research can be summarized in: (1) introducing a low-pressure-tire vehicle as a sensor manipulator. It is capable to move inside a mine field without detonating a group of anti-personnel landmines; (2) introducing a signal processing technique for the enhancement of GPR images for an undulating surface. Signal processing for ground adaptive scanning and its image results are presented applying a vector FMCW GPR; (3) an automatic detection method of an anti-personal land mine based on fuzzy fusion rules for GRR-MD is presented. Fuzzy technique is applied for learning a fuzzy rule-base from examples. The proposed method is easy to be implemented in a real field and easy to be executed by a normal operator or a deminer. It was possible to automatically differentiate between a land mine and other objects which would minimize the false alarm rate significantly.

Prospects:

The future work would include: (1) developing the low-pressure-tire vehicle through increasing the contact area between the tire and the ground; (2) extending the presented sensor fusion technique to geography adaptive scanned ground applying both MD and GPR; (3) treating sensors' positions as fuzzy variables in the sensor fusion algorithm.

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7

Vehicle Mounted Dual Sensor: SAR-GPR

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1. Introduction

Tohoku University, Japan has developed a new dual sensor SAR-GPR since 2002, which was designed to be used on a robotic arm mounted on an unmanned vehicle. SAR-GPR employs the combination of metal detector and GPR (Ground Penetrating Radar). Dual sensor is a common approach for landmine detection. However, imaging by GPR is very difficult in strongly inhomogeneous material due to strong clutter. We proposed therefore to use a Synthetic Aperture Radar (SAR) approach to solve this problem. SAR-GPR antennas are scanned mechanically near the ground surface and acquire the radar data. SAR-GPR uses an array antenna composed of 6 elements, in order to suppress the ground clutter. The data is then processed for subsurface imaging.

In order to achieve the optimum SAR-GPR performance, we believe that the adaptive selection of the operating frequencies is quite important, and that antenna mismatch causes serious problems in GPR. Most of the conventional GPR systems employ impulse radar, because it is compact and data acquisition is fast. However, most of the impulse radar system have disadvantages such as signal instability, especially time drift and jitter, strong impedance mismatch to a coaxial cable, which causes serious ringing, and fixed operating frequency range. An alternative way to solve this problem is the use of a vector network analyzer, which is a synchronized transmitter-receiver measurement equipment composed of a synthesizer and a coherent receiver. It enables quite flexible selection of operation frequencies, and stable data acquisition. We have therefore chosen to equip the SAR-GPR with 3 sets of vector network analyzer operating in the 100MHz-4GHz frequency range. The optimal operational range can actually be selected as a function of the soil conditions.

In this chapter, we discuss the concept of SARGPR, and its hardware development and software implementation. Then we show an example of field evaluation test which was held in Croatia in 2006.

2. Mine Hunter Vehicle (MHV)

SAR-GPR has been developed under a research project which was supported by JST (Japan Science and Technology Agency). In this project, Tohoku University has developed dual sensors including SAR-GPR, which is to be equipped on vehicles, and a hand-held dual sensor ALIS. Under the same research projects, unmanned vehicles which will be used for demining sensors have been developed. Mine Hunter Vehicle (MHV) is one of them, which was developed by Chiba University and Fuji Heavy Industries. MHV was designed for safe access to minefields and scan sensors over the field.

(a) SAR-GPR mounted on a robotic arm and scans in front of the MHV.

(b) SAR-GPR in operation in CROMAC test site. SAR-GPR scans in the side of MHV

Fig. 1. Mine Hunter Vehicle (MHV) equipped with SAR-GPR

3. SAR-GPR Array Antenna System

3.1 Transmitting/Receiving Antenna

Anti-personnel (AP) mines are normally deployed in very shallow subsurface. In order to detect such AP mines, GPR is required to have a very wide frequency range to realize a fine range resolution so that the shallow target echo can be separated from the strong ground surface reflection. SAR-GPR covers the frequency range wider than 5GHz, which realizes the range resolution of the radar to be 2.5cm in air. Soil has larger dielectric constant than air, typically larger than $4\varepsilon_0$ which makes the range resolution in subsurface smaller than 1.25cm, where ε_0 is the dielectric constant of vacuum.

Vivaldi antenna shown in Fig. 2 (Langley, 1993) was adopted as transmitting and receiving antennas for SAR-GPR, primarily due to its wide frequency performance. Fig.3 shows the return loss of the optimized Vivaldi antenna, which is used for SAR-GPR. We can find that the return loss above 1GHz is over 10dB, and it works efficiently over a very wide frequency. And a very narrow transmitting pulse can be realized in the time domain as shown in Fig.4.

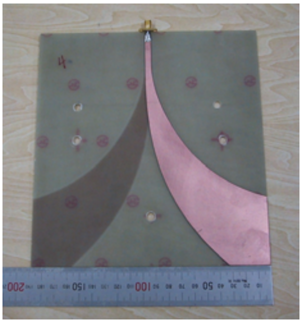


Fig.2 Vivaldi antenna for SAR-GPR

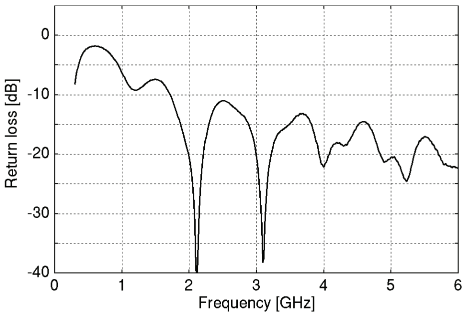


Fig.3. Return loss of the Vivaldi antenna shown in Fig.2.

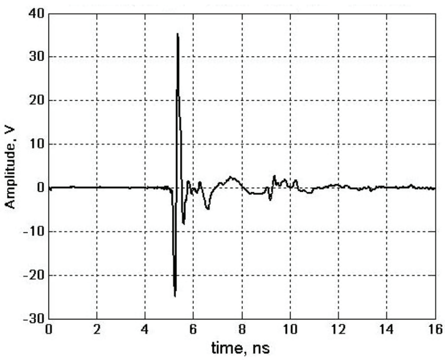


Fig. 4. Time domain waveform of the SAR-GPR radar pulse

3.2 CMP Array

The array antenna of SAR-GPR consists of three pairs of transmitting/receiving antennas as shown in Fig. 5. They are arranged in the Common Mid Point (CMP) arrangement where each antenna pair is placed on the base line symmetrically regarding to the common mid point. The CMP arrangement enables one easily apply CMP stacking technique (Yilmaz, 1987) to data processing which reduces strong surface clutter while enhancing subsurface object echo.

A Vivaldi antenna has planar shape thus is easily manufactured to construct an antenna array shown in Fig. 5. On the other hand, however, when it operates in an array structure, the antenna performance considerably suffers the antenna mutual coupling to adjacent antennas of which effect depends on the antenna spacing. In addition, CMP stacking performance also depends on the antenna spacing. Therefore, antenna spacing should be carefully determined to optimize the array system.
In order to determine the optimal antenna spacing, we evaluate the effect of antenna spacing on CMP stacking performance under rough surface and the effect of antenna spacing on the antenna efficiency of the Vivaldi antenna by model simulations.

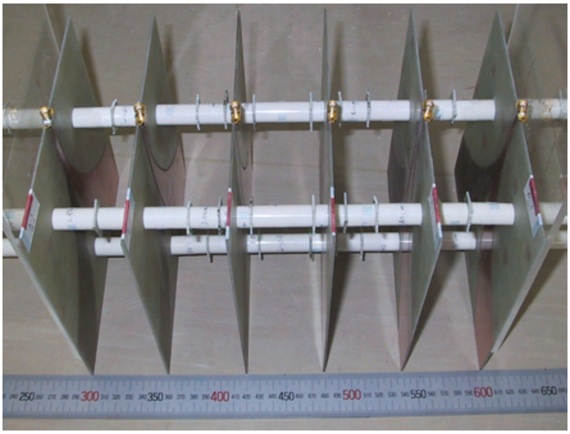


Fig. 5. SAR-GPR antenna array. The array system is installed in an antenna casing

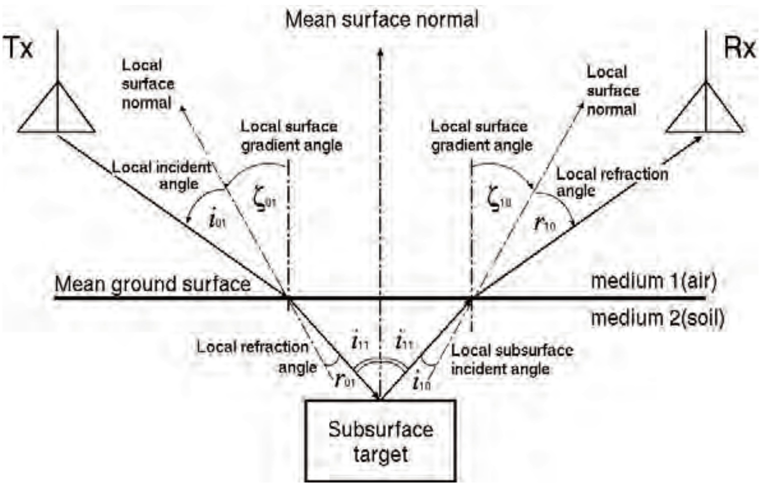


Fig. 6. Schematic diagram of the geometrical optics model

3.3 Geometrical Optics Model

The effect of antenna spacing on CMP stacking performance under rough surface condition was evaluated by a geometrical optics model. Fig.6 shows a schematic sketch of the model. Air and soil; two media model was considered. A one dimensionally rough surface, namely, corrugated surface, was assumed to be the media boundary interface.
The transmission antenna was modeled as a point source antenna that transmits a spherical wave pulse of an unit amplitude. The propagation path of the pulse was defined by Snell's law. Fresnel's coefficients of reflection/refraction at the incident point on the boundary interface and on the subsurface target determine subsurface echo amplitude. The effect of the ground surface roughness was taken into account by the local surface gradient at the incident point of the radar pulse. Height distribution of the rough surface was not considered. Subsurface target was assumed to have a flat horizontal surface and to be located on the CMP lines of the CMP array antenna. Therefore, provided the incident angle of the radar pulse onto the ground surface, refraction angle at the air-ground boundary interface, reflection angle on the target surface, incident angle at the ground-air boundary interface are uniquely determined in order that the subsurface echo should be received by the receiving antenna.

3.4 Target Echo

We consider the problem in the plane that contains both transmitting and receiving antennas and the target. The amplitude of the subsurface target echo A under given incident angle θ was calculated by the following:

$$A(\theta) = T_{01}(\theta) \cdot R_{\text{Target}}(\theta_{11}) \cdot T_{10}(\bar{\theta}) \cdot \frac{1}{R} \qquad (1)$$

where T_{01}, R_{Target}, and T_{10} are Fresnel's coefficient of refraction at the air-ground interface, reflection at the subsurface target face, and refraction at the ground-air interface, respectively. Horizontally polarized electric field was assumed. θ_{11}, $\bar{\theta}$ are the incident angle on the subsurface target and the local incident angle of the subsurface echo pulse onto the ground surface from subsurface, respectively. R is the geometrical distance measured along the propagation path. Since the target was assumed to be located on the CMP line and that both transmission antenna and the receiving antenna were located symmetrical position to the CMP line, the propagation path was uniquely determined once the incident angle θ was given. Furthermore, the incident angle θ is the only independent variable due to the symmetry of the problem, therefore, all the terms in the right hand side in (1) are dependent variables on θ. Considering the statistical property of Gaussian random rough surface, we evaluate the statistical expectation of the subsurface target echo by integrating $A(\theta)$ with the weighting of the Gaussian distribution function of local surface gradient, $P(\theta)$, as

$$\langle A \rangle = \int_0^{\pi/2} P(\theta) T_{01}(\theta) \cdot R_{\text{Target}} \cdot P(\theta_{11}) T_{10}(\bar{\theta}) \cdot \frac{1}{R} d\theta \quad . \qquad (2)$$

The distribution function of surface gradient of a Gaussian random rough surface also has the form of a Gaussian (Ogilvy, 1991). $P(\theta)$ is written as

$$P(\theta)=\frac{1}{\sqrt{2\pi}\tan\theta_{RMS}}\exp\left\{-\frac{1}{2}\left(\frac{\tan\theta}{\tan\theta_{RMS}}\right)^2\right\} \tag{3}$$

where θ_{RMS} is the RMS gradient of the surface of concern. The integration was carried out from 0 to $\pi/2$ in accordance with the possible incident angle. Note that $P(\theta)$ appears twice in (2) corresponding to that, due to the symmetry of the problem, the local surface gradient at the two incident points on the ground surface must have the same absolute value but with opposite signs.

3.5 Antenna Efficiency

Closely arranged antennas have strong mutual coupling that gives effect on radar pulse transmission of the antenna. We defined the antenna efficiency by the maximum amplitude of the transmitted radar pulse. And we numerically investigated it by FDTD simulations shown in Fig. 7 finally to model the antenna efficiency, W, as a function of the antenna spacing, d, as follows:

$$W(d)=\begin{cases} 0.2+\frac{1}{2}\left[1-\cos((d-2)/8\cdot\pi)\right] & (2\,\mathrm{cm}\le \mathrm{d}\le 10\mathrm{cm}) \\ 1.2 \quad (d>10\mathrm{cm}) \end{cases} \tag{4}$$

3.6 CMP Amplitude

Finally, the CMP signal amplitude of the target, A_{CMP}, for the case of the antenna spacing of d cm was calculated from (2) and (4) as

$$A_{CMP}(d)=W(d)\sum_n \langle A\rangle_n \tag{5}$$

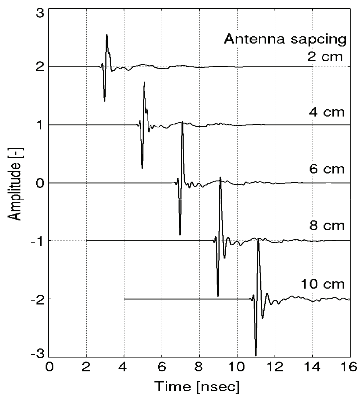


Fig. 7. Time domain waveforms of transmitted pulse for various antenna spacing cases

where n refers to the number of the nth antenna pair of the CMP array. In calculation of $\langle A \rangle$, we assumed a Gaussian random rough surface with 54degrees RMS gradient, in other words it had the same value of RMS height and correlation distance.

3.7 Confirmation by Full Scale Simulations

FDTD simulation of CMP measurement was carried out with a full scale model. The Vivaldi antenna array was modeled in the real scale. The position of the antenna in the present paper was defined as the antenna stand off that was set 10cm as had been designed to do in actual field measurements.

The air-ground interface was a Gaussian random rough surface whose RMS gradient was 54 degrees. Two dimensional height distribution was considered for several roughness scale cases. The roughness scale, or the RMS height was changed from 5mm to 4cm but keeping the RMS gradient as 54 degrees. Five independent surface realizations were numerically generated for each roughness scale case and examined.

Antenna spacing was investigated from 2cm to 10cm with 2cm interval. The subsurface target had the pancake shape whose diameter was 8cm and whose thickness was 4cm, which were the same as those of Type-72 AP mine. The target was embedded in subsurface horizontally so that its upper face was at the depth of 6cm. The dielectric constant of the target was set $3\varepsilon_0$ and that of subsurface medium was $4\varepsilon_0$. Fig. 8.. shows the CMP amplitude of the subsurface target. Those results from different scale surface realizations were plotted together. The result of the geometrical optics model is also plotted for comparison.

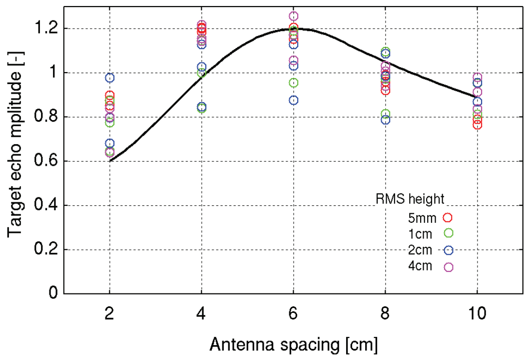


Fig. 8. Comparison of the estimated CMP target echo amplitude (solid line) and full scale FDTD simulation results (colored open circles). The color of circles denotes the roughness scale (RMS height) of the ground surface. Note that both are in a good agreement

Considering the fluctuation of random phenomena, the FDTD simulation results and numerical estimation show a good agreement: CMP signal amplitude behaves as a function of antenna spacing and has a maximum at 6cm of the antenna spacing. Receiving this result, the antenna spacing of the CMP antenna array system of the SAR-GPR was finally determined as 6cm.

4. Image Reconstruction

Two stage signal processing was carried out after the acquired data was transformed into time-domain data by inverse Fourier transformation. At first, the CMP stacking was carried out for suppression of ground clutter. In this processing, 5 data sets acquired at one position is stacked by calculating the time delay differences due to different propagation length between antenna sets. Clutter from the ground surface and homogeneous gravel can be suppressed by this CMP processing. The stacked signal is then processed by the diffraction stacking algorithm and a 3D image is reconstructed. The diffraction stacking is one of the standard migration algorithms used for GPR and seismic measurement. The reconstructed image $P(x, y, z)$ by the diffraction stacking is given by

$$P(x, y, z) = \int f(\tau, x', y')dx'dy' \tag{6}$$

where $f(\tau, x', y')$ is the measured signal at the antenna position $P_A(x', y')$ at time $t = \tau$ where

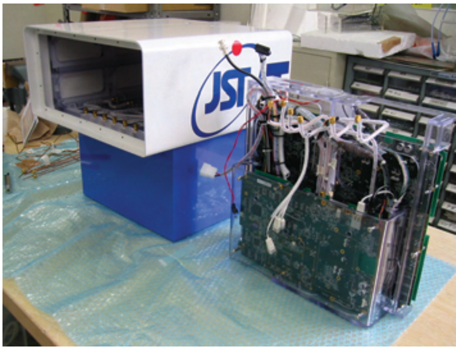
$$\tau = \frac{2\sqrt{(x-x')^2 + (y-y')^2 + z'^2}}{v} \tag{7}$$

is the travel time from the antenna position $P_A(x', y')$ to the focusing point $P(x, y, z)$, and v is the assumed velocity of wave in the material.

At the same time, we developed more advanced signal processing which can be used together with SAR-GPR(Sato, et.al., 2004). We can also use the GPR data set for estimation of ground surface topography, and estimation of velocity model, which can be implemented in the image reconstruction algorithm. If the ground surface is not flat, we can adopt more sophisticated signal processing for 3-D image reconstructions (Feng & Sato 2004, Feng et. al, 2005).

5. Compact VNA

In order to achieve the optimum SAR-GPR performance, selection of adaptive operational frequency is quite important. Also, antenna mismatching causes serious problems in GPR. Most of the conventional GPR systems employed impulse radar, because it is compact and data acquisition is fast. However, most of the impulse radar system had disadvantages such as instability in signal, especially time drift and jitter, strong impedance mismatching to a coaxial cable, which causes serious ringing, and fixed frequency range. Vector network analyzer is a synchronized transmitter- receiver measurement equipment. It is composed of a synthesizer and coherent receiver. It enables quite flexible selection of operation frequencies, and stable data acquisition. In addition, commercial vector network analyzers are equipped with a calibration function, which masks impedance mismatching caused by RF hardware. Impedance matching of antennas to coaxial cables in GPR is quite difficult in all the frequency range of operation. Therefore refection caused by impedance mismatching returns to a generator, and signal wave deforms. In order to avoid these effects, many GPR antennas adopt strong damping by impedance loading, which decreases antenna efficiency. If we use a vector network analyzer, reflection from antennas can be perfectly absorbed by the vector network analyzer, therefore, we can operate antennas without heavily impedance loading.



(a) Three vector network analyzers mounted in SAR-GPR

(b) One unit of a compact vector network analyzer

Fig. 9. Compact Vector Network Analyzer. (VNA)

However, due to the large size and weight, conventional network analyzer cannot be mounted in SAR-GPR. Compact vector network analyzer has been available, which can be used field measurement, however, these existing compact vector network analyzer had a limited frequency range, which cannot be adopted in GPR for landmine detection, and data acquisition speed was too slow for practical use. Therefore, we developed a new compact vector network analyzer which fits to our requirements. Table 1. show the comparison of the specifications of commercial and new vector network analyzers.

	Developed VNA	MS4624	E5071B
Measurement	S21	S21,S11,S22	S21,S11,S22
Operation condition	-20 - +50C		
Frequency	100MHz-4GHz	10MHz-9GHz	300kHz-8.5GHz
Dynamic range	70dB	125dB	122dB
Acquisition rate	646pt/sec	6,500pts/s	1,000,000pts/s
Accuracy	±1dB	±1.5dB	±1dB
Power supply	DC12-15V10W	100-200V,540W	100-200V
Size	250x170x60	352x222x457	
Weight	1.7kg	25kg	17.5kg

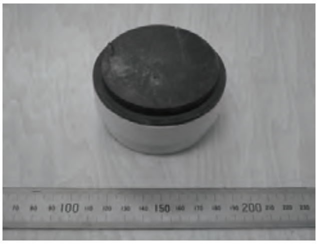
Table 1. Comparison of commercial and developed vector network analyzers (VNA)

The SAR-GPR system is composed of the array antenna and 3 sets of vector network analyzer. The system configuration can be found in Fig.9(a). Three vector network analyzer boards shown in Fig.9(b) is placed in a box , and are connected to the antennas just below the vector network analyzers. The total size of the system is 40Cm x 40cm x 40cm and the weight is 15kg.

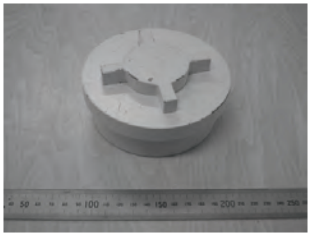
6. Experimental Results

6.1 Laboratory Experiments

Laboratory experiments were carried out at a sandpit in the GPR Lab., Center for Northeast Asian Studies, Tohoku University, Japan. This sandpit is 4m x 4m x 1m (depth) . The targets were landmine models Type 72 and PMN-2 shown in Fig. 10 and a *mine-like*[1] stone, which were buried in the layout shown in Fig. 11. They were all buried at a depth of 2 cm[2], and the landmine model PMN-2 was vertically buried. The soil was dry sand mixed with gravels whose diameters were approximately 2 cm. The GPR antennas were scanned at a velocity of 100 mm/s. The interval of data acquisition was 30 mm in both x- and y-directions.



(a) Type 72



(b) PMN-2

Fig. 10. Landmine models used in laboratory evaluation

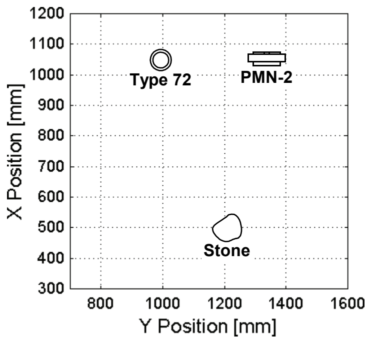


Fig. 11. Layout of the buried landmine models. PMN-2 landmine model was vertically buried

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[1] The term *mine-like* object is defined as an object whose shape and dimension resemble that of a landmine.

[2] A buried depth is defined at the top of a target.

The raw GPR data acquired with the inner pair of the antennas is transformed into time domain and is shown in Fig. 12 as a horizontal slice (C-scan) at a time instance of 2.4 ns, which corresponds to a depth of about 2 cm. The three objects are hardly visible, and clutter can be seen. The responses from the targets are not clear and not round shaped. They thus cannot be recognized without *a priori* knowledge. Then the subsurface image was reconstructed by migration. Fig. 13 shows a horizontal slice (C-scan) of the processed data at a depth of 2 cm. The three targets are clearly imaged and they obviously have different shapes and dimensions than those of clutter imaged at left on the slice.

The measurement was a blind test, i.e. the operator did not know the types, positions, depths, and numbers of buried objects prior to the measurement and only the radar system was tested. By observing the data, the operator could detect all of the objects including the stone on site.

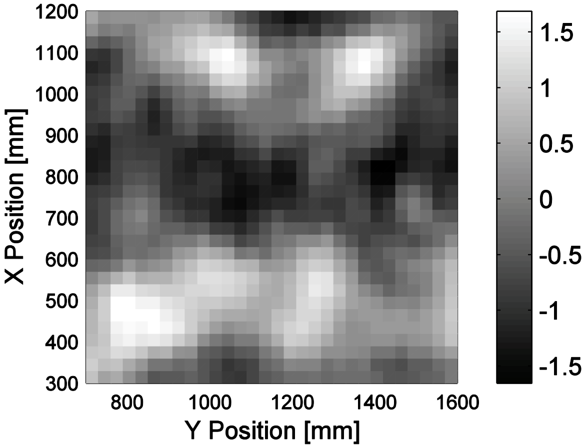


Fig. 12. Horizontal slice (C-scan) at a time instance of 2.4 ns measured with the inner pair of the antennas. The time of 2.4 ns corresponds to a depth of 2 cm

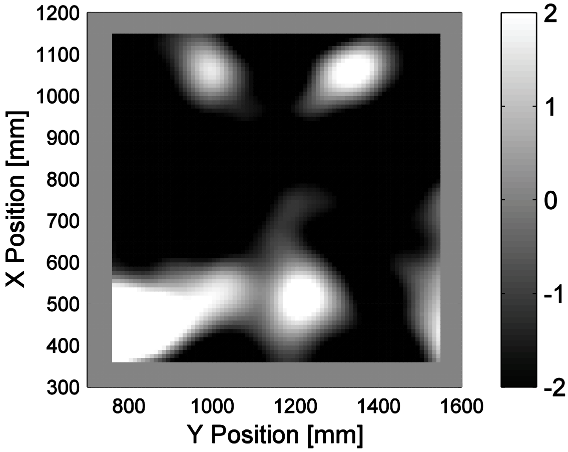


Fig. 13. Reconstructed horizontal slice image (C-scan) by migration. 2 cm depth

6.2 Field Trial

An evaluation trial was conducted in Croatia during February – March 2006 (Ishikawa et al., 2006). The campaign was organized by Japanese Science and Technology Agency (JST), which is a subordinate organization of Japanese Ministry of Education, Science and Technology, and was in cooperation with Croatian Mine Action Centre, Centre for Testing, Development and Training (CROMAC-CTDT).

The trial was carried out at a test site of CROMAC-CTDT in Benkovac, Croatia. Three lanes (Lane #1, #3, and #7) were chosen to evaluate the performances in various soils. The lanes have mineralized and homogeneous soil, natural and homogeneous soil, and mineralized and heterogeneous soil containing stones, respectively (see Guelle et al., 2007 and Preetz & Igel, 2006 for more detailed descriptions of the soils). During the trial, the relative permittivity of the soil was more than 20, sometimes more than 40 after raining and snowing. All the lanes are 1 m wide and 50 m long.

Two kinds of former Yugoslavian anti-personnel landmines, PMA-1A and PMA-2 shown in Fig. 14 and Table 2, were exploited as targets. The landmines were inert and real with the first explosives in the detonators removed and the inner structures intact. In addition, a standardized metal clutter, ITOP I0 (CEN, 2003), and small piece of random-shaped metals were also buried as representatives of metal clutters.

Fig. 14. PMA-1A (left) and PMA-2 (right) used in the trial

	PMA-1A	PMA-2
Weight	400 g	135 g
Explosive weight, type	200 g, TNT	100 g, TNT
Fuze	UPMAH-1	UPMAH-2
Size	140 (L), 30 (H), 70 (W) mm	68 (D), 61 (H) mm
Operation pressure	3 kg (min)	7 – 15 kg
Detectability	Very difficult	Very difficult

Table 2. Specifications of the landmines used in the trial (King, 2003)

In order to construct a dual sensor system, a commercial metal detector (MIL-D1) was mounted on the robotic arm together with SAR-GPR radar. Due to the limitation of the arm movement, an area of approximately 1.1 x 1.2 m was surveyed at a vehicle position, and then the vehicle moved to scan the neighboring area. The area of the next scan is overlapped approximately 1.1 x 0.2 m. The surveyed areas of the metal detector and the radar have a 0.5 m shift.

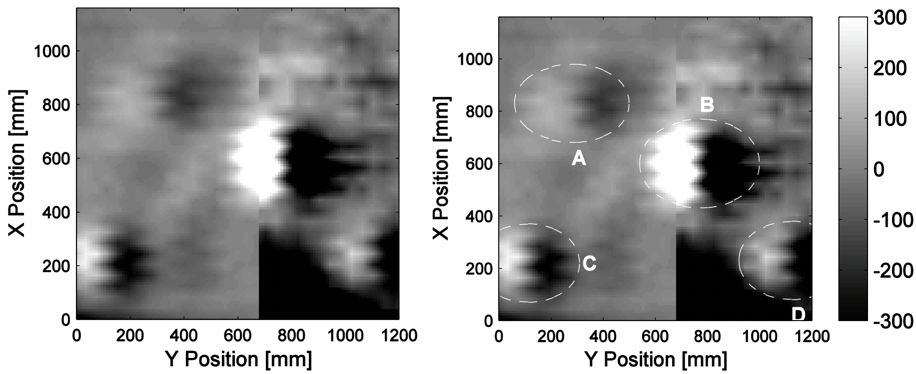
Examples of the surveys are shown in Figs. 15– 20. The data shown is taken from in Lane #3, which is natural and homogeneous soil.

Fig. 15 shows the metal detector image and its interpretation. In principle, a metal response can be observed in an image as positive and negative valued two semi-circles because of the coil configuration. Four responses can be recognized at locations marked A – D in this example. Note that a discontinuity at y = 700 mm is caused by combining two images scanned separately on two neighboring areas. Fig. 16 shows a horizontal slice (C-scan) of processed GPR data at a depth of 75 mm in the same area of Fig. 15 and its interpretation. Two round-shaped contrasts can be found in this image (marked B and C). They can also be seen in the metal detector image (Fig. 15), and we therefore are able to recognize that they are landmines. Since a high contrast marked E is not round shaped but is continued from left to right, it is a topographic change. Landmines in areas marked A and D are buried at different depths, resulting that no contrasts for them are observed at this depth but they are visible in other slices at different depths.

Data acquired at another area in the same lane is shown in Figs. 17 and 18. In the metal detector image (Fig. 17), three responses can be seen. In this step, however, it cannot be identified whether it is a landmine or metal clutter. The GPR image (Fig. 18) has only two contrasts at the areas marked F and G and no contrast can be seen at the area E even a clear metal response appears in the metal detector image. This metal response is, thus, identified as metal clutter.

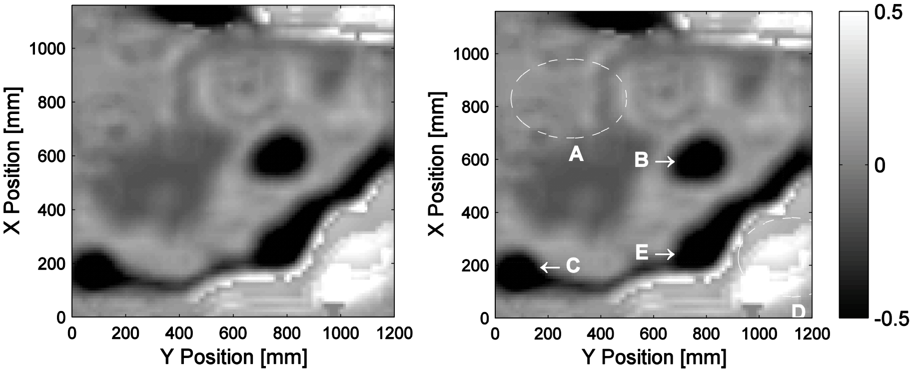
The ground truths for these areas are shown in Fig. 19. Note that the ground truth was provided after the surveys and the interpretations, and the trial was therefore completely blind tests. The data were interpreted by observing the series of horizontal slices (C-scan) at all the depths and the vertical slices (B- and D-scan) as well. It is impossible to make a decision by observing only one slice. Moreover, images are colored in the real interpretations.

Fig. 20 shows examples of fused image of the metal detector and the radar images. By displaying metal detector intensity as contour lines overlaid on a radar image, the locations of the responses in the two sensors are easily compared.



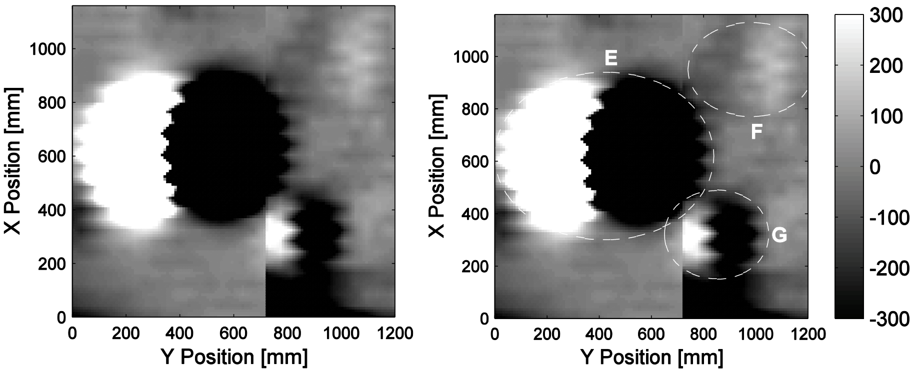
(a) Raw Image. (b) Interpretation.

Fig. 15. Metal detector image. The discontinuity at y = 700 mm is caused by combining two images separately scanned on two neighboring areas



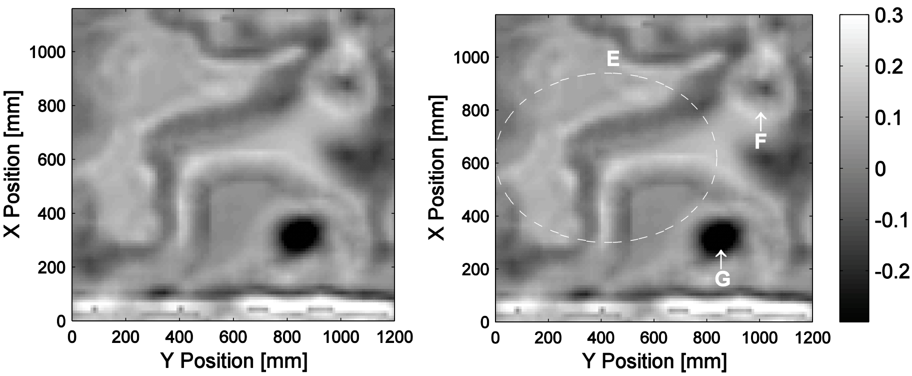
(a) Processed Image. (b) Interpretation.

Fig. 16. GPR Image at a depth of 75 mm



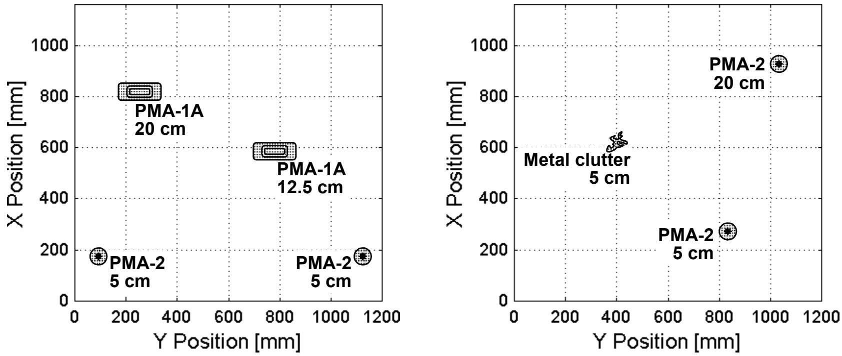
(a) Raw Image (b) Interpretation

Fig. 17. Metal detector image. The discontinuity at y = 700 mm is caused by combining two images separately scanned on two neighboring areas



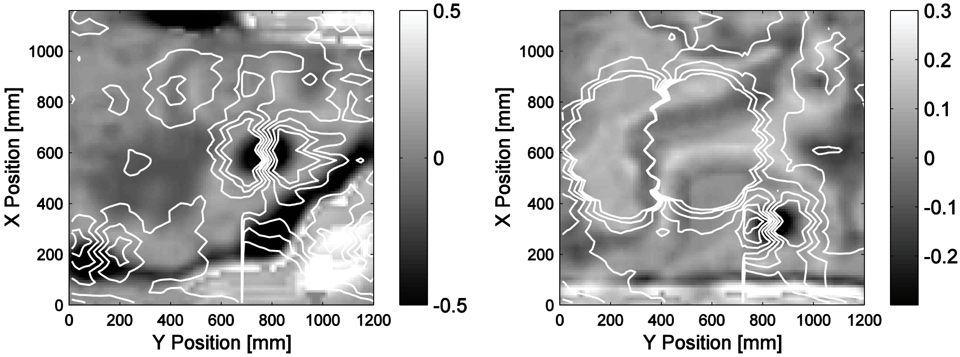
(a) Processed Image (b) Interpretation

Fig. 18. GPR Image at a depth of 87 mm



(a) The area shown in Figs 15 and 16. (b) The area shown in Figs. 17 and 18.

Fig. 19. The Ground truth



(a) The area shown in Figs 15 and 16. (b) The area shown in Figs. 17 and 18.

Fig. 20. An example of the image fusion of the metal detector and GPR images. Contour lines show metal detector intensity and are overlaid on the horizontal GPR image

7. Conclusion

SAR-GPR, which is an array GPR sensor unit, which is to be used on an unmanned vehicle MHV was developed by Tohoku University. It is equipped with 3 VNAs, and has 3 pairs of Vivaldi antenna. The operation frequency of the system can be selected between 100MHz-4GHz, dependent on the soil characteristics. Signal processing including CMP and migration is applied to the acquired GPR signal, and they reduce the clutter and can image the buried targets.

Then SAR-GPR has been tested in test sites in Japan, the Netherlands and Croatia. In any cases, SAR-GPR could provide clear images of buried landmines, when the ground has relatively flat surface. Since the SAR-GPR has 10cm offset above the ground surface, it can separate the reflection image of the ground surface and subsurface objects. Now we are continuing development new algorithms which can be used such a rough ground surface conditions.

8. Acknowledgements

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8

Humanitarian Demining Using an Insect Based Chemical Unmanned Aerial Vehicle

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1. Introduction

Nowadays, there are about 100 million active landmines distributed around the world as the result of earlier conflicts (Habib 2007). These cheap and simple to manufacture weapons have a long lasting effect that cause injury to the civil population even decades after the conflict has ended. Their removal is very expensive, dangerous and time consuming, and it has a high social and economical impact. Hence, although demining is a necessity for the affected populations to recover, it poses fundamental technical challenges.

At the present time, the use of animals, i.e. biological sensors, still provides the highest accuracy and safety standards in demining tasks. A number of animal species including dogs, rats and bees have been successfully trained to detect and localize landmines following the minute chemical trails of leaking explosive compounds (Fjellanger et al. 2002; Bromenshenk et al. 2003; Verhagen et al. 2006). Insects, and in particular moths, are highly optimized chemical detection systems that are extremely proficient at the detection and localization of different chemical compounds, in particular pheromones, at very long distances, i.e. several hundreds of meters. Moths use pheromone signals for sexual communication and it has been shown that males are able to detect and distinguish minute amounts of female pheromones (as little as 10^4 molecules$\cdot$cm^{-3}) against a background of other chemicals in very irregular and unpredictable plumes (Wyatt 2003). As a consequence, the evolutionary pressure to detect pheromones has generated specific neural and behavioral adaptations to deal with this specific problem. Nonetheless, the chemical search task is not reduced to a unique olfactory process but is a multi-modal task that includes the integration of complex behavioral strategies with visual, olfactory and wind sensing information (Kennedy & Marsh 1974; Ludlow 1982; Charlton & Cardé. 1990).

In this chapter we analyze the relationship between the chemical detection and localization problem and its biological solution, and we will show how our understanding of the biological solution can be exploited to construct efficient autonomous chemo-sensing Unmanned Aerial Vehicles (cUAV). Firstly, we describe a blimp-based technology for a cUAV. Subsequently, we investigate the computational and behavioral principles underlying the opto-motor system of the fly and the locust, and we show that relying solely on vision, biologically constrained neuronal models of the fly visual system suffice for course stabilization and altitude control of a blimp-based UAV. Then, we augment this system with a collision avoidance model based on the Lobula Giant Movement Detector neuron of the Locust. A number of chemical search experiments are described with a mobile robot in a controlled wind tunnel environment. In these experiments, a number of chemical mapping strategies and behaviorally and biologically constrained models derived from the moth are tested and their performance is assessed. Finally, some of these solutions are evaluated in outdoor chemical detection, mapping and localization tasks using a cUAV. We show that our insect based approach that combines detailed biologically constrained models of the fly, locust and moth provides for a robust system and can constitute a viable approach towards the detection and localization of explosives and therefore be used for humanitarian demining. Moreover, our insect based cUAV demonstrates that the detailed understanding of biological solutions to real-world problems can provide for novel and robust artificial systems.

2. Technology

Sensor Technology

The effectiveness of the landmine detection process depends fundamentally on the sensor technology used and the target mine. The most commonly used sensors are metal detectors, electromagnetic, acoustic and seismic methods, and biological sensors (Bruschini & Gros 1998; Habib 2002; Gooneratne et al. 2004). However, the current technology is still too limited to deal with the great variety of mines available, and usually is rather specific to a particular kind of explosives or mines.

Aiming at mimicking the best sensors known so far, here we propose the use of an artificial nose sensor sensitive to a wide range of volatile compounds in combination with the current understanding of the best studied chemical detection system, the male moth (Pyk et al. 2006; Bermúdez i Badia et al. 2007a). The artificial nose sensor consists of a 6 grid array of broadly tuned thin film metal oxide chemo-sensors (Alpha MOS SA, France). The sensitivity of each of the individual sensors is controlled by variations in their dopants and semiconductor materials (Nanto & Stetter 2003; Pyk et al. 2006). These variations render variable binding properties of each sensor to chemical compounds and, hence, differential sensing capabilities. The interaction of the surface of each of the sensors with the odor molecules provokes a change in the bulk resistance of the semiconductor material, and this is then converted to voltage and measured (Nanto & Stetter 2003). To allow the release of bound compounds, the temperature of the surface of the sensor is regulated by an external circuit. Given that the compounds the sensor needs to detect are presented in the real-world in complex plume-like dynamics it is essential to also understand the dynamics of the sensor. We measured the time constants of the artificial nose sensor and showed a rise time of 2.0±0.77 s (mean±std, n=5) and a decay time of 3.1±0.84 s (mean±std, n=9) (Pyk et al. 2006). The low power consumption (of approx. 270 mW) and the lightweight and relatively high degree of miniaturization (2 x 3 x 0.38 mm) make it a suitable sensor for real-time use on an Unmanned Aerial Vehicle (UVA).

The different robotic platforms used in this project are equipped with lightweight and high-resolution cameras (628 [H] x 582 [V] pixels) (“Module 3“, Conrad Electronics, Germany) fitted with wide-angle lenses (2.5 mm lenses, Conrad Electronics, Switzerland).

Subsequently, the obtained video stream from the cameras is broadcasted via compact PAL transmitters (SDX-21LP video transmitters on the 2.4 GHz band, produced by RF-Video, Canada). The robots use Lithium-Polymer rechargeable batteries (KOK 3270, Kokam, Kyunggi-do, Korea, www.kokam.com) that provide up to 5 times higher energy per unit of mass than regular Nickel Cadmium rechargeable batteries. On the ground station side, the camera images are received and processed by the neural simulator **iqr** (http://iqr.sourceforge.net/) (Bernardet et al. 2002). **iqr** is a software for the graphical design and control of large-scale neuronal models, and their interfacing to real-world devices in real-time. Our large-scale insect based neural models communicate with the robots via a wireless radio link in the case of the indoor blimp (BIM433-F transceivers, Wireless World AG, Switzerland), and Bluetooth in the case of the mobile moth robot.

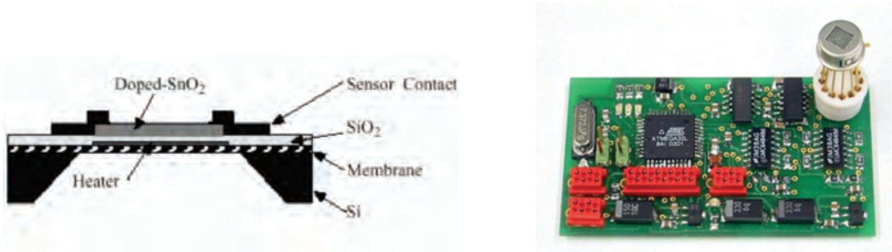

Fig. 1. The artificial nose sensor system. Left panel: schematic of each of the sensors of the 6 grid array including its main components. The size of a sensor is 0.18 x 0.2 mm (with x length), with an active area of 0.032 mm^2. Right panel: the full chemo-sensor package and its readout PCB. The sampling frequency of the PCB is 16.3 Hz, its dimensions 60 mm x 35 mm, and its weight 13.8 g. Adapted from Pyk et al. (2006)

The Robotic Platforms

Humanitarian demining clearly deviates from military demining in its objectives and approach. For humanitarian demining it is essential to locate and clean up every single mine in post-conflict areas for the recovery of the population. Seeking the highest accuracy and safety standards, many autonomous or remote controlled demining robots have been developed (Nicoud & Habib 1995; Nonami et al. 2000; Gonzalez de Santos et al. 2002; Marques et al. 2002; Santana & Barata 2005). Ideally, a robotic platform suitable to work in human non-accessible or unspecified environments with the highest degree of user safety is desired. Therefore, we propose the use of Unmanned Aerial Vehicle (UAV) technology since it provides a terrain independent solution and it is unable to detonate mines during inspection. In particular, the use of a blimp-based UAVs offers us a cheaper, more stable and easier to control solution than fixed-wing or helicopter like platforms. In addition, we need to consider that the sensing platform itself should not disturb the plume structure when it wants to localize the source.
We have developed a number of robots to approach the chemical localization problem from different angles. First, we constructed a blimp-based robot designed to work within indoor environments to study course control systems based on the understanding of the neuronal principles of insect visual navigation (Fig 2, left panel). This robot was constructed from a balsa wood structure, uses a lightweight Lithium-Polymer battery, and has independent control for altitude and translation (08GS - 8mm motors, API-Portescap, La Chaux-de-

Fonds, Switzerland, www.portescap.com) (see Bermúdez i Badia et al. (2007b) for further details).

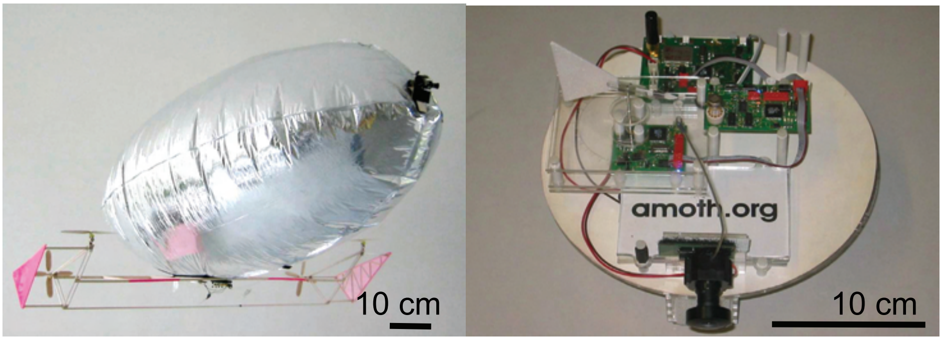

Fig. 2. The indoor artificial moth robots. Left panel: the blimp-based UAV consists of a 30 x 120 cm hull (radius x length) with a payload of about 250 g, a remote control board that provides with independent altitude and translation control, and 2 wide-angle wireless camera systems. Right panel: the ground chemosensory vehicle, of 20 cm diameter and 16 cm height, provided with, from top to bottom, a Bluetooth control board, a chemo-sensor, a wind direction sensor and a wireless camera equipped with a wide-angle lens. Right panel adapted from Pyk et al. (2006)

Subsequently, we developed a chemosensory ground vehicle as the first approach to study the odor mapping and localization problem in indoor and controlled environments (Fig 2, right panel). The robot is equipped with a chemo-sensor, a wind direction sensor and a wireless camera. The control board controls two motors, collects the sensory input from a chemo-sensor and a wind direction sensor and communicates with a ground station via a Bluetooth module. The wind direction detection sensor consists of a lightweight styrophore vane that is attached to a rotating shaft fitted with a small magnet. Then, a magnetometer is used to read out the orientation of the vane (MicroMag2, PNI Corporation, Santa Rosa, USA, www.pnicorp.com). All sensory boards are fitted with an ATmega32L microcontroller (ATmega32L, Atmel, San Jose, CA, USA, www.atmel.com) that makes local computations and interfaces the sensor with the robot infrastructure via a Two-Wire-Interface (TWI) bus. A Lithium-Polymer battery provides the robot with approximately 8 hours of autonomy.

To conclude, we constructed a blimp-based outdoor chemo-sensing UAV (cUAV) to perform field experiments (Fig. 3). One of the advantages of using a blimp-based cUAV is that it can carry additional sensors for conventional control, monitoring and analysis such as a GPS, accelerometers, altimeters, cameras, etc. In this case, the cUAV has a control board that interfaces a GPS, a 3D compass, 2 altimeters and a chemo-sensory board via a common TWI bus. The cUAV exchanges sensor readings and motor commands with a ground station via a 2.4GHz communication system (AC1524 transceiver, Aerocomm, Lenexa, USA). The total weight of the electronics is 90 g. 8 Lithium Polymer cells with a capacity of 13 Ah provide up to 2 hours of run time in moderate wind speeds. Based on the sensor readings, a control layer was developed to allow for unsupervised cUAV operation (see Bermúdez i Badia et al. (2007a) for further details).

Our custom developed cUAV consists of a PVC hull filled with helium (4.5m long, 1.2m diameter, 6m^3 volume) with an approximate payload of 3 kg. Four independent DC motors are fixed on a modular and scalable carbon fiber frame of about 3 kg (Fig. 3, right panel). Each of the propellers fixed to a DC motor generates a thrust of approximately 620G. The resulting mass/power ratio turns the cUAV into a more unstable platform than conventional blimps, while faster in dynamic responses. To solve the instability problem, the motor frame is constructed around the hull as opposed to be attached exclusively to its lower part as in the case of conventional blimps (Fig. 3). The arrangement of the motors is such that the forces are applied directly at the center of mass of the cUAV, hence reducing the oscillatory behaviors that result from fast flight maneuvers. The distance between the motors used for rotation is significantly increased, meaining that greater torque forces can be generated by the same thrust. Furthermore, fins of about 0.2 m^2 are used as a passive stabilization mechanism. As a result, our design of the motor frame renders the cUAV more stable and with better maneuverability than standard off the shelf solutions.

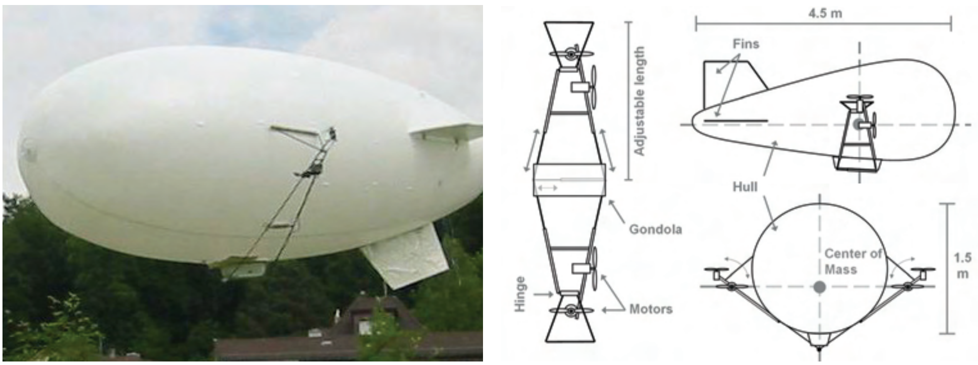

Fig. 3. The outdoor artificial moth robot. Left panel: the cUAV during autonomous flight. Right panel: scheme of the cUAV. It includes 2 pairs of motors, a carbon fibre frame that builds around the hull of the blimp, and a hinge and a variable length mechanism that makes it adjustable to different hull sizes. Adapted from Bermúdez i Badia et al. (2007a)

The Wind Tunnel and the Odor Delivery System

In order to investigate the responses of our sensor technology to different chemical stimuli and a number of moth based localization algorithms, we constructed a wind tunnel suitable for mobile robot experiments. The wind tunnel measures 3 x 4 x 0.54 m and was constructed out of wood and transparent plastic sheets. The front part of the wind tunnel was left open to let the air in. Four ventilators with adjustable wind speed were placed at the back to generate a negative pressure and create an air flow of about 0.7 $m \cdot s^{-1}$ from front to back, and to adjust for a uniform and symmetric velocity profile. Then, the air sucked out of the tunnel goes into an exhaust tunnel where it is removed.

As delivery system for the chemical substances we used an ultrasonic release system (Mist of Dreams, XrLight, Zhongshong City, China) that generates a rapidly evaporating mist at a rate of about 3.33 ml min^{-1}. The vaporizer was enclosed in a 40 x 30 cm chamber and the delivery from this chamber was controlled via an impeller (CGW/EDF-50, GrandWing Servo-tech C0, Ltd, Taiwan). Unless otherwise is specified, a solution of fixed concentration of ethanol and distilled water (20% ethanol) was used for all the chemical search experiments. The delivered rate of ethanol was approximately 0.8 ml · min^{-1}.

3. Insect Based Flight Control

In order to deal with the accessibility challenge faced in humanitarian demining we propose to use a flying platform. The first property of such a system is that it can autonomously maintain a specific course and compensate for perturbations. Insects localize odour sources by using multiple sensor modalities including: chemosensing, vision, anemotaxis and mechano-sensing. It is for this reason that this particular behavior observed in the moth is referred to as ***opto-motor anemotactic*** behavior (Kennedy & Marsh 1974). Hence, for the moth, vision is as important as olfaction since they cannot orient without visual cues (Kennedy & Marsh 1974; Charlton & Cardé. 1990). In a brain of about $1mm^3$, insects incorporate principles for visual navigation that are not only efficient in their implementation but also robust and reliable (Posey et al. 2001). Generally in insects, about two thirds of their brain is dedicated to visual processing to support navigation (Strausfeld 1976). Visual processing is mainly done by feed-forward neural structures dedicated to extract wide filed directional optic flow that is believed to be used for flight control (Hausen 1982a; Hausen 1982b; Egelhaaf & Borst 1993a; Krapp et al. 1998; Franz & Krapp 2000; Douglass & Strausfeld 2003; Higgins et al. 2004). In later processing stages, this information is integrated and used for landing, course and altitude control and collision avoidance (Rowel 1971; David 1982; Rind & Simmons 1992; Egelhaaf & Borst 1993b; Srinivasan et al. 1996; Srinivasan et al. 2000; Tammero & Dickinson 2002; Higgins et al. 2004).

In the particular case of the moth, it is believed that vision is used to assess the wind direction by computing the optic flow caused by drifts in position generated by the wind airflow (Ludlow 1982). Moreover, vision is also known to be used to control the flight speed and set it to a constant ground speed (Kennedy & Marsh 1974; Kennedy et al. 1978).

Here we look into the flight control question in relation to the computational and behavioral principles of the opto-motor system of the fly and locust. We choose these two preparations since they are the best studied species with respect to opto-motor behaviors. An important question is to what extend these insect based principles of visually guided 3 dimensional navigation can generalize to man made flying platforms (Srinivasan et al. 1999; Franceschini et al. 2007). From the technological point of view, the idea of using insect based task oriented models for flight control appears appealing because of their computational efficiency and flexibility. Consequently, we aim at providing a flight control infrastructure based only on biologically plausible and realistic neuronal models of the insect opto-motor system that can bring in the essential capabilities for the autonomous navigation of a flying robot.

Course and Altitude Control

The visual system of insects is commonly seen as a feed forward system with clearly defined functional and anatomical divisions (Strausfeld 1976). These divisions, known as neuropils, process the visual information at different levels, from a contrast enhancement to visual motion extraction (Fig. 4). Our synthetic insect visual system models the first three neuropils (Lamina, Medulla and the Lobula complex), and starts with the capture of visual information by means of a video camera, mimicking the photo transduction that takes place in the photoreceptors. The first process on the visual input is a compression of the luminance levels (Fig. 4a), followed by an edge enhancement (Fig. 4b). These 2 simple operations render the system more robust to changes in illumination (Dubs 1982). At the level of the Medulla we find the first visual motion sensitive neurons (Borst & Egelhaaf 1993; Douglass & Strausfeld 2003). Since the 60s, when Reichardt first proposed the, so called, correlation model, insects are believed to possess neurons that are capable to compute local directional motion, the Elementary Motion Detectors (EMD), and that they use this information for navigation purposes (Reichardt 1961) (Fig. 4c). Furthermore, at the level of the Lobula complex a number of wide field neurons have been identified in many species that provide motion information on horizontal and vertical displacement, as well as on rotations and collisions in the full visual field (Krapp et al. 1998; Gabbiani 2004). In the case of the fly, the neurons known as the Horizontal and Vertical System (HS and VS) can extract this information from the optic flow and have been suggested to be used for flight control (Egelhaaf & Borst 1993a; Franz & Krapp 2000; Tammero & Dickinson 2002).

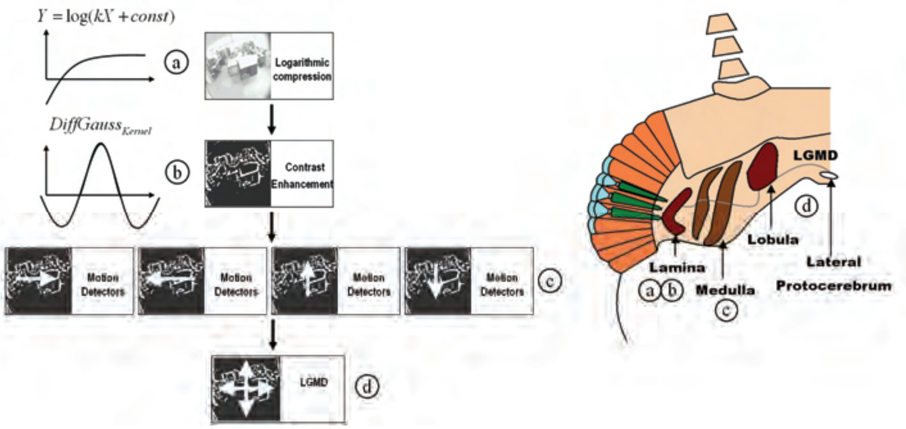

Fig. 4. The main functional and anatomical components of a prototypical insect visual system based on the locust. See text for further explanation. Adapted from Bermúdez i Badia et al. (2007b)

A course stabilization and altitude control system should make sure that the flying device follows a desired trajectory, and corrects for eventual drifts and altitude changes. Indeed we find that the HS and VS neurons of the fly exactly provide reliable information for the above mentioned functionalities (Krapp et al. 1998; Haag et al. 2004). These neurons have been widely modeled using the correlation model proposed by Reihardt to extract local directional motion information (Borst & Egelhaaf 1993; Egelhaaf & Borst 1993b; Franz & Krapp 2000; Haag et al. 2004; Bermúdez i Badia et al. 2005; Harrison 2005; Bermúdez i Badia et al. 2007b) (Fig. 5). Conceptually, the model performs a time delayed-spatial correlation to compute time dependent correlations on the normalized and enhanced input pixel values, and as such extracts local motion information (see Bermúdez i Badia et al. (2007b) for model details). Subsequently, all the correlations computed per pixel are summed to extract wide field motion information (Fig. 5). Therefore, depending on the two parameters that define the spatio-temporal correlation (δ and spatial shift), wide field neurons can be modeled to be sensitive to different kinds of optic flow such as the ones generated for horizontal and vertical displacements during flight (Fig. 5).

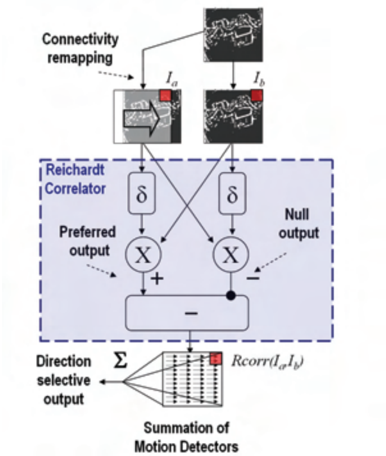

Fig. 5. The functional principles underlying a model of the Horizontal System neuron that extracts directional motion information from the optic flow based on the, so called, Reichardt correlator. In this particular case, the model is maximally sensitive to rightward motion (preferred direction). δ represents a delay, x the multiplication operation and – the subtraction operation. See text for further explanation. Adapted from Bermúdez i Badia et al. (2007b)

To detect rotations and altitude changes from the optic flow of the video stream broadcasted from the cameras of the indoor UAV, wide field HS and VS neurons are modelled. In order to map displacements detected by the HS and VS systems we used a P control system (proportional) that executed a motor command proportional to the responses of the HS and VS neurons, and in the opposite direction. The P system was chosen since it is the simplest solution and the one that makes the least assumptions on the computations that an insect brain could perform.

A blimp has a very prototypical and inconvenient dynamics caused by the added mass and Coriolis forces that prevent it from following a straight course. In order to evaluate the performance of our altitude and course control systems, we implemented them in the neural simulator **iqr** and we recorded synchronously the motor commands, UAV position and neuronal responses of our model. The effects caused by the added mass and Coriolis forces seem to disappear after applying our model to the UAV (Fig. 6, left panel). Several test flights were performed with the UAV to quantify the performance of the model. A maximum off-course deviation of 15° with respect to the perfect trajectory, with a mean deviation of 7.05°, was measured. During all these tests, a mean velocity of 0.62 $m \cdot s^{-1}$ was maintained. In addition, we used the same method to quantify the performance of the altitude control system to support a constant altitude. The examination of the responses of the UAV shows that the motor compensation forces of the altitude control system are tightly coupled to the variations of the altitude of the UAV (Fig. 6, right panel). Hence, we observe that the altitude control system is compensating the upwards and downwards displacements of the UAV with strong motor responses proportional to the vertical displacement detected by the neural model (Bermúdez i Badia et al. 2007b).

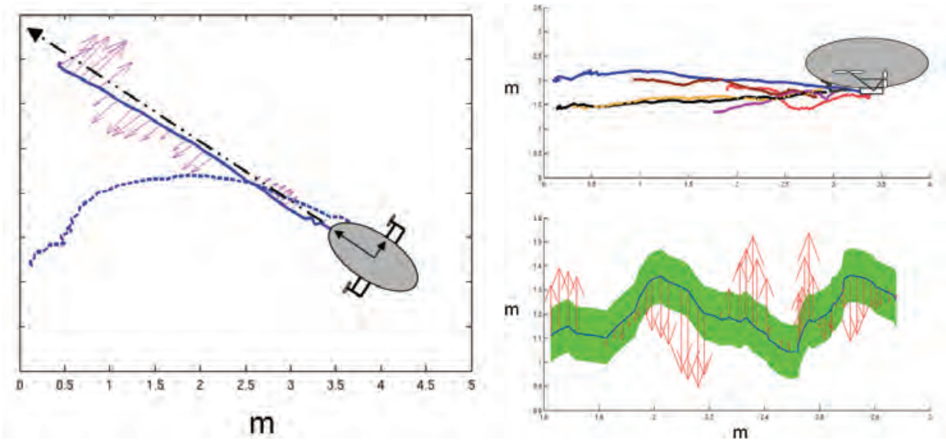

Fig. 6. UAV behaviour under the control of the proposed biologically based neuronal models for course stabilization. Left panel: top view comparison of a trace of the blimp-based UAV without the course control system (dashed line) and a trace of the UAV controlled by the neuronal models. Top right panel: side view of 6 UAV traces under the control of the altitude control system. Bottom right panel: side view showing the compensation motor forces (arrows) and the standard deviation (filled area) of an example trace. Adapted from Bermúdez i Badia et al. (2007b)

Collision Avoidance

A collision avoidance system is a must for any autonomous navigation system. Many sensors, from ultrasonic, infrared and laser sensors to vision have been applied to this purpose, although no general solution has been found (Fox et al. 1997; Surmann et al. 2003; Harrison 2005). The neural correlate of collision avoidance has been identified in many insect species, and due to its impressive performance and accessibility it has been subject of abundant research (Rowel 1971; Gabbiani 2002; Tammero & Dickinson 2002; Krapp & Gabbiani 2005). The best studied collision avoidance system in insects is the one of the Locust, known as the Lobula Giant Movement Detector (LGMD), which relies exclusively on vision. The LGMD has been shown to robustly signal collisions with objects independent of their size, texture, shape and approaching angle (Gabbiani et al. 1999; Gabbiani 2001; Gabbiani 2002; Gabbiani 2004).

Previous studies shave shown that a system that extracts visual expansion, i.e. looming sensitive, based on Reichardt's correlation can account for many aspects of the responses generated by the LGMD at the same time it is a suitable system for a robot implementation (Indiveri 1998; Blanchard et al. 2000; Bermúdez i Badia & Verschure 2004; Harrison 2005; Bermúdez i Badia et al. 2007b).

Relying on the same principles as the course and altitude control models, the local computation of motion, our LGMD model computes motion in a radial outward fashion (Fig. 7, left panel). This alignment of EMDs makes the system looming sensitive. Looming is greater when it is caused by faster approaching objects or by closer ones. Thus, the level of the looming signal is used to trigger collision detections as opposed to be used to estimate distance-to-contact or time-to-contact. All the neural responses of the specifically arranged EMDs are integrated by the excitatory pre-synaptic fan of the LGMD and inhibited by a global motion signal (Rowel 1971; O'Shea & Williams 1974; O'Shea & Rowell 1976) (Fig. 7, right panel). This connectivity converts the LGMD neuron into a looming sensitive system (excitatory pathway) with a normalization signal that regulates the looming sensitivity of the system with respect to the properties of the visual input (inhibitory pathway). The regulatory signal is crucial since more activity at the input level generates more spurious activity at the EMD level, which may lead to random correlations and therefore to more false positives. After the integration of the activity of the inhibitory and excitatory synaptic connections, a threshold operation is used to decide when the looming signal is high enough to be considered a collision (see Bermúdez i Badia et al. (2007b) for model details).

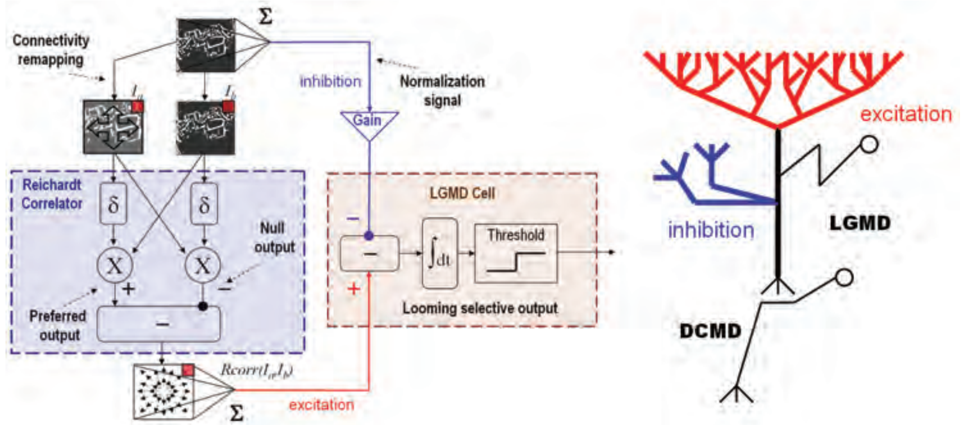

Fig. 7. The functional principles of our model of the Lobula Giant Movement Detector, that extracts expanding motion information from optic flow, and the morphology of its biological counterpart. δ represents a delay, x the multiplication operation and – the subtraction operation. See text for further explanation. Adapted from Bermúdez i Badia et al. (2007b)

To successfully avoid collisions, the UAV not only has to reliably detect approaching objects but also do it at a prudent distance. This is also critical for fast moving vehicles, vehicles with slow reaction times or when inertial forces play an important role. To test the performance of the proposed model of the LGMD, we implemented it in **iqr** and employed it to trigger avoidance manoeuvres on the indoor UAV whenever a collision was detected. The avoidance manoeuvre was triggered in the opposite direction of the collision detection, and with a rotation speed proportional to the amplitude of the looming measure provided by the model

The tests were run in an empty room (~ 5 x 4 m) equipped with curtains with random black filled squares to provide visual cues. An analysis of the system showed robust collision detection and a correlation between detection distance and translational speed where later responses were observed for high speeds, being in the worst case at a distance of about 1.75

m. In addition, the peak response always occurs before the collision takes place, largely independent of the approaching speed (Bermúdez i Badia et al. 2007b). This system allowed for successful autonomous navigation of the UAV with a minimal number of collisions (~ 90% correct detections) (Fig. 8). Most missed collisions occurred at very shallow angles where the cameras and their optics do not capture sufficient visual information.

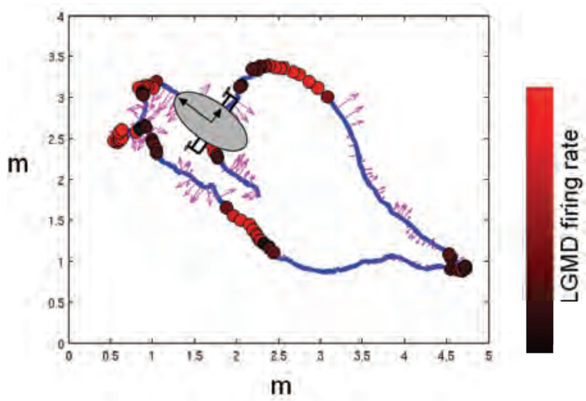

Fig. 8. Trace example for one minute of flight controlled by our LGMD neural model. The blue line represents the position of the UAV within the test area, the arrows represent the motor commands of the course stabilization model, and the filled dots indicate when a collision is detected. The intensity of the red colour is proportional to the amplitude of the model's response. Adapted from Bermúdez i Badia et al. (2007b)

4. Localization Strategies

Usually, the study of mine clearance is reduced to the investigation and development of sensor technology that can detect a number of mines. However, the ultimate sensor technology does not yet exist among the technologies of potential use to this problem. Moreover, demining does not only depend on the selection of the appropriate sensor technology but more aspects play a role. Often overlooked, the efficiency of the clearance process largely depends on the chosen localization strategy. This becomes more relevant when the mined areas are very large or unknown, or when clearance is urgently required. Thus, there is a need for an efficient explosive localization strategy that is not only able to locate possible explosive artifacts but that performs this task in an efficient way.

Our target model, the moth, has developed the appropriate sensor neural structures to be extremely sensitive in the detection of chemical signals (Kennedy & Marsh 1974). In addition, via evolution it has developed a behavioral strategy to optimize success rate when tracing a particular odor in a plume of complex dynamics and within complex odor blends (Kennedy et al. 1978; Baker & Kuenen 1982; Baker 1990). Therefore, the understanding of the origin of the high sensitivity of moths to pheromones is very valuable when studying optimal odor encoding and processing mechanisms, and developing a real-time mine localization robot. Hence, the objective is to learn the key elements from the neural substrate of the systems of the moth involved in the odor localization task, and to present the according biologically constrained models of our cUAV.

Mapping of an Area

The first and most straight forward approach for localization is to perform a mapping of the area to be examined. The objective of mapping an area is to generate a density plot in which sensor measures are associated to specific locations in space. There are many ways to generate such maps, by means of numerous static sensors located at specific points in space, by means of a dynamic scanning of the full area, a random search within the area, etc. The resulting maps contain information that, independent of the sensor technology used, can be used to derive the probability of having an explosive at specific x and y coordinates. Interestingly enough, this approach has been also used to locate explosives with bees. Bees trained to detect certain chemical compounds were released in a mined area, and then the measured density of bees $\cdot$ m^{-2} was used to estimate the position of the mines (Bromenshenk et al. 2003).

Mapping using multiple sensors and parallel measures speeds up the process but it becomes unfeasible when the sensor technology is very expensive. Alternatively, the scanning of an area may lead to the best results but requiring a long time to explore the entire surface, becoming then impracticable for very large areas. A trade off would be to use a mapping strategy that maximizes the area coverage per unit of time. In particular, a random search strategy applied on larger areas explores initially a larger surface per unit of time but then it requires an infinite amount of time to explore the entire area. Thus, depending on the time and surface area constraints, a strategy has to be chosen to maximize coverage, i.e. probability of mine detection (Bermúdez i Badia et al. 2007a).

The mapping of known areas or environments can also be used as a way to characterize the sensitivity, reliability and dynamic responses of our sensor technology. This is a necessary step to assess the limitations of the sensor technology and therefore its applicability to a particular task, in this case the autonomous chemical search by means of a cUAV. The first question that arises is whether our metal thin oxide sensor technology can reliably measure a chemical plume and reconstruct it. In order to assess that, we constructed a 3 x 4 m wind tunnel in which we generated a chemical plume using an ultrasonic delivery system with a 9.4% solution of ethanol in distilled water and a wind speed of 0.7 m $\cdot$ s^{-1} (see section 2).

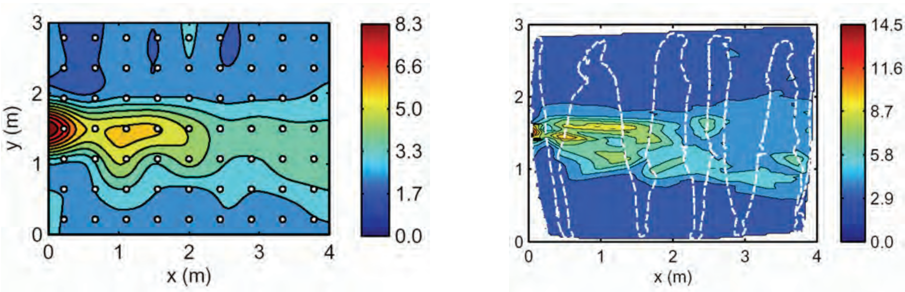

Fig. 9. Wind tunnel chemical mapping experiments by means of static (left panel) and dynamic (right panel) measurements of a chemical plume. Both maps are generated by the sensor responses to a 9.4% solution of ethanol in distilled water delivered at position (0 m, 1.5 m). The map was smoothened using a bi-cubic filter and divided

into 11 contours. The dots represent the sensor location, the trace the position of a remote controlled mobile robot, and the color bar the sensor response strength. Adapted from Pyk et al. (2006)

In order to investigate the effect of the sampling strategy on the accuracy of a chemical map we performed windtunnel experiments comparing static and dynamic smapling approaches. The chemical plume generated in the wind tunnel was sequentially measured during 2 min using a single sensor placed at 9 times 7 equally spaced locations which were interpolated to generate a map (Fig. 9, left panel). The resulting map shows that the static mapping of a controlled chemical plume can be done using our sensor technology, clearly displaying the ethanol distribution in the wind tunnel. Moreover, as a control experiment, the wind tunnel was remapped using the same procedure but this time with a distilled water plume, this demonstrated that the sensor was responding exclusively to the ethanol content of the plume (see for Pyk et al. (2006) further details).

However, it is not clear how time-averaged static measurements generalize to measurements performed by sensors in behaving artifacts. Therefore, we repeated the experiment using our mobile robot equipped with a thin metal oxide chemo-sensor. In this case, the robot was manually driven scanning the wind tunnel from back to front at a speed of 10 $cm \cdot s^{-1}$. Its position was tracked using a custom made visual tracking system called AnTS. The map generated using the dynamical measurements is consistent with the previous one, and shows that the chemo-sensor provides a rapid and reliable measurement of the ethanol concentration while the robot is moving. Hence, we can conclude that this technology seems suitable for an on board implementation in our cUAV that performs dynamic mapping (Fig. 9, right panel).

A Moth Behavior Based Localization Strategy

The problem of odor localization is considerably more complex than the one of mapping since the chemical cues are carried by filamentous plumes of a complicated structure and dynamics that are unpredictable and follow complex patterns (Murlis 1986). Localization, as opposed to mapping, can be less time consuming and does not necessarily require the exploration of the complete area.

In nature we can find a large amount of animals that solved the localization problem of odor cues as an effective way of chemical communication (Kennedy & Marsh 1974; Thorp & Ammerman 1978; Johnston 2003). Female moths release extremely low concentrations of sex attractant chemical signals (pheromones) that male moths are capable of tracing over large spatial scales (hundreds of meters). Therefore, the understanding of the mechanisms underlying moth chemical communication would allow human made robots to reproduce their accuracy, sensitivity and strategies adapted to a number of applications such us fire detection, environmental monitoring, demining, etc.

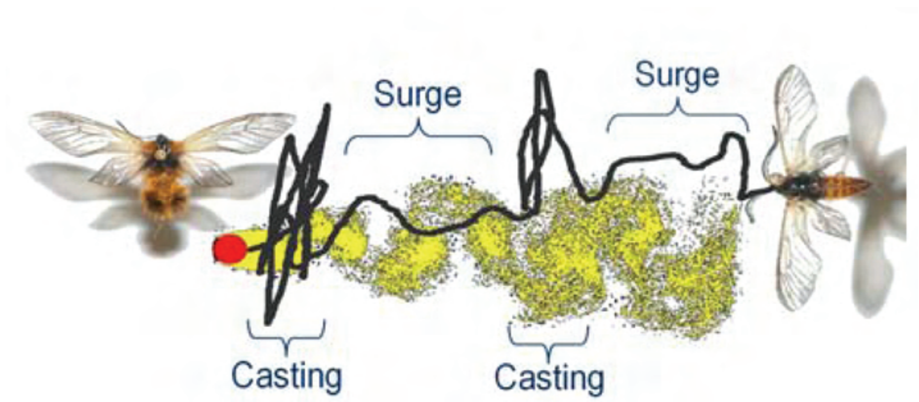

Fig. 10. An actual moth trace (black line) following upwind a pheromone plume (in yellow) released by a female moth (left). The male moth displays two stereo-typical behaviors, surge up-wind and casting cross wind. The red dot represents the location of the release point

The remarkable performance of the male moth in the chemical location task has been largely attributed to the alternation of two behaviors that help it to sample the pheromone plume. The surge behavior consists of a relatively straight upwind flight believed to be triggered by the contact with a pheromone filament. Instead, the casting behavior is a zigzagging crosswind movement triggered in this case by the absence of pheromone contact (Kennedy et al. 1978; Kennedy 1983; Baker 1990; Olberg 1993; Balkovsky & Shraiman 2002).
Based on the moth chemical search behavior, many models have been proposed and tested in both simulations and robot experiments (Kennedy et al. 1978; Kennedy 1983; Baker 1990; Olberg 1993; Balkovsky & Shraiman 2002). We have proposed a model augmented with the previously introduced opto-motor course stabilization and the collision avoidance system based on the LGMD neuron of the locust. This model of the opto-motor anemotactic behavior of the moth is based on the surge and casting behavioral modes observed in the moth, and the switches between them are triggered by the contact with the targeted chemical compound. Additionally, the LGMD collision avoidance system overwrites any of those behaviors triggering an avoidance maneuver whenever an imminent collision is detected (Fig. 11). As a result, the model requires of a chemo-sensor, wind direction information for the upwind and crosswind flight (anemometer), and a partial insect visual system to detect collisions (wireless camera system). All these sensor systems are integrated in our mobile platform (Fig. 2, right panel), and a biologically plausible neural implementation of the opto-motor and chemical search model, consisting of 7082 neurons, aggregated in 97 groups, and 180 connections with 11887 synapses, is simulated in real-time using iqr (see Pyk et al. (2006) for further details).

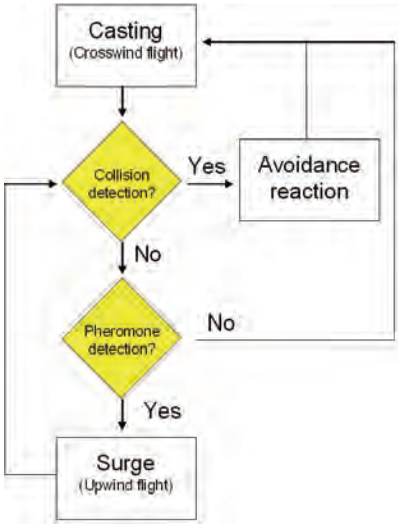

Fig. 11. Block diagram of the moth opto-motor anemotactic behavior model augmented with a collision avoidance system. Adapted from Pyk et al. (2006)

The previous mapping experiments described earlier demonstrated that the chemo-sensor technology proposed provides a functional signal for the detection of ethanol. Further, the wind vane sensor provides the wind direction to the chemical search model. We tested the performance of the proposed moth behavioral model in our wind tunnel in two test and two control conditions. 37 trials were performed and for each trial the robot was placed around 3.5 m downwind from the source on an arbitrary y-coordinate.

Firstly, the model was tested without the collision avoidance system to evaluate the performance of the chemo-sensing mobile robot for an ethanol plume. Two chemical concentrations were tested (17 trials on 9.4% and 20 trials on 23.5%) of water ethanol solution. In all the cases the robot was able to locate the ethanol delivery point, and it required of a median time of 74.2 s (Fig. 12, top left panel) (see table 1 for details). The search times did not differ significantly between the two conditions (Wilcoxon rank sum test for equal medians), being the performance not dependent on the chemical concentration. We observed that the casting mode can be distinguished from the surge mode without difficulty because of the zigzag pattern, lower sensor readings and smaller upwind displacement (Fig. 12, top left panel).

Ethanol source	Mode	Median [s]	Percentile 10% [s]	Percentile 90% [s]
9.4%, n=17	Casting	39.90	28.37	45.72
	Surge	33.10	17.91	103.66
	Total	74.97	62.35	121.89
23.5%, n=20	Casting	32.32	16.42	61.73
	Surge	31.88	14.23	136.53
	Total	67.83	45.50	174.37

Table 1. Performance analysis of the chemical search neural model. Median, 10% percentile and 90% percentile total search time for the two plume conditions

Secondly, the experiment was repeated with an obstacle and the collision avoidance system enabled. The robot behavior demonstrated a successful integration of the moth anemotactic chemical search model with the insect based collision avoidance model, being capable of finding the odor source even in the presence of objects obstructing the direct path (Fig. 12, top right panel).
Finally, two control experiments were performed in the absence of a chemical plume and in the absence of wind flow (Fig. 12, bottom). In the first case, the robot was unable to detect the ethanol plume and therefore displayed exclusively the casting behavior (Fig. 12, bottom right panel). In the second case, the robot not only could not detect the chemical trail but it was unable to measure the wind direction, and thus unable to find the source direction. This resulted in an erratic behavior without a clear movement direction or target direction (Fig. 12, bottom left panel). This demonstrates that both airflow and chemical stimuli are required for the robot to complete the localization behavior.

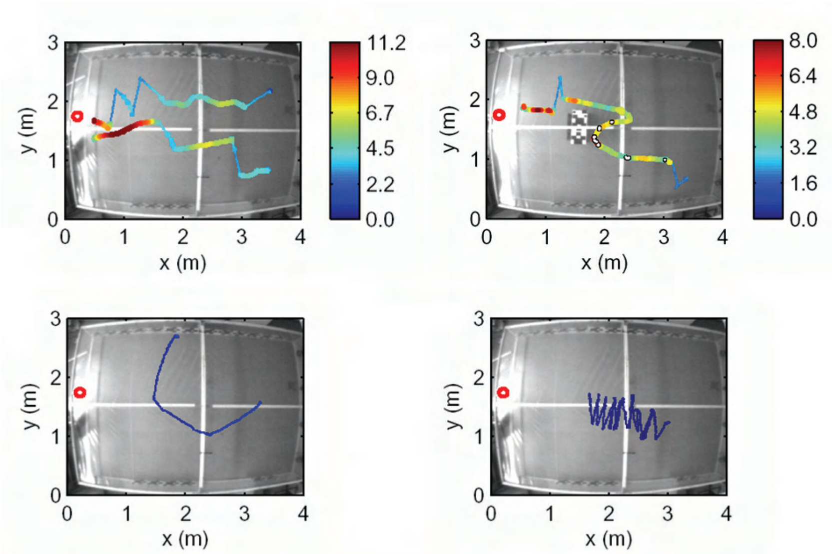

Fig. 12. Prototypical robot trials for the chemical search experiments using the moth behavior based localization model. Top left panel: two trials of the chemical search model with the collision avoidance system disabled. Top right panel: example trial of the chemical search model augmented with the collision avoidance system in the presence of obstacles. Bottom left panel: example trial of the chemical search model in the absence of airflow. Bottom right panel: example trial of the chemical search model in presence of airflow and absence of chemical plume. The thick robot trace indicates surge mode whereas the thin one indicates casting mode. The color of the trace represents the amplitude of the sensor readings of the robot in that particular position. The white dots indicate collision detection and the red dot indicates the position of the ethanol delivery system. Adapted from Pyk et al. (2006)

Consequently, the moth based search behavior model seems to be a comparatively faster odor localization strategy than mapping. Moreover, its success rate demonstrates not only the reliability of this model to successfully localize the odor source under turbulent conditions, but also the matching between chemical plume dynamics and sensor readings, and its integration and enhancement with the LGMD collision avoidance model.

A moth Neural Based Localization Strategy

It has been very difficult to assess more detailed aspects of moth chemotaxis directly because of the impossibility of visualizing a plume without interfering with the flight behavior of the moth. Hence, it is still not quantitatively established whether the moth responds to a chemical gradient, filament contact or uses a more complicated behavioral strategy. However, experiments have been performed where a male moth was equipped with a third antenna with a wireless transmission system to approximate what it would sense (Kuwana et al. 1999). Although the results of this approach were technologically interesting and challenging, it is insufficient for a proper characterization of the relationship between the stimuli the moth is exposed to and the behavior it displays since it does not directly measure from the real antennae.

As shown by our behavior based model, a simple strategy switching between upwind (surge) and crosswind flight (casting) can be very successful in solving the localization problem. Nevertheless, the moth developed some neural systems to deal with the specific characteristics of the structure of the pheromone plume that are not exploited in our behavior based strategy. For instance, it is known that the temporal structure of the stimulus is encoded in the responses of the nervous system of the insect, and that this structure is crucial to keep the moth flying upwind in the direction of the source of pheromone (Murlis & Jones 1981; Vickers & Baker 1994; Mafra-Neto 1995; Kuwana et al. 1999; Quero et al. 2001; Justus 2002). In this case, the frequency of the odour filaments has been shown to have a strong impact on the behavior of the moth, where the moth appears to be tuned to respond maximally to a specific detection frequency (Willis & Baker 1984; Vickers & Baker 1994; Vickers 1996).

The question arises whether a model based exclusively on phenomenological observations of the moth can fully account for its behavior without taking into account the neural substrate that regulates it. Hence, we aim at constraining our localization model with the current knowledge of the odor processing stages in the moth and identified neuronal mechanisms.

Our neural based model relies on two important hypotheses, the use of ***stereo information*** and the ***pheromone frequency dependency***. The first hypothesis is supported by the, so called, flip/flop neurons (Kanzaki et al. 1989)**.** These are, so called, Descending Neurons of the protocerebrum that arborize in the Lateral Accessory Lobe, and that show a bi-stable high and low frequency response. The activity of these, so called, flip/flop neurons is directly correlated with the body orientation and zigzagging of the moth while tracing a pheromone trail. Moreover, the orientation switches appear to be caused by the difference of pheromone concentration in the anteanne (Olberg 1993; Mishima & Kanzak 1998; Wada & Kanzaki 2005). Therefore, olfactory stereo information is used in our model to trigger the orientation changes whenever the sensor reading difference of two chemo-sensors is above threshold (Fig. 13).

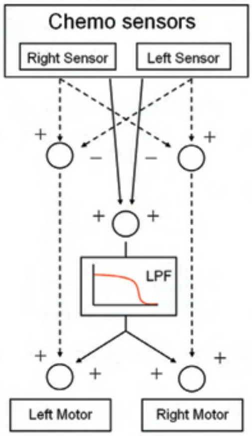

Fig. 13. Scheme of the proposed neural based model for the control of chemical search. The left and right chemo-sensor responses are continuously compared to re-orient the robot in the direction of the maximum concentration. The Low Pass Filter of the sum of the sensor readings (LPF) is used to drive the two motors of the robot at the same speed to obtain an upwind translation. Adapted from Bermúdez i Badia et al. (2007a)

The second corner stone of the model is based on the Macro Glomerular Complex (MGC) of the Antennal Lobe (AL) of the moth, a glomerulus that evolved to solely process the pheromone signals (Christensen & Hildebrand 1987; Kanzaki et al. 1989; Hansson et al. 1991; Christensen et al. 1993; Christensen et al. 1995). Approximately 85% of the neurons of the MGC display transient responses correlated with the pheromone signal, but are only able to resolve odor pulses of up to a few Hz (Christensen & Hildebrand 1987; Christensen et al. 1993; Lei & Hansson 1999). Surprisingly, this frequency response range is similar to the characteristics of the plume pulsing experiments that show that moths display a faster upwind displacement for pulsed pheromone signals (Murlis & Jones 1981; Murlis 1992). Thus, a Low Pass Filter (LPF) of the readings of the chemical sensors is used to trigger translation displacement (independent of the heading direction) (Fig. 13).

As opposed to the previous behavior based model, in this case the wind direction information is not used to direct the robot upwind but only to prevent the robot from an undesired downwind displacement.

To quantify the performance of the neural based model we used the following criteria: from an evolutionary point of view one can assume that the most advantageous strategy has to trade off some aspects such as the consumption of energy, the search time, the number of competitors, the number of female moths and, of course, the success rate. Therefore, and given the amount of male moths that can receive the chemical cues of a single female, we assume that the optimal search strategy has to mainly balance search time with success rate, i.e. the longer a moth takes to search the more chances it has to find the female, but it is also more likely that another male moth will have found it before while the probability to be detected by a predator will increase. Hence, in the subsequent experiments we compared the accuracy and search time of a modified version of the behavior based model, which uses a single chemo-sensor, with the neural based model, which uses two chemo-sensors mounted on our mobile robot. Inspired by the theoretical studies of Balkovsky et al., the casting mode of the behavior based model was modified from having a fix crosswind length to increasing it over time, increasing consequently the probability of the robot intercepting a pheromone filament over time since it explores a larger area (Balkovsky & Shraiman 2002) (Fig. 11).

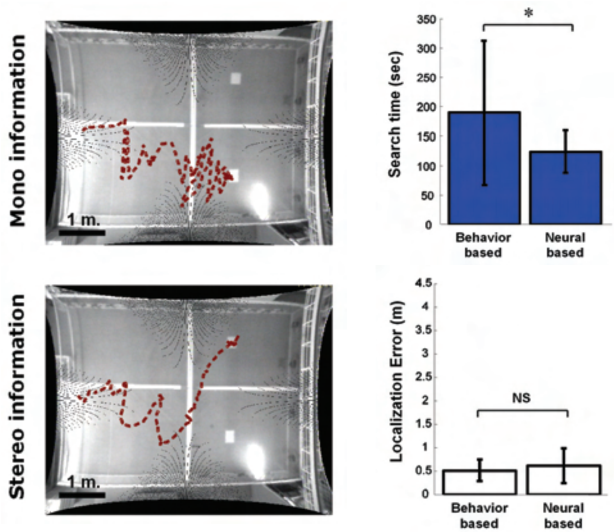

Fig. 14. Comparative behavior analysis of the two proposed moth based chemical search models. Left panel: Example traces for the behavior based (mono) and neural based (stereo) chemical search models. Right top panel: Search time comparison between models. Right bottom panel: Localization error comparison between models. A total of 100 test runs were performed for the two conditions. Bars indicate the data variance. Adapted from Bermúdez i Badia et al. (2007a)

In order to compare the performance of both models, a total of 100 robot test runs were done starting randomly at the rear left or right side of the wind tunnel (Fig. 14, white areas in the left panel). Then a chemical plume was created using a water/ethanol solution of 20% ethanol (see section 2). The performance of both moth based models was evaluated measuring the total search time and the localization error. The accuracy of the behavior and neural based models, measured as the distance between the ethanol delivery system and the robot end position, is of about 0.5 m, with no significant difference (2 sample t-test, $p > 0.05$) (fig. 14, bottom right panel). Nevertheless, when we take into account the total search time we observe that the neural based model outperforms significantly (reducing the average search time by more than one minute which is 31% of the mean task duration) the performance of the behavior based model (2 sample t-test, $p < 0.05$) (Fig. 14, top right panel). Thus, the neural based model is significantly faster than the behavior based yet displaying the same localization precision. If we compare the mean search time of the neural based model (approx. 2 min.) to the time required for the robot to scan the whole wind tunnel (approx. 5 min) it is more than twice faster. Moreover, this difference will increase even further for greater areas, since scanning search time directly depends on the area size to be explored.

Outdoor cUAV Experiments

In order to test the different models studied in indoor controlled environments in more realistic scenarios we constructed an outdoor chemo-sensing UAV (see section 2). As starting point, we equipped the outdoor cUAV with a single chemo-sensor, a GPS, an altimeter, a gyroscope and a compass. These traditional sensing technologies were added for monitoring and analysis purposes. Then, a standard Proportional Integral Derivative (PID) control software was developed to allow for autonomous and remote navigation of the flying platform (see Bermúdez i Badia et al. (2007a) for further details). Besides the robot and sensor technology, the performance of the proposed mine detection technology in large and unspecified terrains does not only depend on the localization strategies but also on the scheduling and coordination of a number of these cUAVs that are applied to the demining problem. Therefore, we propose to use a control layer that permits the scheduling of a fleet of cUAVs to coordinate the search in large environments. A base station divides the target area into a number of sub-regions in which each of the cUAV performs an autonomous flight. For that, the cUAVs make use of their GPS to ensure that they do not surpass the limits of the region assigned to them.

The first outdoor scenario used to test our cUAV was a university football field (40x80 m.) in which we placed a single odor delivery source. For these experiments, the ultrasonic delivery system released a solution of 40% ethanol in water at a rate of 200 $ml \cdot h^{-1}$. The weather station reported an average wind speed of 3 $km \cdot h^{-1}$ during the experiments.

In these experiments, the platform was successfully tested to perform a number of autonomous mapping strategies (random search and scanning). These experiments demonstrated the reliability of the hardware and software control infrastructure of the cUAV, and the feasibility of fully autonomous chemical localizations based on predefined strategies (see Bermúdez i Badia et al. (2007a) for further details).

Nevertheless, the chemical source localization becomes impracticable by a single cUAV when search is required over very large areas. Thus, we tested the possibility of scheduling a cUAV fleet based on non-overlapping divisions of the area to explore. Inside each of these regions, the cUAVs perform an autonomous chemical mapping. Therefore, we scheduled our outdoor cUAV to perform a chemical mapping using a random search strategy on a predefined area, and we re-scheduled to another adjacent area after it realized the first mapping (Fig. 15). These experiments show that the cUAV is able to sequentially examine non-overlapping areas autonomously and create a consistent chemical map of the sensed ethanol distribution in the football field (Fig. 15). Moreover, the data provided by the reconstructed map suffices to detect and locate the position of the ethanol delivery system, although false positives can occur.

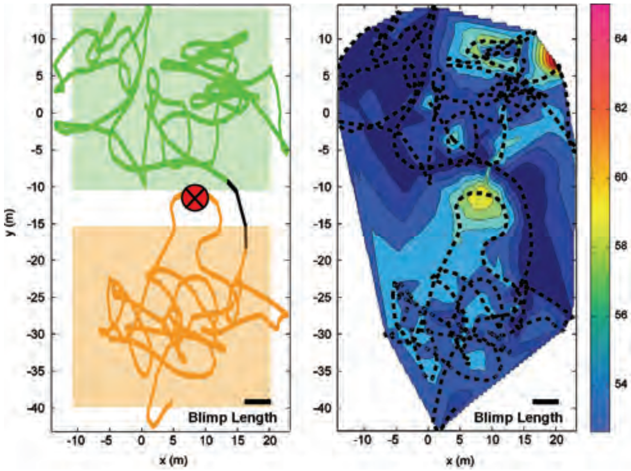

Fig. 15. Autonomous cUAV scheduling and mapping experiments using a random search strategy. Left panel: the cUAV explores sequentially the two search areas (green and orange filled areas). The red circle represents the position of the odor delivery system, and the color lines the trace of the cUAV. Right panel: reconstructed ethanol distribution map of the explored area using a bi-cubic filter and divided into 11 contours. The dashed line represents the cUAV trace. The sensor reading amplitude and the blimp dimensions are indicated. Adapted from Bermúdez i Badia et al. (2007a)

5. Conclusions

In this project we investigated the use of a chemo-sensing Unmanned Aerial Vehicle (cUAV) for humanitarian demining tasks. In this chapter we have shown a wide spectrum of developments oriented towards the autonomous and non-supervised mine detection on large scale and unspecified environments by means of a blimp-based chemo-sensing UAV equipped with a broadly tuned metal thin oxide chemo-sensor. These developments include the design and construction of a number of indoor robots (mobile and flying robots), the first outdoor chemo-sensing UAV, novel insect based flight control methods and a number of moth based localization strategies. The central assumption of our work is that we can develop advanced and effective demining systems by basing them on insect solutions to flight control, navigation and chemical communication.

First, new methods for the autonomous flight control of flying robots have been developed and tested using an indoor blimp-based UAV. These methods, based on the Horizontal and Vertical System neurons of the fly, include a course stabilization and altitude control system. The robot tests demonstrate the feasibility of this technology and that the principles of the neural substrate of the fly visual system can successfully control the course and the altitude of the UAV. Then, the indoor UAV system has been augmented with a collision avoidance system that captures the computational principles of the Lobula Giant Movement Detector neuron of the locust. The UAV tests confirmed the collision avoidance neural model to be robust and reliable during a free indoor flight in a controlled environment.

In addition, the feasibility of the proposed chemo-sensor technology has been proven first by static and dynamic chemical mapping experiments of a controlled environment, then by two moth based odor localization experiments, and finally by a mapping and scheduling experiment of an uncontrolled outdoor environment using the chemo-sensing UAV. This outdoor platform is shown to be very well suited to the mine detection task since it is terrain independent, does not trigger mines, and can perform either fully autonomous chemical search or it can be manually driven.
Our results corroborate the viability of the proposed technology for demining in real-world scenarios. Further, the results support our biologically based approach where the knowledge of biological systems is used to solve challenging engineering problems. This is contrasted to a "biologically inspired" approach that does not require its solutions to satisfy standard scientific norms of validity and or plausibility. Given our results we suggest that a biologically based approach is more effective since it is both advancing our understanding of nature and the construction of real-world artefacts.
All the biological systems considered in this study are of great interest for robotics and computation because of their simplicity (implementation wise) and effectiveness. Research with robots permits to study those systems by making complex models of the different subsystems involved in the flight control and moth chemical search, and test them in controlled and in more realistic and complex scenarios. Moreover, these new models that are developed contain implicit hypothesis on unknown neural mechanisms of the moth, and as such robotics can contribute to a better understanding of biological systems at the same time novel and robust solutions are developed. Hence, the convergent validation of physiology, anatomy and behavior advances our understanding of the insect solution to chemical communication.
We have explored the main components required to build a fully synthetic moth robot. However the full integration of some of these system parts is not yet completed. In future work, we expect to be able to test the different moth based chemical localization strategies using the outdoor cUAV in more complex outdoor environments. Further, the biologically based flight control neural models have been shown to deliver a rotation and altitude change related measure, thus in the future we plan them to replace the altimeter and gyroscope sensors used in the outdoor cUAV.
In addition, the limit of the sensitivity of the thin metal oxide chemo-sensing technology, and in particular the applicability to the particular case of the detection of leaking explosives has to be further assessed. It has been shown that the sensitivity of this type of technology can go up to few parts per million (ppm), providing a wide range sensitivity that allows for identification of organic compounds (Neubecker et al. 1997; Eickhoff et al. 2003). Nevertheless, the chemical traces of some explosives such as TNT are shown to be made of few parts per billion (ppb) (Rose et al. 2005). Despite this problem, the particularities of the sensor technology used for demining do not alter the important contribution of the biologically based approach, the studied search strategies, the flight control mechanisms, and the terrain independent platform approach.

8. Acknowledgements

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9

Development of Deminer-Assisting Robotic Tools at Tokyo Institute of Technology

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1. Introduction

Robot operation and interaction in unstructured environment is difficult. The problem becomes even more difficult if the environment is hazardous, presents a potentially wide temperature range, and is subject to rain, dust and other natural factors. Such conditions are typical in minefields. Current demining technology is slow, costly and dangerous, and has virtually not evolved in the last 60 years except for heavy and armoured soil-digging machines that are limited to well-conditioned terrain. Assisting human deminers in the mine searching task, or giving them better means of protection during the dangerous task of soil prodding and mine neutralization is challenging. However it is worth pursuing this goal: not only will deminers benefit from the development, but the demining *industry* itself will benefit from it with eventually faster paces, more efficient detection and removal rates, and this at reduced costs.

The Tokyo Institute of Technology started developing robotic tools and machines for humanitarian demining more than a decade ago. The first steps were performed literally, with a quadruped walking robot named TITAN VIII (cf. Figure 1) that was able to adapt its gait to navigate on difficult terrain and use one of its legs as a manipulator to scan the soil for mines, cut vegetation or even dig the ground [Hirose & Kato, 1998; Kato & Hirose, 2001]. A sophisticated system including a tool-changer and tele-operation functionality allowed the robot to perform the most dangerous tasks without proximate assistance of humans. Scenarios in which one of the robot's legs was blown off by accidentally stepping onto a mine were overcome by appropriately readjusting its walking gait for 3 legs. Other research institutions and laboratories have followed into Tokyo Institute of Technology's footsteps by developing legged robots for humanitarian demining; one example is COMET-1 [Nonami et al., 2000], a 6-legged walking robot equipped with several cameras, an attitude control sensor mechanism, and 6 small metal detectors integrated into the extremity of each leg. Another legged example is the pneumatic multisensor demining robot [Rachkov et al., 2005], that can be equipped with a metal detector, an infrared detector and a chemical explosive sensor for mine detection.

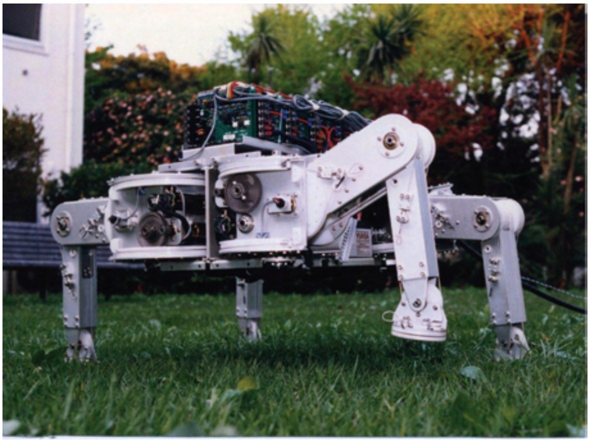

Fig. 1. Titan VIII

However, walking robots, usually equipped with a large number of actuators, still have several serious challenges to overcome: they are difficult to control, expensive and prone to technical malfunction. On the other hand, machines that roll on tracks or wheels can be quite inexpensive, much faster and more stable than legged devices [Shiller & Mann, 2004]. Some early demining-related examples include PEMEX-B [Nicoud & Maechler, 1995], a simple, lightweight two-wheeled vehicle, carrying a sensor to detect mines, and light enough not to trigger surface or buried mines. There are also other robotic systems based on alternative locomotion means. One such system for mine clearance has been proposed by Trevelyan [Trevelyan, 1996] and consists of a tool carrier suspended by cables and controlled by winches on poles at the corner of the minefield. This approach allows covering a wide span of terrain but is limited to relatively flat and vegetation-poor surfaces. In [Fukuda et al., 2006] an adaptive mine scanning framework, attached as payload of a long reach crane, was developed. The system is able to reach locations otherwise hardly accessible for other devices and can operate adaptively on very steep slopes.
The Tokyo Institute of Technology took, since the development of TITAN-VIII, a more pragmatic and practical approach. A more careful analysis of the common important characteristics to consider during the design of a robotic demining vehicle, as weight, level of autonomy and self-recovery to name only a few [Havlik, 2005], has lead to the development of two practical robotic tools that can assist and protect the human deminer in the mine-searching or mine-removal/mine-neutralization tasks: *Gryphon* and *Mine Hand*. While *Gyphon* is a semi-automatic robot capable of autonomously scanning the terrain that surrounds it, generating high-quality sensor images, and also allowing the marking of suspected mine locations, *Mine Hand* is meant to be used afterwards, to inspect positions previously marked by *Gryphon*, prodding the soil and neutralizing potential mines.

2. Gryphon

The development of *Gryphon* started in early 2001. Wanting to switch to a more reliable, less expensive and faster system for mine detection, an experimentation platform was developed [Fukushima et al., 2001].

2.1 Early Developments

Based on a commercially available 4-wheel buggy, the platform features a combustion engine that can be employed for locomotion and also for on-board electric energy generation, and mechanical adaptations that allow the remote control of its steering, throttle, gearshift and brakes. The *hyper-tether* concept was developed at the same time, allowing the transmission of the generated electrical energy to other robots and tools. As such, the following demining scenario became conceivable: a mine-sensing tool, suspended on the *hyper-tether* between the buggy and some auxiliary vehicle, scanning the terrain without touching it (cf. Figure 2), and receiving electric energy through the tether. This allows for good autonomy, large workspace and limited exposure to accidental mine explosion. However, this scenario suffers from similar handicaps as Trevelyan's tool carrier.

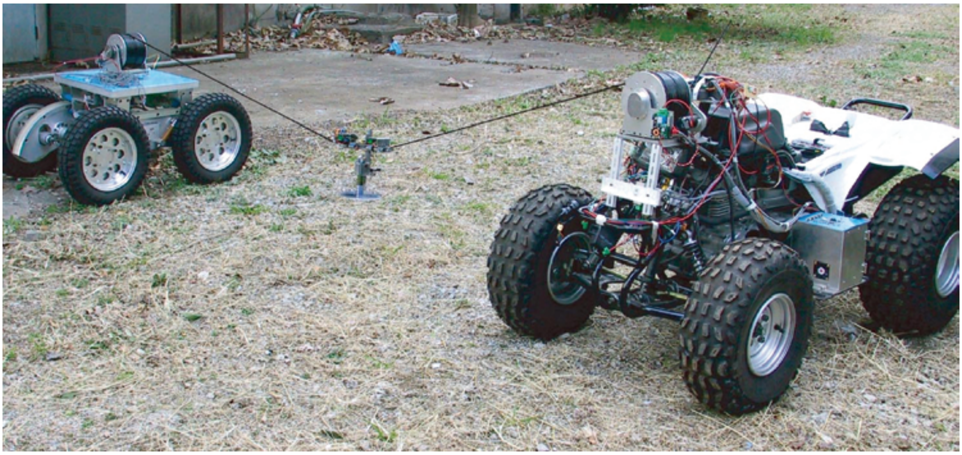

Fig. 2. Mine detection concept with *hyper-tether* and two mobile platforms

The next version of *Gryphon* was more elaborate [Debenest et al., 2005], and featured a 3 degree-of-freedom manipulator, named *Field Arm* (cf. Figure 3). For field applications in remote areas, it is important to consume little electric energy since it may be limited. *Field Arm*, a pantographic manipulator, especially devised for such applications, is theoretically in perfect balance for any given base posture or arm configuration: the arm payload is balanced by a counter-weight (housing batteries) in the rear, thus requiring power only in dynamic situations. In reality, however, the mass of the various links and joints cannot be ignored, and the arm is never perfectly balanced. In spite of that, experiments showed that the nearly-perfect balance implies a considerable reduction of power consumed in static and quasi-static cases. The use of a counter-balanced manipulator will also help reduce the dependence of the buggy's posture on the *Field Arm*'s configuration. Even though the buggy's suspension is fairly compliant, its inclination is drastically reduced when *Field Arm* reaches far out. Additionally, a two degree-of-freedom wrist mechanism was attached to the tip of *Field Arm*, allowing the positioning and orientation of any type of sensor over the ground.

Fig. 3. *Field Arm* mounted on top of the mobile platform

2.2 Later Developments

Today, *Gryphon* became a robust, well-thought and practical robot that has undergone several field tests in Japan, Croatia and Cambodia. Compared to the previous version, it has increased in size, and was added many features making the mine-searching task easier and faster. As shown if Figure 4, the current *Gryphon* is based on a bigger buggy, a so-called All Terrain Vehicle to which a larger version of *Field Arm* was added. The robot is equipped with a stereo vision camera to acquire topographical information of its surrounding environment. The 3D model of the terrain is then used to autonomously move a mine-detecting device (hereafter called mine detector) at close distance from the ground – that is not necessarily flat – while describing a precise scanning motion over an effective surface of approximately 3 square meters. The recorded mine detector data is then presented to the operator who, after careful inspection and evaluation, can indicate suspect spots that will be marked directly onto the minefield with an onboard paint- or plate-marking system.
For maximum safety, Gryphon always operates along the minefield borderline and from the cleared side. Only the mine detector and a part of the manipulator are operating over the dangerous area – hovering at close distance to the ground without ever touching it – during the scanning motion. Additionally, most operation steps are fully automated and Gryphon can be operated and monitored from a safe distance by means of a portable control box. Figure 5 shows *Gryphon*'s control system. From the beginning on, more than just a research project, *Gryphon* was meant to be a practical robot, with the idea to undergo practical tests in near to real-world conditions. Thus, emphasis was put on system integration, robustness (water-proofing, extended temperature range, etc.), cost and easy operation/maintenance.

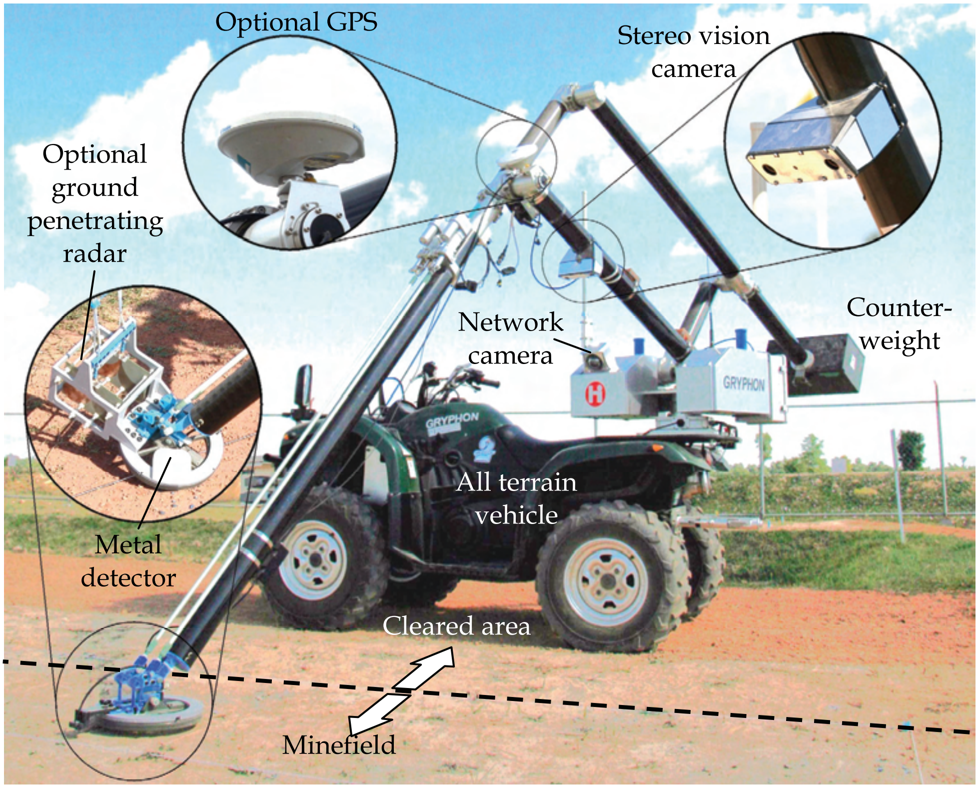

Fig. 4. Overview of *Gryphon*'s main elements

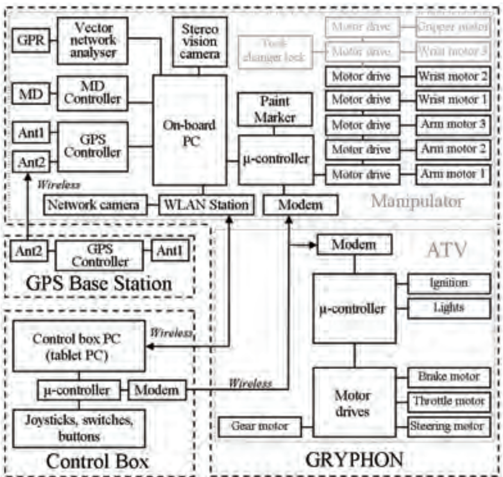

Fig. 5. Overview of *Gryphon*'s control system

THE WRIST MECHANISMS

Two new wrist mechanisms have been developed (cf. Figure 6, (a) and (b)). The first one, entirely made of metal-free materials with remotely positioned actuators, has two degrees of freedom and is ideally suited to orient an inductive metal detector over the terrain. Indeed, a metal detector's performance can be drastically reduced if used in proximity of interfering metallic objects. The second wrist mechanism that can be attached to *Field Arm*, possesses one additional degree of freedom. It was originally developed as the ankle mechanism of a walking robot [Ogata & Hirose, 2004], but serves nicely its purpose here too: carrying and orienting heavier payloads. Additionally it has a tool-changer mechanism integrated, allowing *Gryphon* to seamlessly switch tools when needed. Figure 6 (c) shows a gripper compatible with the tool-changer.

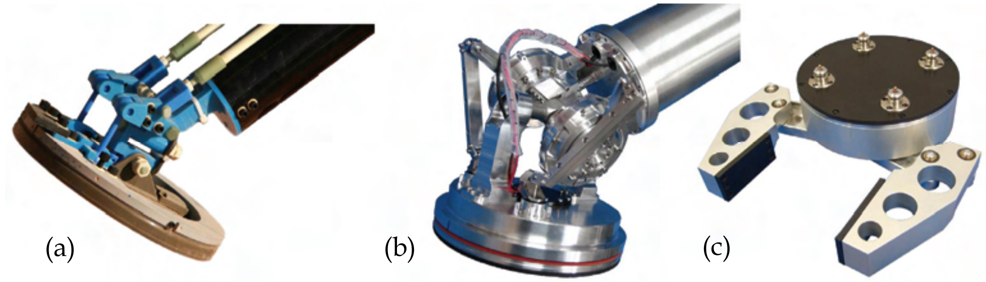

Fig. 6. Metal-free wrist mechanism with metal detector (a), heavy payload wrist mechanism with tool-changer (b), gripper compatible with tool-changer (c)

THE STEREO VISION CAMERA

Gryphon is operating in a model-centric manner in order to avoid traditional traps a reactive control system is facing, namely local minima. This enables *Gryphon* to plan the whole scanning procedure in advance and recognize potential problems before even starting to scan. This approach also takes advantage of the static nature of the terrain in typical minefields. In order to compute the trajectory of the detector over the terrain, a model of the terrain to scan is constructed by using a stereo vision camera (BumbleBee model no. BB-HICOL-60, Point Grey Research, Vancouver, Canada); the camera is attached to the manipulator's first link, at a position allowing for easy topographic data acquisition around the vehicle's position without suffering interferences from the manipulator or vehicle themselves.

THE DETECTOR

Considering that a vast majority of mines contain a substantial amount of metal, the obvious choice and most commonly used mine sensing technology is still the inductive metal detector [Guelle et al., 2004]. However, such a sensor will not only detect buried landmines; it will equally well detect any other fragment of metal. This leads to a high false positive rate that slows down the demining pace and drastically increases the costs. Such shortcomings of the metal detector have given rise to a multitude of other technology. One of them is the ground penetrating radar, typically detecting bigger heterogeneities in the ground. While it also suffers from a high false positive rate, using it in conjunction with a metal detector can help reducing that number to a minimum. The detector – representing the sensor payload – in its standard configuration, as of July 2007, is composed of a metal detector (CEIA MIL-D1, Arezzo, Italy) that can optionally be completed with a ground penetrating radar [Takahashi et al., 2006]. Each individual sensor composing the detector has its data recorded together with its tracked position in order to generate precise sensor images, and one can imagine attaching a multitude of sensors to the detector – each with a specific sensing property – and so increase *Gryphon*'s overall detection performance. Figure 7 shows the sensor payload composed by the metal detector antenna and the ground penetrating radar antenna.

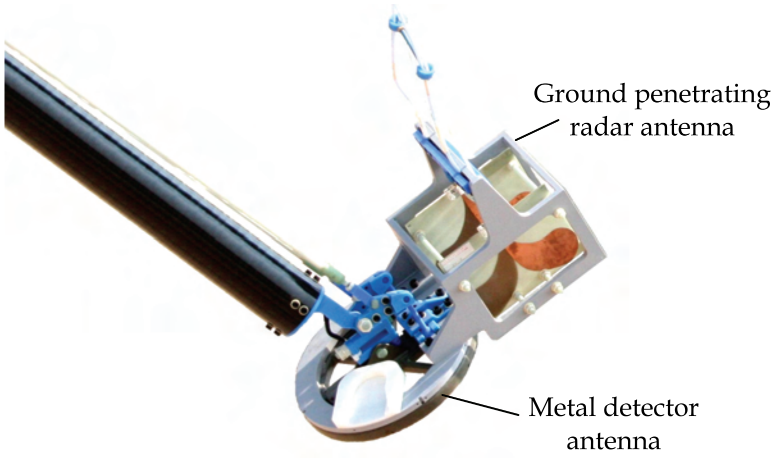

Fig. 7. Gryphon's payload composed by a metal detector and a ground penetrating radar

THE MARKING SYSTEMS

The standard version of *Gryphon* (as of July 2007) is an exclusively sensing robot, and as such, still requires manual prodding of suspected mine locations. This step is preferably done in a decoupled and independent manner from *Gryphon*, so that each operation on the terrain (e.g. sensing and prodding) can be performed at its own pace and time. To this end, two different marking systems have been developed and can optionally equip *Gryphon*. The first marking system is based on water-soluble color paint, and allows marking suspected landmine locations in a semi-permanent way. A paint reservoir with pump is located near the manipulator base and paint is conducted through a tube to a nozzle attached on the detector (cf. Figure 8 (a)). The paint marker is the most flexible of both marking system, providing more than just location information: suspected spots can be numbered or classified according to preliminary data evaluation, and additional information written directly onto the terrain. This can help in the following inspection and prodding step, with faster target identification. The second marking system is based on a marking plate dispenser that drops marking plates one-by-one on a holder fixed on the detector upon a push from the latter against a lever (cf. Figure 9 (b)). The detector then places itself appropriately closely above the spot to be marked and inclines itself so as to let the marking plate slide onto the terrain.

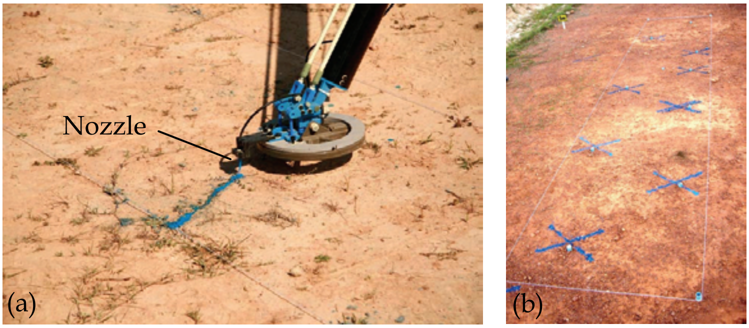

Fig. 8. Paint marker (a), marked suspected mine locations (b)

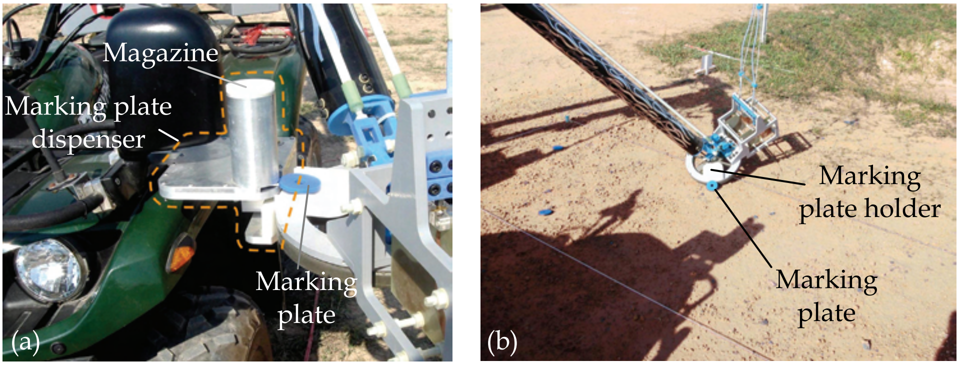

Fig. 9. Marking plate dispenser (a), marking plate dropping (b)

THE OPTIONAL GPS

In order to localize itself relative to the minefield, but also to mark suspect spots virtually as coordinates to allow a later resumption of work, Gryphon can be equipped with an optional satellite navigation system based on the currently most accurate form of Global Positioning System: Real Time Kinematics (RTK GPS), enabling centimeter-level accuracy for the mobile GPS antenna, relative to a base station. Gryphon optionally uses two RTK GPS units (MS750™, Trimble Navigation Limited, CA), one being configured as the base station (immobile), and the other one as the rover unit (mobile). Precision is typically 1cm horizontally and 3cm vertically. The GPS antenna is attached at the top of the first link of the manipulator. This placement gives good clearance to the sky and allows calculating not only the position of the vehicle but also its orientation by measuring a succession of positions at different manipulator configurations.

THE CONTROL BOX

The control box (cf. Figure 10), which is the remote user interface unit of *Gryphon*, is built – as is *Gryphon* – in a rugged and weather-proof manner. Its upper part contains an embedded tablet-pc that runs the higher-level control software of the manipulator. From there the operator can acquire topographical terrain information with the stereo vision camera, launch automatic movement sequences, monitor the system state, display acquired detector images and mark suspected mine locations. Communication with *Gryphon* is achieved by wireless LAN. The lower part of the control box contains – next to batteries for over 8 hours of non-stop operation – two joysticks and several switches. A modem communication transmits signals to *Gryphon* and allows controlling the manipulator and the all terrain vehicle manually.

Fig. 10. The control box

<u>THE MODUS OPERANDI</u>

The standard operation procedure of *Gryphon* can be described in 5 steps, which are repeated for each scanning position:

1) The all terrain vehicle is driven into position (manually or through the control box). Since *Gryphon* operates along the minefield borderline, the vehicle is positioned so as to be able to scan on its left or right side.
2) In case *Gryphon* is equipped with the optional RTK GPS, position and orientation of the vehicle relative to the minefield is calculated.
3) The surrounding terrain is geometrically modeled by acquiring several depth maps with the stereo vision camera (cf. Figure 11). In case *Gryphon* is not equipped with the optional RTK GPS, position and orientation of the vehicle is evaluated using artificial landmarks placed on the minefield borderline.
4) Autonomous scanning is executed; the detector data is processed and visualized in the control box.
5) After the evaluation of the acquired data, the suspected mine locations are marked using one of the onboard marking systems and/or registered with the optional RTK GPS.

Fig. 11. Environment modelled with the stereo vision camera

Gryphon uses a special overall calibration procedure combined with an advanced terrain-following method to guarantee ideal and precise sensor placement over the terrain [Freese et al., 2006]. Additionally, a robust feed-forward vibration control technique [Freese et al, 2007] allows competitive accelerations rates despite the system's rather compliant elements (*Field Arm* links and vehicle's suspension). This enables a maximum scanning speed of 0.8m/s. However, when recording metal detector data, the speed is limited to 0.5m/s to guarantee a good data density. When the detector is composed of the optional ground penetrating radar, the speed is limited to 0.08m/s. This results in scanning times for a 1 square meter surface of 1 and 6 minutes, respectively. These timings do not include moving the vehicle to the next position, mapping the terrain, evaluating the data and marking suspected spots. Terrain mapping and marking typically take less than 25s/m^2 and 20s/spot, respectively.

FIELD TESTS

Gryphon has been field-tested with a combined 95 days of testing on flat ground, bumpy terrain, and slopes. This includes operation on various test minefields, including evaluations conducted under the supervision of the Japan Science and Technology Agency in Japan in early 2005 [Ishikawa et al., 2005] and early 2006 in Croatia [Ishikawa et al., 2006]. Recently, two Gryphon robots also took part in extensive trials in Cambodia, organized by the Cambodian Mine Action Center. Operated by Cambodian deminers, the Gryphon machines performed tests for more than 150 hours of semi-autonomous operation (cf. Figure 12).

Fig. 12. *Gryphon* autonomously scanning a test minefield in Cambodia under the supervision of Cambodian deminers

Gryphon operates by scanning a 1 meter wide lane, 2 square meters at each vehicle position. Metal detector and ground penetrating radar sensing is performed simultaneously and the recorded data is presented as a series of images, which can be evaluated separately by the operator. Figures 13 and 14 represent a typical metal detector image and corresponding ground penetrating radar images respectively. While the metal detector data is relatively easy to evaluate (metal targets can easily be located between corresponding red and blue lobes), the ground penetrating radar data comes in several different layers, each associated with a depth layer in the ground, and requires a trained eye to spot possible landmines.

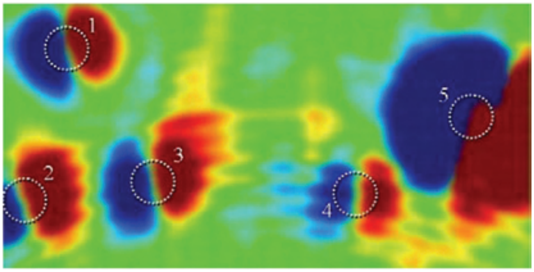

Fig. 13. Metal detector image of a 2 m^2 scan

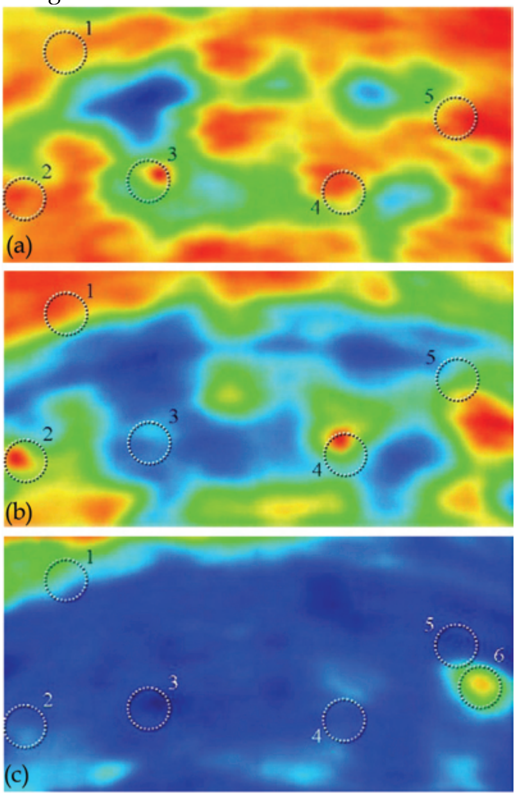

Fig. 14. Ground penetrating radar images of a 2 m^2 scan, layer 49 (a), 52 (b) and 55 (c)

Five metallic targets of 3 different types (cf. Figure 15 and Table 1) have been buried at a depth of 5 or 12.5 cm.

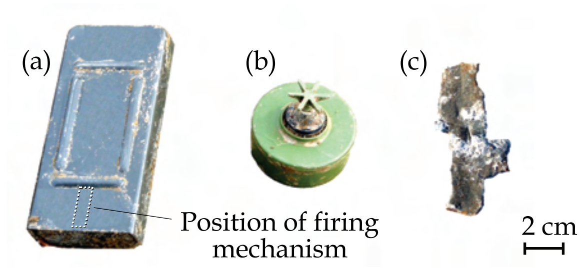

Fig. 15. PMA-1A and PMA-2 landmines, and metal fragment (shown to scale). The metallic part of the PMA-1A mine (the detonator) is not centered within the mine body

Looking at Figure 13, five metallic targets can clearly be recognized in the metal detector image and their locations have been reported on top of the corresponding ground penetrating radar images. Since ground penetrating radar data comes in several different layers, only relevant layers have been displayed; while layer 49 clearly shows correspondence with target #3 identified with the metal detector image, layer 52 allows matching two additional targets: target #2 and target #4. Small positional mismatches can be noticed between the targets identified by the metal detector and ground penetrating radar. Those differences can be explained by looking at table 1: targets #2, #3 and #4 correspond to a landmine type known as PMA-1A, in which the metallic part (the firing mechanism) is not centered within the mine body (cf. Figure 15(a)). While the ground penetrating radar did not detect target #1 (landmine type PMA-2, cf. Figure 15(b)), it detected an additional target (cf. Figure 14(c)) that corresponded, after verification, to some bigger stone buried in the ground. As expected, target #5 (cf. Figure 15(c)), a metal fragment, was not detected by the ground penetrating radar.

Target#	Target type	Depth [cm]	Detected by metal detector	Detected by ground penetrating radar
1	PMA-2	5	Yes	No
2	PMA-1A	12.5	Yes	Yes
3	PMA-1A	12.5	Yes	Yes
4	PMA-1A	12.5	Yes	Yes
5	Fragment	5	Yes	No
6	Stone	~10	No	Yes

Table 1. Target visibility in metal detector and ground penetrating radar images

Out of the 5 metallic targets, 3 could clearly be identified as landmines (detected by both sensors), while the remaining two targets needed further investigation.

3. Mine Hand

In parallel with the development of *Gryphon*, the Tokyo Institute of Technology searched for ways to improve the demining personnel's safety during the most dangerous phase of the demining operation: the manual inspection of a suspected mine location. This phase is particularly dangerous because it requires the deminer to be within a small distance to the potential landmine, typically less than 50 centimetres. This is mainly due to the meagre nature of current prodding tools, often just consisting of a simple metallic stick. This phase of the demining procedure has received little attention from the research community. Trevelyan proposed several simple and inexpensive tools, improving the deminers' safety compared to the traditional tools [Trevelyan, 1997]. However, deminers are still required to work in dangerous proximity to the landmine.

Mine Hand is a tool that was developed with the central idea of having the deminer operate from a remote and protected location for safety reasons (cf. Figure 16): *Mine Hand* is a mechanical master-slave hand allowing prodding the soil and removing landmines and UXOs.

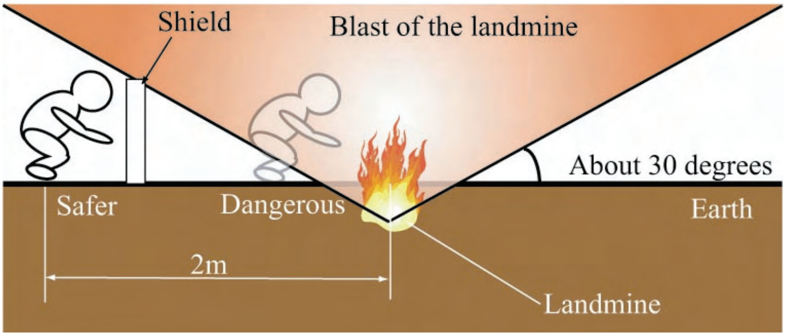

Fig. 16. *Mine Hand*'s concept: keeping the deminer at a safe distance from the landmine

3.1 Early Developments

The first version of *Mine Hand* was a sophisticated mechanical master-slave device [Furihata & Hirose, 2005]. It consists of an arm part and a weight compensation mechanism. The arm part mechanism is illustrated in Figure 17(a). It has two degrees of freedom in the wrist (pitch and yaw), plus one additional degree of freedom in the form of a grasp motion.

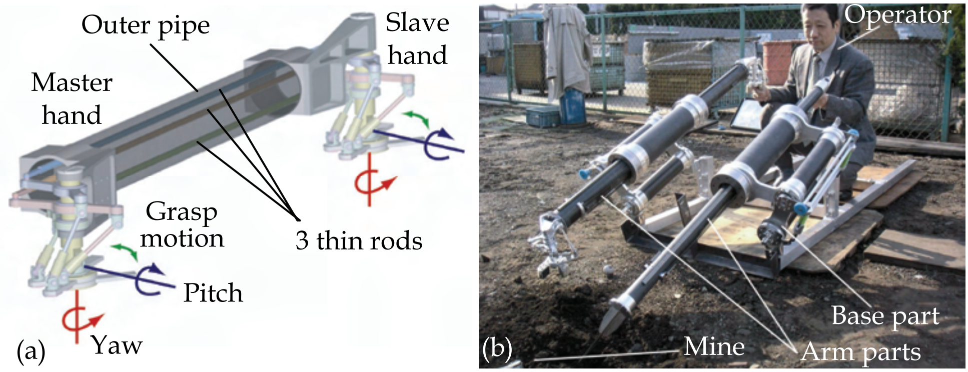

Fig. 17. Early version of *Mine Hand* : arm part (a), overview of the system (b)

Three thin rods, running inside the main pipe, transmit the wrist and grasp motions and allow for good haptic transmission. The weight compensation mechanism, integrated into the base part of *Mine Hand* (cf. Figure 17(b)), supports the arm part while giving it additional 4 degrees of freedom: two translational degrees perpendicular to the arm axis, one translational degree parallel to the arm axis and one rotational degree about the arm axis. A sophisticated weight compensation mechanism based on springs guarantees minimum manipulation effort for the operator. Motion transmission is symmetric, so *Mine Hand* is quite intuitive to use and does not require long training.

3.2 Later Developments

Once the first version of *Mine Hand* was completed, demonstrations and qualitative tests were conducted together with the directors of the *Mine Action Center for Afghanistan*. The following observations were made:

- The three degrees of freedom of the arm part are too complicated to use in severe situations. Much simpler and stronger tools are needed.
- The base part is too heavy. A lightweight and portable tool is preferred.
- The master-slave mechanism does not allow for enough force to be exerted onto the soil, which can sometimes be very hard.

By incorporating the above-mentioned design observations, *Mine Hand* was drastically simplified. As can be seen in Figure 18, its improved version consists of an arm part that goes through a spherical joint incorporated into a transparent shield made of polycarbonate, which has good fracture resistance. The motion of the arm part has four degrees of freedom (one in translation and three in rotation). A fifth degree of freedom is incorporated into the arm in form of a grasp motion. Brushes can be attached to the slave hand, and an exhaust nozzle can be used to blow sand or soil particles away. The basic motions are shown in Figure 18(a) and (b). Although the master and slave side move in opposite directions, a brief training allows overcoming this limitation.

Fig. 18. Simplified *Mine Hand* : translation and roll motion (a), yaw and pitch motion (b), carrying mode (c)

Exploding experiments were conducted with several *Mine Hand*-tools to assess the device's reliability and the operator's safety. Two landmine imitations were used: MS-3 (310g of TNT) and M16A2 (601g of TNT). Although all devices were damaged, they withstood the explosion of the MS-3 landmine imitation: little damage was reported in the shield, and the operator (modelled by a 50 kg sandbag) seems to have experienced no direct effect of the blast. The M16A2 landmine imitation, on the other hand, has severely damaged the shield and the operator experienced an impact force from the *Mine Hand* arm of 2300N.

4. Conclusion

Gryphon and *Mine Hand* are complementary tools; while the former was developed to efficiently search for buried landmines, the latter one is meant to be used once a suspect spot was found to assist and protect deminers in the landmine neutralization task.

Gryphon and *Mine Hand*, more than just research prototypes, were conceived from the beginning on to be practical and well integrated systems. Minefields are no laboratories; working conditions are extremely varied and far from ideal, requiring robust systems, and based on the invaluable experience acquired during field tests, trials and discussions with deminers themselves, *Gryphon* and *Mine Hand* were continuously improved to come closer to practical and useful tools for humanitarian demining.

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10

Mine Detection Robot and Related Technologies for Humanitarian Demining

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1. Introduction

Currently, more than 100 million anti-personnel mines are under the ground all over the world. These mines not only disturb the economic development of mine-buried nations, but also injure or kill more than 2000 people a month. As a result, the removal of landmines has become a global emergency. The current method of removing mines manually is costly and dangerous. Moreover, removal of all mines by this method would require several hundred years (it would takes one thousand according to a CMAC report based on Cambodian Mine Action Center Current Activities 1998), during which time, more mines might be buried in war zones.

There are three kinds of demining strategies. The first is human deminier based demining. The second is mechanical equipment based demining like Fig.1(Geneva International Center for Humanitarian Demining,2002). The third is advanced robot based demining. Currently, the most common demining approach is the first type. The second type is applied in some limited mine field area. The third type is partially tried as mine detection or brush cutting with the exception of research oriented robots and some of them will be expected in future demining approaches. Figure 2 shows the robotic brush cutter which was developed in the Demining Technology Workshop in Cambodia. This robot can cut grass and bush by teleoperation.

Figure 3 shows the four legged mine detection robot which was studied by CSIC-IAI, Spain in 1999(Armada et al.2005). Under this extreme environment, a walking robot may be an effective and efficient means of detecting and removing mines while ensuring the safety of local residents and people engaged in the removal work. The six-legged and crawler type hybrid robot COMET-III(Nonami et al.2003) shown in Fig.4 with two manipulators based on the added stability, mobility, and functionality that this platform offers. This latest robot COMET-III, which is fully autonomous, has been developed by one of this paper’s authors.

Fig. 1. Mechanical demining equipment

Fig. 2. Tempest for brush cutter

Fig. 3. Four legged mine detection robot

Fig. 4. Mine detection robot COMET-III

The total weight is about 1000kg, the size is 4m long, 2.5m wide, and 0.8m high. The COMET-III has 40 litter gasoline tank to continuously work for 4 hours and 700cc gasoline engine like an automobile engine to generate DC power supply and to drive the hydraulic motor. So, the driving force is based on hydraulic power with 14 MPa high pressure and the total power is 25PS. The walking speed on six legs is about 300m/h and the running speed by rubber crawler is 4km/h. Therefore, the COMET-III is a hybrid system and it has two manipulators which are used for mine detection and marking. Also it has a 3D stereo vision camera to make online mapping and trajectory planning, so the COMET-III can be called a fully autonomous mine detection robot. This kind of robot is the third type of demining strategy, based on advanced robotics, and is the future's approach.

Currently our group is participating in the Japan Science and Technology Agency's (JST) Sensing and Access Control R&D for Humanitarian Mine Action project with our effort to develop a small vehicle for mine detection and clearance. This small vehicle is named Mine Hunter Vehicle(MHV). Specifically we were concerned with the development of a 4 degree-of-freedom robot arm which is called as SCARA arm for sensing buried anti-personnel mines. We have divided the project into several tasks to be tackled. Our team, in cooperation with Fuji Heavy Industries and Sato's group from Tohoku University, and Arai's group from University of Electro-Communications has proposed a small teleoperated vehicle-based system. The task of landmine detection is being undertaken by Sato's group at Tohoku University, who are developing an array-style ground penetrating radar (SAR-

GPR). Our group including Fuji Heavy Industries is responsible for the development and control of an arm that the sensor will be mounted on and the mine clearance manipulator.

2. State of the art of Teleoperated Mine Detection by Vehicle Mounted Mine Detector

Conventional vehicle-mounted mine detector systems employ an array of sensors elements to achieve a detection swath typically 2~4m wide. Some systems employ more than one type of sensor technology. These systems, while being very useful are often expensive, complex and inflexible. A human operator, on the other hand, sweeps a mine detector from side to side while moving forward to cover ground. The operator can follow the ground profile with the detector head close to the ground without hitting the ground or any objects on it. The operator can also vary the wide of sweep to suit a particular situation, and is usually not limited by terrain. However the manual method is slow, harzardous, manpower-intensive, and stressful to the operation who, as a result, can perform this task only for short periods at a time. As well, the task is monotonous and at times errors result due to operator inattentiveness.

Canadian Center for Mine Action Technologies (CCMAT) developed the robotic scanner shown in Fig.5 which uses a robotic device capable of autonomously moving a mine detection sensor over natural ground surfaces including roads and tracks in a manner similar to a human operator. Such a device, operated remotely, will increase the safety of the personnel performing mine detection. As well, this will provide a more flexible and less expensive way of sweeping surfaces such as roads and fields than systems which employ a static array of a vehicle-mounted systems. Although several vehicle-mounted systems are protected against conventional antitank mines, they still may require a precursor vehicle to neutralize antipersonnel and tilt-rod mines. For the system proposed by CCMAT, the requirement for protection will be much reduced primarily because mines will be detected ahead of the vehicle without the sensor contacting the ground.

Figure 6 shows the vehicle mounted mine detector (VMMD). The VMMD is a modified small utility vehicle. The VMMD sensor package consists of Ground Penetrating Radar (GPR) and infrared and ultraviolet cameras. The VMMD did well in detecting antitank mines, but had difficulty identifying antipersonnel mines and proved very complicated to operate.

Figure 7 shows the semi-autonomous mine detection system (SAMS). The SAMS is designed to reduce the threat to deminers by remotely detecting, marking and allows towing of a Sciebel Metal Detection Array. SAMS can remotely navigate into minefields to detect, mark,and map buried mines using a metal detection array and differential GPS position location equipment under semi-autonomous remote control.

Fig. 5. Robotic Scanner mounted on teleoperated vehicle[5]

Fig. 6. Vehicle Mine Detector (VMMD)[6]

Figure 8 shows another Vehicle Mounted Detection System (VMDS). The VMDS concept is based on a commercial skid steer chassis modified to incorporate a remote control capability. The VMDS sensor package consists of a 2m wide Sciebel metal detection array, a Thermal-Neutron Analysis (TNA) sensor, and an infrared sensor. The 2meter array detects metal objects in the vehicle's path, while the TNA indicates those targets that contain explosive. In testing, the 2meter detection array performed extremely well. The TNA found most AT mines, but had difficulty identifying AP mines and proved very complicated to operate.

3. Concept and Implementation of Mine Hunter Vehicle (MHV)

As above mentioned, our group was participating in the JST Sensing and Access Control R&D for Humanitarian Mine Action project with our effort to develop a small vehicle for mine detection and clearance. This small vehicle is named Mine Hunter Vehicle (MHV) and is equipped with mine detection sensors. The general design considerations were as follows;

(1) A robot that can be loaded into 2 ton vehicles.
(2) Division is easy.
(3) The weight of the main part of the vehicles is 1100kg - 1500kg.
(4) It has an environment-proof nature, able to carry out a certain operation in the climate of Afghanistan.
(5)The vehicle can climb up and down slopes in mountain regions.
(6)The vehicle has durability against blasts from antipersonnel mines.
(7)A reliable control device should be developed.
(8)Both front detection and side detection are possible.

The design specification of the main body of MHV was as follows;

(1) Simple body structure
(2)45-degree slope climbing capability, and spin turn.
(3)Durability and reliability test of an engine system, a drive system, and axle part
(4)Development of the axle which can easily fitted with crawlers or tires
(5)Durability and reliability test of bulletproof equipment of an anti-personnel mine level

(6)Durability and reliability test of the protection-against-dust nature which prevents invasion of minute sand etc. into flexible regions
(7)Development of a reliable controller, a remote control, and image transmission equipment

The body full length of MHV is 2.8m, and when the sensor arm is lengthened, it is 4.5m. The width of vehicle is 1.5m in the case of crawler, and is 1.6m in the tire. The height of vehicles is 1.9m in the crawler, and is 1.8m in the tire. The full weight is 1650kg including SCARA arm. The drive is a diesel engine and a HST (Hydraulic Static Transmission) system. Four independent crawlers are attached to the front right, the front left, the back right, and the back left. The engine was selected to be applicable to the 2,000m high elevation in Afghanistan. The left-hand side crawler (front, rear) and right-hand side crawler (front, rear) have a separate hydraulic pump and the hydraulic circuits are independent of each other. Furthermore, MHV crawlers can rotate in ±25 degrees centering on an axle. Because of this reason, the slip of the crawlers on road surfaces decreased and it became easier to negotiate irregular ground and ascend and descend sloped ground. Changing between crawlers and tires can be down easily by removing eight bolts, like changing a tire of a normal car. A high-strength steel plate of 4.5mm was attached in front with the bolts. The rotation part of the axles are bush bearings strong against shock and do not require lubirication, however in order to prevent sand and dust from invading the bearings, oil seals are attached to both sides. Even if the axles are submerged in water, there will be no leak.
The control device consists of modules which include the controller for hydraulic pressure, a proportionality electromagnetic valve driver, a remote control, image transmission equipment, manipulator control equipment and the controller equipment of a mine detection sensor. In failure, in consideration of maintenance nature, correspondence was made possible by module provision. The body became heavier as a result of strengthening, better waterproofing, protection against dust, and bulletproofing. As a result, the target weight limit was set to 1,600kg. The engine power is 39PS, and the hydraulic pressure is $180kg/cm^2$

The design specification of the sensor arm of MHV is as follows;
(1) In order to secure horizontal accuracy of position for a wide working range, a horizontal SCARA (Selective Compliance Assembly Robot Arm) robot arm with multiple joints was adopted.
(2) Reduction gears were made into the plunocent rucksack system instead of a harmonic drive to minimize vibration.
(3) The sensor arm itself has a waterproof level of IP30. For this reason, the whole arm was dressed with the jacket and waterproofing and protection against dust were secured.
(4) In order to always keep the direction of a mine detection sensor constant, a timing belt was used to move a joint in synchronization with the rotation of the arm..
(5) The SCARA arm has four-degeree-of-freedom. Two-degree-of-freedom are horizontal, one is the perpendicular, and one is the yaw of the sensor. Also they are driven by AC servo motors.
(6) The maximum payload is 40kg. Each arm length is 80cm. The maximum speed at a tip

is 10 m/min and repetition positioning accuracy is ±1mm in the horizontal direction and ±1mm in the perpendicular direction.

(7) The maximum payload size is 400mm x 400mm x 400mm, and the SCARA arm full weight is 150kg.

(8) GPR and a metal detector are installed at the tip of the SCARA arm, with gap control used for the metal detector and gap control used for the GPR.

The system consists of three parts which are control for the main body of MHV, SCARA arm control, and the mine detection sensor. Figures 7 and 8 show the field test in Sakaide city, Kagawa prefecture in March,2006. Also, the performance of MHV was carried out in March, 2007, Croatia.

Fig. 7. Mine Hunter Vehicle with two manipulator

Fig. 8. Mine detection test of MHV

After this, the controlled metal detector installation schedule on MHV is explained in detail. And then, the current state of development in the anti-personnel mine exposure and clearance system is described, focusing on the robot arm. In particular, we have achieved the reasonable performance of a 6-degree of freedom robot with multi-function tool by means of nonlinear control based on “LOOK AT TABLE” scheme or control theory scheme and also the master-slave hand.

4. Controlled Metal Detector Mounted on Mine Detection Robot

4.1 Overview

Metal detectors are considered as the most reliable sensors for mine detection work. However, landmine detection performance of the metal detectors is highly dependent on the distance between the sensor heads and the buried landmines. Therefore, the landmine detection performance of the metal detectors could be substantially improved if the gap and attitude of the sensor heads can be controlled. In case of robots assisted land mine detection, this function can be performed in a convenient manner where the sensor heads should accurately follow the ground surface maintaining almost uniform gap between the ground surface and the sensor heads by controlling the gap and attitude of the sensor heads. Few mine detection robots that have the capability to recognize ground surface and can control

the gap and attitude of the sensor heads are reported in (Armada, M.A. et al. 2005), (Chesney, R. et al. 2002), (Nonami, K. et al. 2003).
However, to the best of the knowledge of the authors, no research work has been reported in the literature that quantitatively addressed the relationship between the landmine detection performance and controlling the gap and attitude of the sensor head to the ground surface.
The CMD system adopts 3-D stereovision camera rather than LASER scanning as a range sensor because 3-D stereovision camera can capture color information also. Ground of real minefield may have substantial amount of vegetation. Therefore, some image-processing algorithm could be applied with the color images captured by the CCD cameras for recognition of the vegetation to autonomous operation of the CMD in vegetated minefield in future work.
The trajectories are generated by the CMD in such a manner that any obstacle or possible impact with the ground can be avoided. The CMD then tracks the generated trajectories by a trajectory-tracking controller so that the sensor head can follow the ground surface. The effectiveness and the impact related to the gap and attitude control on the mine detection performance of the CMD have been demonstrated by experimental studies.
The rest of the paper is organized as follows. The description of the controlled object has been presented in section 4.2. The kinematic analysis of the CMD has been presented in section 4.3. The description of stereovision camera has been presented in section 4.4. The description of trajectory planning has been presented in section 4.5. The results of experiments of trajectory tracking have been presented in section 4.6. The results of experiments of mine detection have been presented in section 4.7, 4.8. The some conclusions have been presented in section 4.9.
In view of the above, authors' research group has developed a Controlled Metal Detector (CMD) having 3-DOF for any arbitrary positioning of the sensor head. The CMD system can generate 3-D high-speed mapping of the ground surface and can generate trajectories of the sensor head with 3-D stereovision camera. 3-D stereo vision is now being widely used for 3-D mapping and robotics (Clark, F. et al. 2007), (Rochaa, R. et al. 2005), (Xiao, D., et al. 2004) for their powerful sensing capability than other range sensors.

4.2 Controlled Object

The controlled object of this research is called Controlled Metal Detector (CMD). It consists of the two-coil metal detector and a 3-DOF mechanical manipulation mechanism driven by electric motors. The overview of the CMD system is shown in Fig.9. The experimental setup is composed of the main body of the CMD, two PCs, 3-D stereovision camera and a XY-stage as shown in Fig.10. The XY-stage *can perform* the two-dimensional motion in horizontal directions.
The schematic diagram of the CMD is shown in Fig.11. The CMD has 3-DOF composed of three motorized linkages (Link 1, Link 2, and Link 3). The ball screws on these links convert the rotational motion into translation motion. The gyrations of pitch and roll, and movement in vertical direction of the sensor head are performed by controlling the lengths of the Link 1, Link 2 and Link 3. The right-handed coordinate system $\{O_b\ X_b\ Y_b\ Z_b\}$ associated with the CMD is described in Fig.11. The lengths l_1, l_2 and l_3 (of Link 1, Link 2 and Link 3 respectively) are measured with encoders installed in each link. The calculation methods are described in next section.

The CMD is mounted on the horizontal positioning arm of the XY-stage at the point P_a. Therefore, the point P_a does not move vertically. After the synchronization of the CMD and the horizontal positioning arm of the XY-stage, it is possible to make the sensor head to follow the target trajectories generated with 3-D stereovision data. Moreover, the CMD has no metallic parts within 600 mm from the sensor head; this practically eliminates any chance of interference on the metal detector. Table 1 shows the specifications of the CMD.

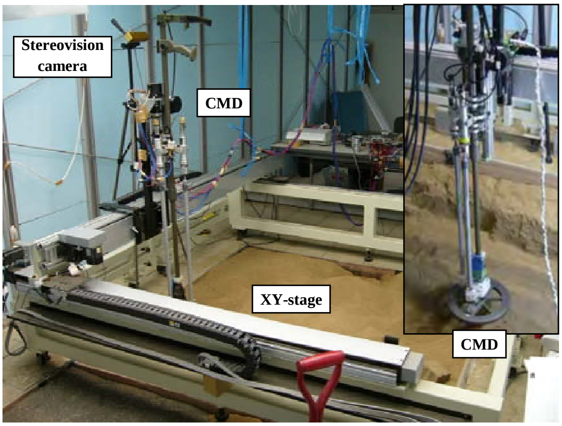
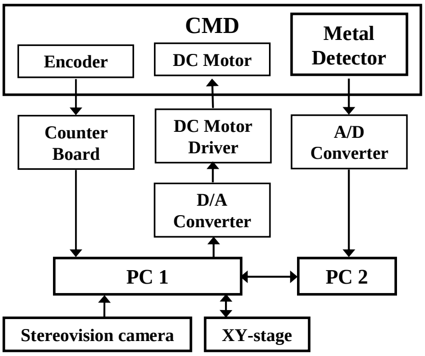


Fig. 9. Overview of CMD system



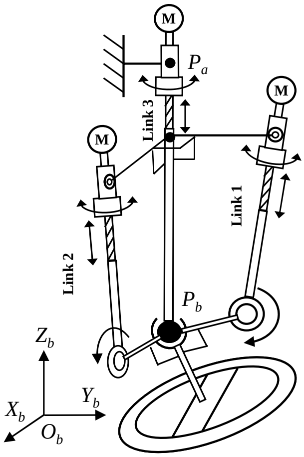


Fig. 10. Architecture of CMD system

Fig. 11. Configuration of CMD

4.3 Kinematic Analysis

The movements of Link 1 and Link 2 are restrained in the perpendicular plane because there is a ditch on the ball joint P_b. The geometrical relationship between the lengths l_1, l_2 and the

Item	Value	Remarks
Length [mm]	1500	Basic position
Width [mm]	282	
Weight [kg]	10	
Degree of freedom	3	
Stroke speed (max) [mm/s]	100	Link 3
Stroke width [mm]	180	Link 3
Angular velocity (max) [deg/s]	10	Pitch, Roll
Angle range [deg]	± 15	Pitch, Roll
Length of l_4 [mm]	835	
Length of l_5 [mm]	80	

Table 1. Specifications of CMD

pitch angle θ_x, roll angle θ_y of the sensor head shown in Fig. 12 In the CMD system, in order to ensure that the sensor head follows the ground surface without any collision, the trajectory of the attitude of the sensor head and the required change in l_3 are calculated with 3-D vision data. Then the changes in lengths l_1, l_2 are calculated from the inverse kinematics as shown below (1) and (2).

$$l_1 = \sqrt{l_4^2 + 2l_5^2 - 2l_5 L \sin(\theta_x + \arctan\frac{l_5}{l_4})} - l_4 \tag{1}$$

$$l_2 = \sqrt{l_4^2 + 2l_5^2 + 2l_5 L \sin(\theta_y - \arctan\frac{l_5}{l_4})} - l_4 \tag{2}$$

Moreover, the direct kinematics is as follows.

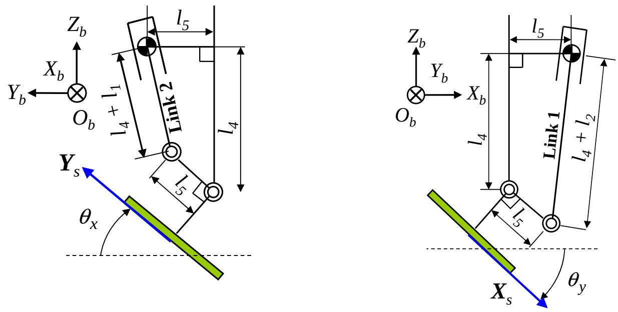
$$\theta_x = -\arctan\frac{l_5}{l_4} + \arctan\frac{-l_1^2 - 2l_1 l_4 + 2l_5^2}{2l_5 L} \tag{3}$$

$$\theta_y = \arctan\frac{l_5}{l_4} + \arctan\frac{l_2^2 + 2l_2 l_4 - 2l_5^2}{2l_5 L} \tag{4}$$

Where l_4 and l_5 are lengths of links, and $L = \sqrt{l_4^2 + l_5^2}$. Moreover, attitude vectors $\boldsymbol{X}_s$, $\boldsymbol{Y}_s$ of the sensor head are defined as $\boldsymbol{X}_s = [\cos\theta_y, 0, -\sin\theta_y]^T$, $\boldsymbol{Y}_s = [0, \cos\theta_x, \sin\theta_x]^T$ with attitude angles θ_x, θ_y.

4.4 Ground Mapping with 3-D Stereo Vision

The commercial stereovision camera, called Bumblebee (Point Grey Research Inc.), has been used for 3-D stereovision based ground mapping. This stereovision camera uses a parallel stereo method. Table 2 shows the specifications of the stereovision camera. Where the coordinate system consists of: the original point and the Z_c axis are taken the optical center and the optical axis of the left camera, the X_c axis and the Y_c axis are taken the horizontal axis and the vertical axis of the left image, is defined as the camera coordinate system $\{O_c\}$.



(a) Pitch of CMD (b) Roll of CMD

Fig. 12. Geometry of CMD

The stereovision algorithm searches for correspondence points between the left image and the right image acquired with the stereovision camera by the template match. The camera coordinate $[x_c, y_c, z_c]^T$ of point P in the 3-D space is decided from correspondence points p, p' in the right and left images as follows.

$$x_c = \frac{x_l B}{x_l - x_r}, y_c = \frac{y_l B}{x_l - x_r}, z_c = \frac{fB}{x_l - x_r} \tag{5}$$

Where the positions of correspondence points p and p' on the right and left images are defined as (x_l, y_l), (x_r, y_r).

As a result, geographical features information in the camera coordinate system is acquired. Therefore, depth information $f_a(x, y)$ on the ground surface in the base coordinate system is generated with the coordinate conversion. Here a photograph of the detection area as an example is shown in Fig. 13, and the 3-D geographical features map is shown in Fig. 14.

Item	Value
Device size [mm]	160(W)×40(H)×50(D)
Weight [g]	375
Baseline [mm]	120
Focal length [mm]	6
Pixels	320(H) × 240(V)
view angle [deg]	50

Table 2. Specifications of stereovision camera

Fig. 13. Detection area

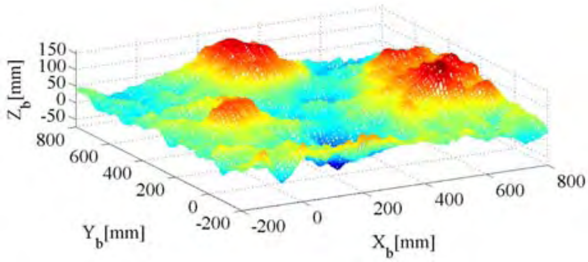


Fig. 14. 3-D mapping

4.5 Trajectory Planning with 3-D Vision Data

The trajectory planning is produced by the off-line. Namely, at first, the 3-dimensional map for the detection area like 1m × 1m will be produced by means of the stereovision based image processing, and then, the trajectory planning will be automatically done. The target trajectory has been generated from the depth information acquired with 3-D stereovision. However, the raw depth information from the stereovision camera contains large data volume and also noise. This large volume of data is inconvenient for the trajectory planning. Therefore, a working depth information $f(n_1, n_2)$ has been generated from the original depth information $f_a(x, y)$ provided by the stereovision camera after sampling it at a grid interval d_g. Thus, the working depth information $f(n_1, n_2)$ can be written as:

$$f(n_1, n_2) = f_a(n_1 d_g, n_2 d_g) \tag{6}$$

Where n_1 and n_2 are assumed integers. This working depth information $f(n_1, n_2)$ on the grid has been used in the trajectory planning algorithm.

Figure 15 shows the trajectory of the mounting point P_a of the CMD on landmine detection area ($l_x \times l_y$). The point P_a moves parallel to the X_b - Y_b axis with velocities v_x and v_y respectively. Here, it is necessary to change the velocities of the point P_a depending on the ground surface. However, during the experiment the velocities v_x and v_y are kept equal because of the technical limitations of the XY-stage.

During the trajectory planning, first the position and attitude angles of the sensor head are decided on each grid point of $f(n_1, n_2)$; then these discrete points in the space are connected by straight lines to generate a continuous trajectory. The following objectives are to be satisfied during the trajectory planning:

1. The sensor head keeps itself approximately parallel to the ground surface.
2. The collision between the sensor head and the ground surface is avoided.

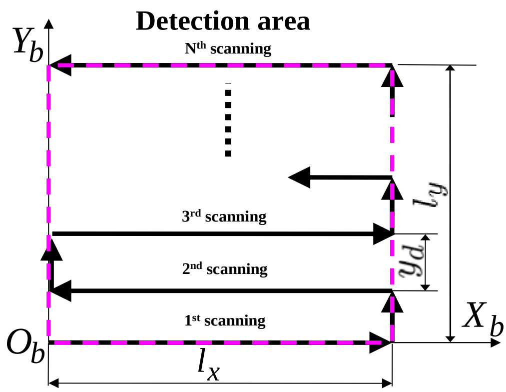


Fig. 15. Trajectory of XY-stage

4.5.1. Decision of Attitude Angles

The target attitude angles θ_x *and* θ_y of the sensor head that fulfill the first objective stated earlier can be obtained from the depth information as the inclinations of the ground surface. The X_b axial inclination at the grid point (n_1, n_2) of the ground surface is decided by the least square method as follows.

$$\theta_y = \frac{n_s \sum_{i=1}^{n_s} x_i z_i - \sum_{i=1}^{n_s} x_i \sum_{i=1}^{n_s} z_i}{n_s \sum_{i=1}^{n_s} x_i^2 - \left(\sum_{i=1}^{n_s} x_i \right)^2} \tag{7}$$

$$\begin{cases} n_s = (2k_s + 1) \\ x_i = n_1 - k_s + i \\ z_i = f(n_1 - k_s + i, n_2) \end{cases} \tag{8}$$

θ_x is similarly decided. Where k_s is defined as an inclination coefficient of determination. However, the target attitude angles are decided in restrictions. One of the restrictions are is the movable ranges of the mechanism. Another one is the limits of attitude movements θ_{dx} and θ_{dy} between each grid point that consider the passing velocity, v_x and v_y, of the point P_a. The limits of the attitude movements θ_{dx} and θ_{dy} are shown below. Where ω_{MAX} shows the maximum angular velocity.

$$\theta_{dx} = \pm \frac{\omega_{MAX} d_g}{v_x}, \theta_{dy} = \pm \frac{\omega_{MAX} d_g}{v_y} \tag{9}$$

4.5.2. Decision of Length of Link 3

Length l_3 of Link 3 that fulfills the second objective stated earlier is decided with the attitude angles. When the position of the point P_a is $\boldsymbol{P}_a = [n_1 d_g, n_2 d_g, P_{az}]^T$, the position of the center point of the ball joint P_b is $\boldsymbol{P}_b = [n_1 d_g, n_2 d_g, P_{az} - d_z - l_3]^T$. Where the fixed height of the point P_a is assumed to be P_{az}. Moreover, the distance between the point P_a and the point P_b in the basic stance is assumed to be d_z. Where position $\boldsymbol{S}$ at the center point S on the sensor head's bottom is as follows with attitude vectors $\boldsymbol{X}_s$ and $\boldsymbol{Y}_s$ on each grid point.

$$\boldsymbol{S} = l_s \frac{\boldsymbol{Y}_s \times \boldsymbol{X}_s}{\left|\boldsymbol{Y}_s \times \boldsymbol{X}_s\right|} + \boldsymbol{P}_b \tag{10}$$

Where l_s is defined as the distance between the point P_b and the point S. At this time, all the points on the sensor head's bottom keep a distance more than a safety allowance l_{mar} to the ground surface. Therefore maximum length l_3 is decided as filled above. However, l_3 is decided in the restriction of the movable range of the mechanism.

4.5.3. Re-decision of Length of Link 3

Because this trajectory planning targets at minefield, the length l_3 of Link 3 is decided again so that the sensor head does not touch the ground surface in spite of the delay is caused in each response of the Links.

On the i_{th} grid point of the trajectory that XY-stage passes, the position of the point P_a is assumed to be $\boldsymbol{P}_a(i) = \left[n_1(i)d_g, n_2(i)d_g, P_{az}\right]^T$, the pitch angle and the roll angle of the sensor head are assumed to be $\theta_x(i)$, $\theta_y(i)$ and the length of Link 3 is assumed to be $l_3(i)$.

In the present research, the CMD does the following three operations at the same time.

1. Attitude changes of the sensor head
2. Vertical motions of the sensor head
3. X_b and Y_b axial motions by XY-stage

Here the length $l_3(i)$ of Link 3 is decided again so that the CMD safely accommodate the time delay caused by these three operations. Here, these three operations are assumed to be completed by the arrival time d_g/v_x, d_g/v_y to the next grid point.

The length $l_3(i)$ is decided again so that all the points on the sensor head's bottom may keep the gap to the depth information on the grid point more than the safety allowance l_{mar} as shown in Fig. 16, evenif the points P_a is at $\boldsymbol{P}_a(i\text{-}1)$ and $\boldsymbol{P}_a(i\text{+}1)$ with the target attitude angles of the sensor head of the i_{th} grid point. Thus, the collisions with the ground surface caused by the delay of the response can be avoided. However, $l_3(i)$ is decided in the restriction of the movable range of the mechanism and the limits of the expansions l_{dx} and l_{dy} between each grid point that consider the passing velocity, v_x and v_y, of the point P_a. The limits of the expansions l_{dx} and l_{dy} are shown below. Where v_{MAX} is assumed the maximum expansion velocity of Link 3.

$$l_{dx} = \frac{v_{MAX} d_g}{v_x}, l_{dy} = \pm \frac{v_{MAX} d_g}{v_y} \tag{11}$$

Figure 17. shows an example of the generated target trajectory at the center of the sensor head's bottom.

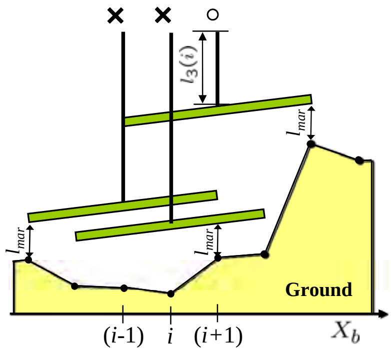


Fig. 16. Decision of l_3

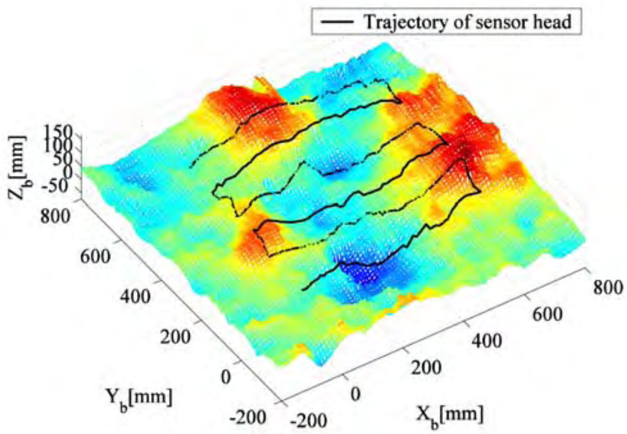


Fig. 17. Trajectory generation

4.6 Experiments of Trajectory Tracking

The trajectory following experiments of the CMD are conducted over the detection area (600 mm × 40 mm) shown in Fig. 18. 3-D range information of the detection area is acquired with the stereovision camera in the experiment and the target trajectory is generated using the methods stated earlier. Here each control input to the motor drivers of the CMD is generated with PID controller of feedback control system so that each expansion of the Links follows to the target trajectory. Where the sampling frequency is taken as 50 Hz. Moreover, each gain of the PID controller is shown in Table 3, and each parameter in the trajectory planning is shown in Table 4.

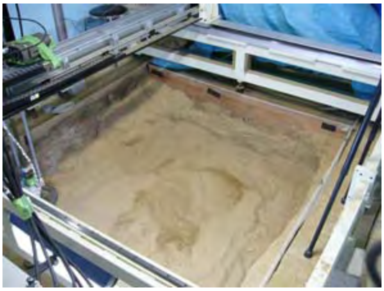


Fig. 18. Detection area for experiment

Link	P	I	D
Link 1	1.5	2.5	0.01
Link 2	3.0	12.0	0.1
Link 3	3.0	12.0	0.1

Table 4. Parameters of trajectory generation

v_x	v_y	y_d	l_{mar}	d_g	k_s
50mm/s	10mm/s	40mm	10mm	10mm	10

Table 3. Gain of PID controller

4.6.1. Experimental Result

Figure 19 showed the generated target trajectory and the result at the center of the sensor head's bottom in the experiment. Fig. 20 showed the time change of the vertical minimal gap between the sensor head's bottom and the ground surface. Fig. 20 shows not real data, but the final data after signal processing in the PC. In addition, these spike peaks are caused by the discrete data like Fig.16. Moreover, the target trajectory and the response of each expansion of Link 1, Link 2 and Link 3 from the experiment beginning for four seconds are shown in Fig. 21.

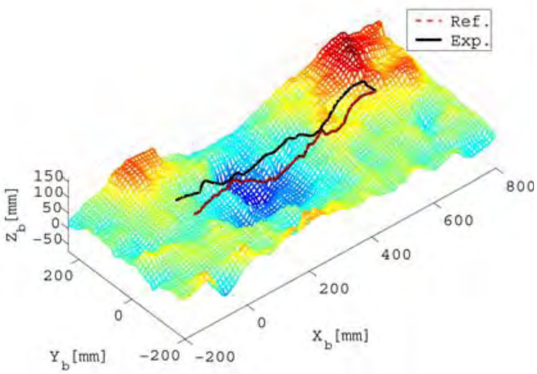


Fig. 19. Trajectory of sensor head

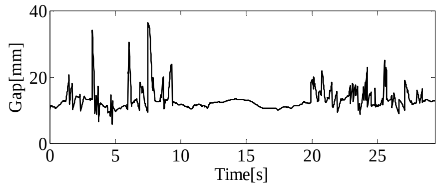
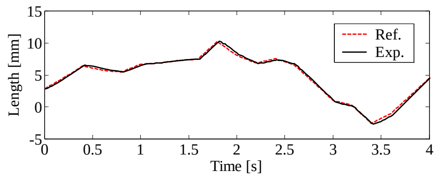
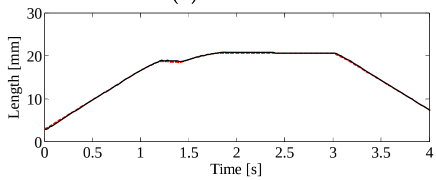


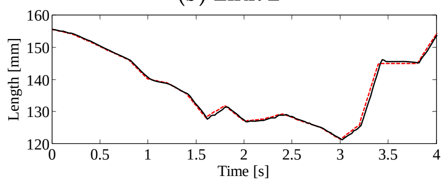
Fig. 20. Gap between sensor head and ground surface



(a) Link 1



(b) Link 2



(c) Link 3

Fig. 21. Trajectory responses of links

4.6.2. Consideration

From Fig. 19, it is obvious that the sensor head follows the generated target trajectory very well. In addition, the sensor head almost keeps the gap more than the safety allowance l_{mar} (Fig. 20) during the detection work, and the trajectory that fulfills the target specifications without contact with the ground surface has been achieved. The safety allowance defined as l_{mar} = 10 mm was appropriate in this experiments. Moreover, each link has an excellent trajectory following performance with a small overshoot and delay respectively as shown in Fig. 21.

4.7 Methods of Estimating the Position of Buried Landmines

Estimating the position of the buried landmines with the data of landmine detection sensors is important in detection work by mine detection robots. The metal detector used in this research has a property that the frequency of the output changes before and after the metal detector mounted on the CMD is passing over a buried metallic object. By using this property, the output signal from the metal detector is converted to a negative value when a landmine exists on the right side from the center of the sensor head along the X_b axis, and to a positive value when a landmine exists on the left side from the center of the sensor head along the X_b axis. The position of the buried landmine is estimated with the processed output of the metal detector.

This section shows the method of estimating the buried position that is confined to the case of the detection area with only one buried landmine. The sensor head is scanned X_b axially in N times in each landmine detection experiment in this research as shown in Fig. 15. In each X_b axially scanning, the strength of the metal reaction: m_i and candidate position of the buried landmine: $[x_i, y_i]$ are decided with the output of the metal detector. After all (N times) scanning finished, the estimated position of the buried landmine is decided with each strength of the metal reaction and each candidate position of the buried landmine as follows.

$$[x, y] = \left[\frac{\sum_{i=1}^{N} m_i x_i}{\sum_{i=1}^{N} m_i}, \frac{\sum_{i=1}^{N} m_i y_i}{\sum_{i=1}^{N} m_i} \right] \tag{12}$$

Where in the i^{th} scanning, the candidate position of the buried landmine $[x_i, y_i]$ is decided as the middle point of the positions in which the metal reactions pass the threshold V_d[V] or -V_d[V] along the X_b axially with keeping the output increases. In addition, the strength of the metal reaction m_i is assumed a difference between the maximum and minimum values in neighborhood at the candidate position as shown in Fig. 22. Where it is assumed that V_d = 0.2 V and N = l_y / y_d + 1 in this research.

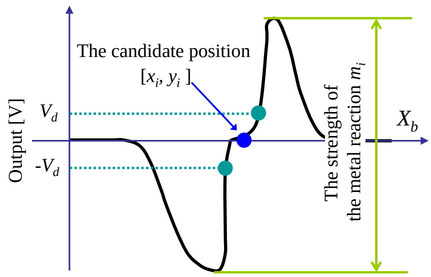


Fig. 22. Definitions of the candidate position (i^{th} scanning)

4.8 Experiments of Mine Detection

Various roughnesses are given to detection area ($l_x \times l_y$) of sands shown in Fig. 18, and the landmine detection experiments by the CMD are conducted. The position of the buried landmine is estimated with acquired data of the metal detector, and effectiveness of the gap and attitude control of the sensor head to landmine detection performance is verified. Here the control method is assumed same to the experiments of trajectory tracking in section 4.6.

4.8.1. Experimental Conditions

Three kinds of trajectories are defined in this experiment to verify effectiveness of the gap and attitude control to landmine detection performance and they are compared. Where Case

1 is a target trajectory that fixes the sensor's posture horizontally with keeping the safety allowance l_{mar} to the highest point of the detection area. Case 2 is a target trajectory that fixes the sensor's posture horizontally, and controls only the gap between the sensor head and the ground surface. Case 3 is a proposed target trajectory that controls the gap and attitude of the sensor head to the ground surface.

The buried landmines are the mostly antipersonnel landmines all over the world, PMN2 (□ 125 mm × 54 mm), made of plastic in Fig. 23 (a) and have some metallic parts. Depths of the buried landmines are defined as the distance between the ground surface and the upper surface of the landmines as shown in Fig. 23 (b). In addition, the buried position was assumed to be $[x, y]$ = [300 mm, 300 mm] on base coordinate system.

About conditions concerning the ground surface, a smooth ground surface is defined as area A, the ground surface, where the position of the buried landmine is slopes, is defined as area B and the ground surface, where it is the valley part of two mountains, is defined as area C.

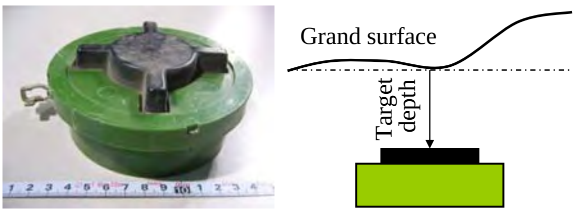
Moreover, roughness of the ground surface is assumed to be shown in based on the roughness of the extent that the sensor head can accurately follow. The depth information $f(n_1, n_2)$ on the grid is assumed an original curved surface. Moreover the curved surface obtained from the original curved surface with the lowpass filter, the cutoff wave length 40 d_g [mm], is defined as the average curved surface $W(n_1, n_2)$. Therefore, the root-mean-square roughness R_s in the ground surface is defined as follows.

$$R_s = \sqrt{\frac{1}{(l_x/d_g+1)(l_y/d_g+1)} \sum_{n_1=0}^{l_x/d_g} \sum_{n_2=0}^{l_y/d_g} R^2(n_1, n_2)} \tag{13}$$

Where l_x/d_g, l_y/d_g are made to become to the integer and rough curved surface $R(n_1, n_2)$ is defined as follows.

$$R(n_1, n_2) = f(n_1, n_2) - W(n_1, n_2) \tag{14}$$

In this experiment, the range of the detection area is assumed to be l_x = 600 mm and l_y = 600 mm, and each parameter is assumed to be same shown in Table 4. Table 5 shows the root-mean-square roughness R_s and the depth of the buried landmine in this experiment.



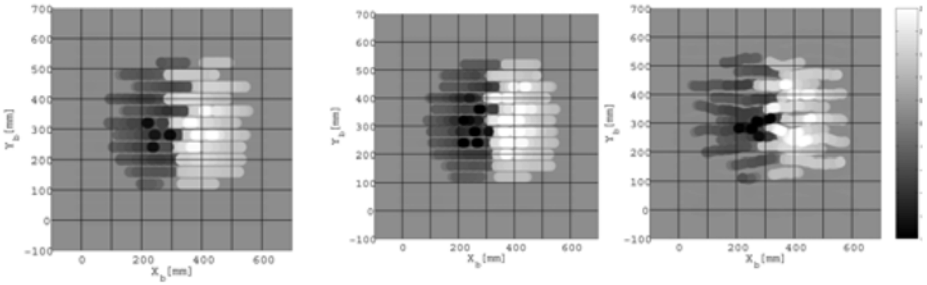
(a) PMN2 (b) Target depth

Fig. 23. Target mine

4.8.2. Experimental Result

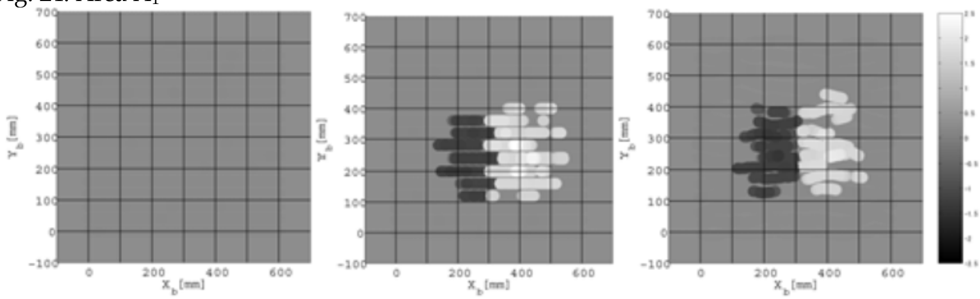
The results of the landmine detection experiments in each detection area were shown in Fig. 24-29. In these figures, the processed outputs of the metal detector were plotted at the trajectory of the center of the sensor head's bottom.

The larger absolute values of the outputs showed that the distances between the sensor head and the buried landmines were shorter.
Moreover, the estimated positions of the buried landmines in each detection area by the method of the description in section 4.7, were shown in Table 6. In addition, in Table 7, these values were the integrated absolute values of the outputs of the metal detectors at the detection time to show the effectiveness of the gap and attitude control. Where relative values were indicated, in which the values of Case 3 were assumed 100.



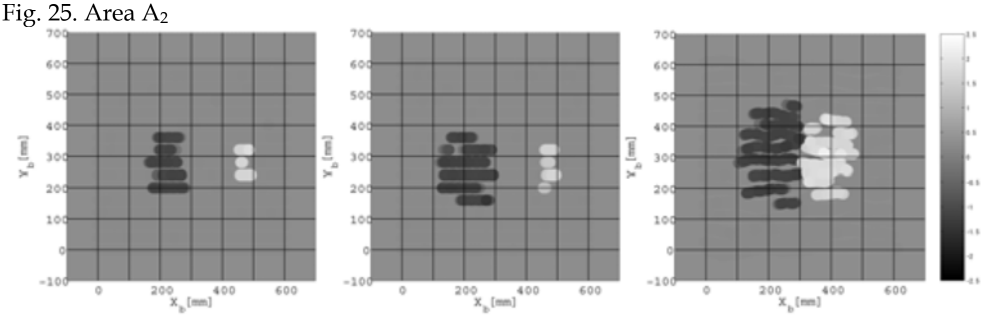
(a) Case 1 (b) Case 2 (c) Case 3

Fig. 24. Area A_1



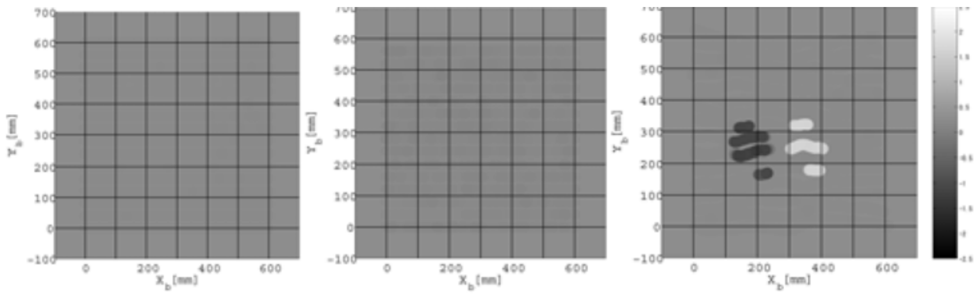
(a) Case 1 (b) Case 2 (c) Case 3

Fig. 25. Area A_2



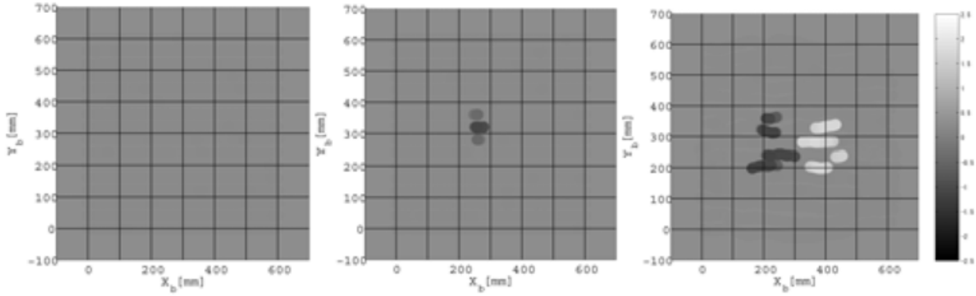
(a) Case 1 (b) Case 2 (c) Case 3

Fig. 26. Area B_1



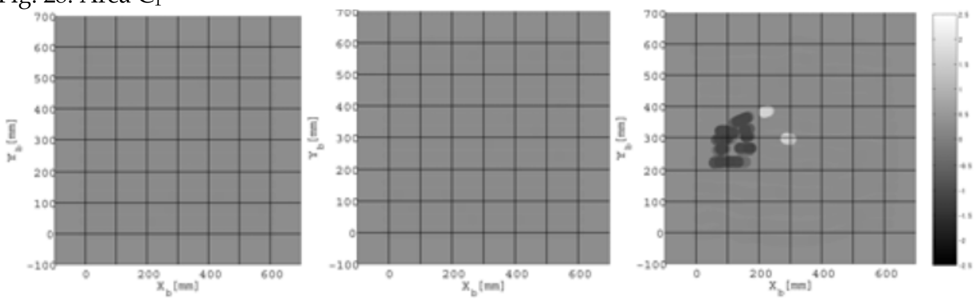
(a) Case 1 (b) Case 2 (c) Case 3

Fig. 27. Area B_2



(a) Case 1 (b) Case 2 (c) Case 3

Fig. 28. Area C_1



(a) Case 1 (b) Case 2 (c) Case 3

Fig. 29. Area C_2

Detection Area	Roughness(RMS)[mm]	Depth[mm]
Area A_1	8.5	50
Area A_2	8.9	120
Area B_1	9.2	120
Area B_2	10.7	120
Area C_1	10.4	120
Area C_2	11.5	120

Table 5. Specifications of detection area

$[x,y]$	Case 1	Case 2	Case 3
Area A_1	[322.5,315.5]	[324.1,321.1]	[319.9,321.4]
Area A_2	NaN	[310.3,252.6]	[319.1,272.1]
Area B_1	[337.5,280.7]	[344.1,259.9]	[309.3,312.6]
Area B_2	NaN	NaN	[263.7,250.7]
Area C_1	NaN	[270.7,319.4]	[312.9,270.3]
Area C_2	NaN	NaN	[192.7,310.2]

Table 6. Estimated position of landmine

	Case 1	Case 2	Case 3
Area A_1	92.5	97.0	100
Area A_2	1.4	96.5	100
Area B_1	24.0	36.1	100
Area B_2	7.4	21.8	100
Area C_1	7.8	14.7	100
Area C_2	8.4	8.4	100

Table 7. Numerical integration value of metal detector

4.8.3. Discussion

In the detection areas except Area A_1 where the depth of buried landmine is shallow, the metal reactions of Case 1 without the gap and attitude control are small, so the landmine detection performance is obviously inferior. It is clear that the gap control of the sensor head is necessary and indispensable in mine detection robots.

In the following, Case 2 and Case 3 are considered. The attitude change in Case 3 is small in a smooth ground surface, so the difference in the detection performance according to two methods, is small as shown in Fig. 24, Fig. 25 and Table 7. The buried position of both Case 2 and Case 3 can be estimated with good accuracy.

If the roughness of the slope is small, the result of Case 3 resembles a metal reaction in a smooth ground surface as shown in Fig. 26. Because the sensor head becomes parallel on the slope in Case 3.

When the ground surface is rough as shown in Fig. 27-29, the metal reaction is lost in Case 2 that is not able to change the attitude. While the metal reaction is clear in Case 3. It is shown to be able to estimate the position of the buried landmine.

As for this result, effectiveness of the gap and attitude control to the landmine detection performance is clearly shown also in Table 7. However, the error is greatly caused in the estimated position of the buried landmine according to the result of Area C_2. Because the gap is greatly caused at the center of the sensor head's bottom, when the attitude angle grows. It is a disadvantage in the attitude control.

4.9 Conclusions

In the present investigation the development of a Controlled Metal Detector (CMD) for controlling the gap and attitude of the sensor head has been presented. The trajectory planning of the sensor head with 3-D stereovision has been carried out for controlling the gap and attitude of the sensor head to the ground surface. The safety margins considered during the development of the trajectory planning algorithm makes it robust against any accidental collision of the sensor head when it is intended to scan an uneven mine affected area. The trajectory planning algorithm makes all efforts to control the gap and attitude of the sensor head such that it follows the uneven ground surface that is conducive for the mine detection by the metal detector. The experimental results presented in this paper exhibit the effectiveness of the CMD for buried landmine detection over uneven ground.

5. Control and Operational of a Teleoperated and Master-Slave Hydraulic Manipulator for Landmine Prodding and Excavation

The focus of the MHV, shown in Figs.7 and 8, has since shifted to being primarily a sensor platform. A high landmine detection rate was the foremost goal of the JST project, and the importance of sensing is evident in the number of sensing robots that have been developed in recent years, but the fact remains that the majority of demining accidents occur during prodding, where deminers do the work manually with a prod or knife, and a little fatigue or momentary breach of SOP can be disastrous. To eliminate the personal risk inherent in prodding, there is need for a small machine that can prod where sensors have detected a possible mine in situations where large flail machines cannot be used.

The aim of this work is to develop a practical machine that can be readily put to work in the field. It is being developed with the following key considerations:

- The machine should be easy to use, with a simple and intuitive user interface; the operator should not require a lot of training time to become proficient.
- It should maintain a speed comparable to manual prodding.
- It should be robust and reliable.

The complete system will require motion control for positioning the arm, and some form of force compliance control for work involving contact with the ground. The scope of this paper is limited to an overview of the system and no-contact motion control of a single joint of the arm. In this section, we first give a description of the tool arm. The envisioned typical operation is then described. Then a short description of the user interface is given along with motion reference generation.

Figure 30. shows the 6-degree-of-freedom hydraulic tool arm, from here called the manipulator. The configuration of the joints and links is shown in Fig. 31. The manipulator's end effector is equipped with a drill for breaking up hard soil, an air jet for clearing loose soil, an electromagnet for collecting small metal fragments, and a gripper for removing large rocks and other obstacles from the area of operation. The drill is vibrational rather than rotary to avoid potentially uprooting the mine or forcibly churning soil onto it thereby causing it to detonate. The manipulator is powered by a hydraulic pump and Joints 1-4 and 6 are actuated by hydraulic cylinders and Joint 5 by a hydraulic motor. Control voltages determine the current supplied to a series of valves that control the flow of fluid to the actuators. Table 8 gives the manipulator specifications. The control computer is a Pentium III PC/104 architecture system running the xPC Target real-time operating system. The control program is developed in MATLAB/Simulink on a host PC and uploaded to the control PC for execution. Angle encoders at the joints send position information to the control PC through an A/D board, and the control PC sends control voltages to the manipulator via a D/A board. Input voltages range from -5V to 5V, though at ±2V the manipulator already moves sufficiently fast. The input is therefore restricted to within ±2V. The system is highly nonlinear and the biggest obstacle to control is the input dead zone, which is explained further in later sections.

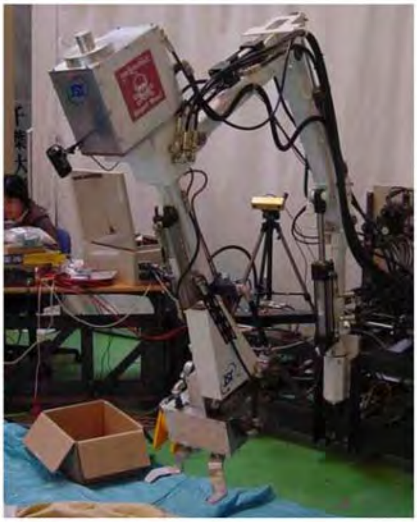


Fig.30 6-DOF hydraulic manipulator

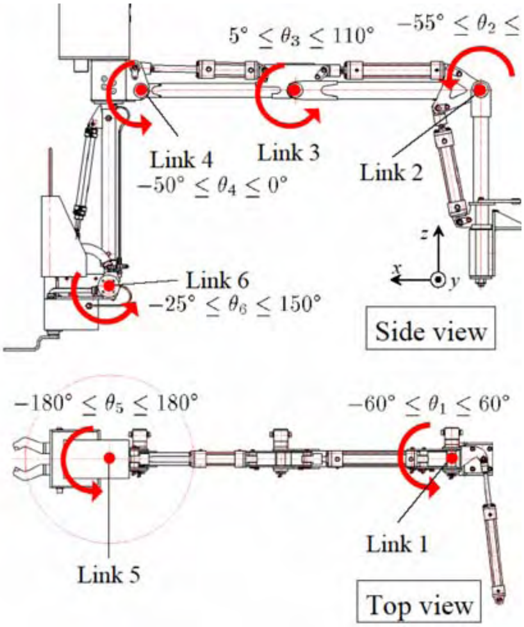


Fig.31 Configuration of manipulator

Manipulator specification

Links	Length [m]	
a_1	0.6	
a_2	0.8	
a_3	0.66	
a_4	0.14	
a_5	0.83	
Joints	Range	Joints in Fig. 3 are at starting position 0°, clockwise is positive
j_1	±65°	
j_2	-60~0°	
j_3	0~110°	
j_4	-50~0°	
j_5	±180°	
j_6	-25~160°	
Weight	200 kg	
Hydraulic Pump	13.7 MPa, 10L/min	
Air Jet	Tank Capacity: 24 m^3 Pressure: 10 MPa	

Table 8. Manipulator specification

5.1 Operation Strategy

5.1.1 Scanning Preparation – Electromagnet

The electromagnet shown in Fig.32 was originally affixed to the end effector under the assumption that the manipulator would work in tandem with a sensor arm on the same vehicle. The motivation was to clear the workspace of small metal fragments before scanning commenced in order to reduce the number of false positive sensor readings. Although the original concept of the MHV has changed (as mentioned in the introduction), a vehicle supporting both a sensor arm and a prodding arm is still the ideal scenario because the operator can switch between sensing and prodding tasks at ease without having to change out vehicles. Changing vehicles would entail extra navigation to and from the work site and great care would have to be taken to ensure the second vehicle was operating in exactly the same location as the first. Needless to say, these extra tasks would consume a great deal of time.

Provided a dual arm system is developed, either through constructing a new vehicle or redesigning the manipulator, the operation of the electromagnet is relatively straightforward. The manipulator makes and automated sweep of the area of interest with the magnet before sensing begins. The magnet collects small metal objects from the area and can release them in an out-of-the-way place. The magnet is kept close to the ground surface using gap control, which will be implemented using a 3-D map of the terrain generated by stereovision.

5.1.2 Prodding – Soil Breaker and Air Jet

A number of operation strategies are under consideration for prodding, including a master-slave system and an automated virtual reality system utilizing sensor data and a 3-D map of the terrain using stereovision. However, recalling the key considerations from the introduction, from an operator's point of view, the simplest and most intuitive strategy is joystick control of the end effector. Joystick control can be divided into two modes – large motion mode (Fig. 33a) for moving the manipulator from one area of interest to another, and small motion mode (Fig. 33b) for positioning the air jet and controlling the drill during prodding.

Precise directional control of the end effector is essential both for obstacle avoidance in large motion and prodding in small motion. Using cylindrical coordinates for the manipulator allows us to consider Joints 2-4 independently of Joints 1 and 5. Joint 1 changes the plane of operation, and Joints 2-4 determine the motion within the plane.

Once the manipulator has been positioned in the desired plane of operation, prodding can begin. If the soil is hard, the soil breaker can be used to loosen it. In keeping with time-tested safety standards, the angle of approach should be no more than 30 degrees from the surface plane. The proposed strategy requires a total of four axes of motion in small motion mode, as shown in Fig 32b. The X and Y axes and pitch are used to set the initial position the drill, and it can then be moved along its longitudinal axis into the soil. Force control will be activated when the drill makes contact with the ground so that the operator can control the strength with which the drill pushes.

The air jet can be controlled in much the same way as the soil breaker, with the same X, Y, and pitching control. When the soil has been loosened, high pressure air from the air jet clears the soil away, exposing the buried object. If the object remains covered, the process can be repeated until the object is identified.

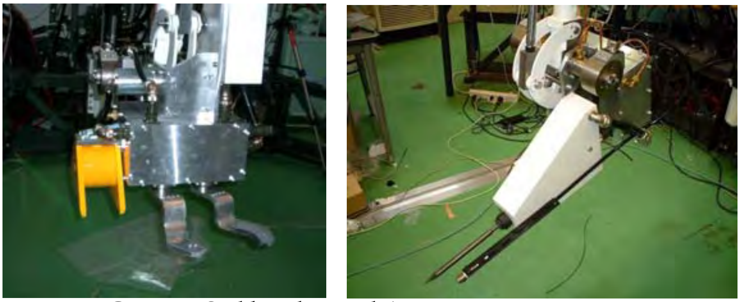


Fig. 32. Electromagnet, Gripper, Soil breaker and Air jet

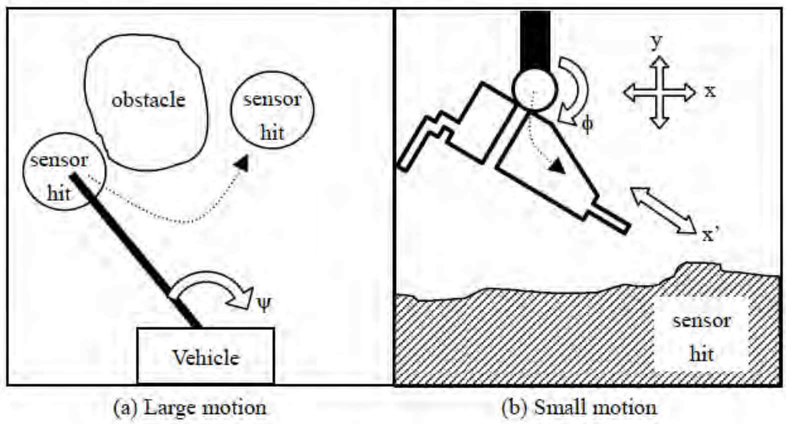


Fig. 33. Two modes of joystick manipulator control

5.2 Master-Slave Manipulator

The teleoperated and master-slave manipulation for landmine prodding and excavation is one of the important technologies in robotics based humanitarian demining. Especially, it will be highly desired to develop a completely autonomous robot which can work without any aid of the deminer in future. However, with the present state of technologies, it is not possible to develop a complete autonomous prodding and excavation robot. Therefore, the teleoperation technologies for the robots with high levels of autonomy become very important. Currently, the technologies where a deminer teleoperates a manipulator from within a safety area are not in practical use yet, like prodding and excavation. For this reason, we have developed the technologies for the teleoperated prodding and excavation of humanitarian demining robots from the safety area for the future demining missions. Figure 34 shows the master arm and the slave arm. It seems that the performance of the master-slave system is very good from Fig.35.

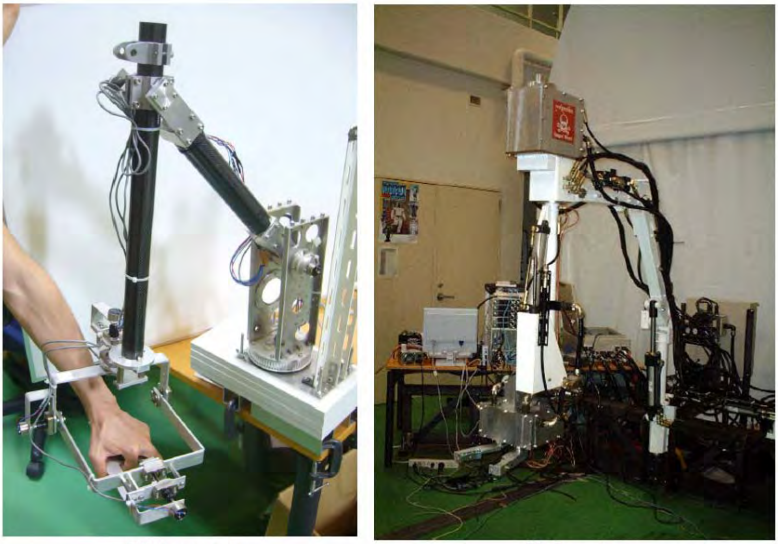

(a) Master Arm (b) Slave Arm

Fig. 34. Master and slave arm

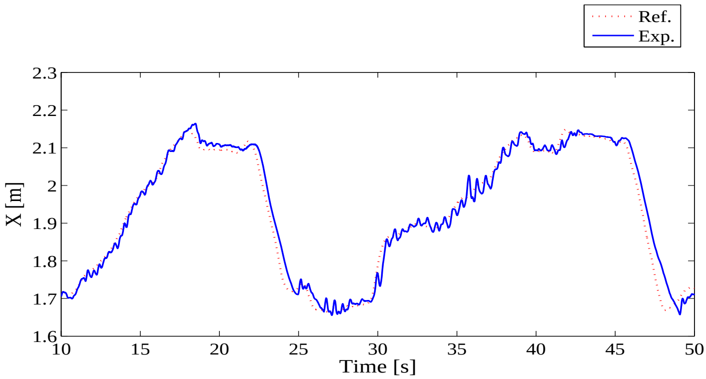


Fig. 35. Response of master-slave control (Red: Master, Blue: Slave)

6. Conclusions

The overview of mine detection robot and related technologies for humanitarina demining has been introduced. The concept which combines the flexibility of a manual system with a rapid and safer mechanized scanning of vehicle- mounted systems, with the advantage of reduced cost, size and overall system complexity. A simplified prototype was built which used a metal detector and GPR to demonstrate the concept. This system uses 3D stereo vision camera to recognize terrain profile which is used to control the trajectory of the metal detector head and GPR. Although the basic concept was successfully demonstrated. a number of deficiencies were apparent. Further development of the system is required before it becomes ready for practical deployment. Planned future work includes the following; (1)In the present implementation, detector and GPR data and poison information are referred to a co-ordinate system fixed to the vehicle. In the future, vehicle navigation information will be used to refer all measurements to an earth-fixed co-ordinate system. (2)The detection rate in the outdoor test field should be much higher than a manual operation. (3)Also, the detection speed should be much faster than a manual operation.

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11

Developments on an Affordable Robotic System for Humanitarian Demining

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1. Introduction

Humanitarian demining is a multi-faceted and broad domain. Occasionally, specific economic interests in specific areas of landmine infested countries may foster an avalanche of investments for massive demining. However, the great majority of the territory is left out of these demining activities, meaning that the problem is prolonged for decades. Affected countries, usually developing ones, lack both economic and educated human resources to tackle this prolonged humanitarian problem. This long-term battle must thus be fought with scarce and locally available resources, restricting greatly the type and amount of employable technology.

Cost, complexity, maintainability, among others, are thus key factors to be taken into account when developing technology to actually help countries facing the humanitarian demining problem. This chapter addresses this concern by proposing a technology development roadmap for the humanitarian demining domain. An outcome of the roadmap is a set of requirements for the construction of a *portable demining kit*, as a possible solution to enable what is already known as s*ustainable demining*. The rationale behind this is that by making *portable demining kits* locally available it will be possible to promptly respond to emergency situations. The number of casualties can then be drastically reduced by providing a fast assessment of the probability of a given land being contaminated with landmines. To see the daylight, the robotic demining kit should be general purpose to some degree, i.e. to be usable as a service robot for other tasks besides demining. This allows operators to practice the interaction with the system during prolonged absence of landmine-related activities. In addition, the owner (e.g. a local authority) can exploit the system to obtain additional profits. This portability is essential to guarantee that the system pays for itself, thus reducing the problems associated with its maintainability.

Three sub-types of *portable demining kit* will also be presented, along with some ongoing developments towards their implementation. These developments include novel mechanical platforms, locomotion, piloting, localisation, and perception systems. The main design guidelines are affordability, robustness, and intuitiveness, so that the system can be easily purchased, maintained, and used.

Along with these robot-oriented developments, a multi-agent supporting software platform will also be presented. The multi-agent paradigm is well suited to enhance multi-experts and multi-robots inter-operability. In addition, the platform facilitates scalability, allowing robots and humans (i.e. agents) to be added/removed to/from a mission in a seamless way. A third feature that comes hand-in-hand with the multi-agent paradigm is modularity, something essential to foster vertical development and integration with off-line tools, such as simulation-based training applications.

This work is being carried out since 2003 by a portuguese SME, *IntRoSys S.A.*, in partnership with UNINOVA research centre of the New University of Lisbon and LabMAg research centre of the University of Lisbon. This joint collaboration emerged from the acknowledgement of a business and scientific opportunity stemming from the unavailability of sustainable robotic systems applicable to the mine action domain.

2. Technology Development Roadmap

Based on (Santana, P. et al., 2005; Santana, P. et al., 2007), this section overviews a set of recommendations for the development of technology for the mine action domain, with special focus on robotics. By carefully considering the specificities of the humanitarian demining domain, the goal of this roadmap is to guide robotic technological developments towards higher levels of acceptance confidence. Typically, the acceptance of a novel technology is dependent on its field applicability and its affordability.

Previous work has identified opportunities (UWA, 1998; GICHD, 2002) and guidelines for the development (UNMAS, 2003b) and procurement (UNMAS, 2003a) of technology applicable to the mine action domain. According to these studies, it is reasonable to assume that *close-in detection* and *area reduction* are priority domains with very significant benefits from demonstrating progress on R&D. Based on this assumption, the remainder of this section develops around these two tasks. However, as it will be shown later on, other tasks can also be easily covered by the same technical solution.

2.1 Cost and Complexity

Usually *high-tech* means high-cost and high-complexity, which are two considerable draw-backs in humanitarian demining. Typically in developing countries, deminers are people with little formal education, which requires simpler human-machine interfaces than those usually considered by technology developers. In addition, operation sites are remote and hazardous, turning a simple repair into a daunting task. This fact leads to the conclusion that the use of local equipment has the advantage of being low-cost, readily available, easily maintained or repaired, and of stimulating local economy (Smith, A., 2003). Donations are being progressively reduced, posing additional financial problems to affected developing countries (Barlow, D., 2007). Finally, it is paramount to remember that detection and clearance of landmines is part of an extensive list of humanitarian problems (e.g. food supply and medical assistance) in a post-conflict situation, meaning that funds must be shared, reducing even further the financial support to demining activities.

Robots performing such a complex task in such demanding environments only rarely can be made low-cost, easy maintainable and locally manufactured. Hence, if the goal is to exploit the current bulk of knowledge present in the mobile robotics literature to solve the demining problem as fast as possible, it is rather preferable to focus on a part of the mine action process where the inherent complexity and cost of the robotic solution are not key factors. Nevertheless, all the development should target simplicity, low cost, easy maintenance, and usage.

An example of a successful introduction of a high-cost technology to the mine action domain is the use of heavy-weight machines to trigger landmines. Although this solution, i.e. mechanical demining, does not cope with the humanitarian demining safety and accuracy requirements, damages the soils, is logistically difficult, and expensive (UWA, 2000; Habib, M. K., 2002a), its application is growing in the area reduction, terrain preparation, and post-clearance tasks (GICHD, 2004). This is because a single machine can work faster than a thousand deminers over flat fields (Habib, M. K., 2007), offsetting its disadvantages until better technologies are developed (Habib, M. K., 2002b). It is now believed that 90% of the land subject to a process of detection and clearance is not contaminated (Barlow, D., 2007). Therefore, a slight improvement in area reduction, terrain preparation and post-clearance tasks (e.g. for quality assurance) have a significant impact in the overall process' efficiency. It is thus reasonable to assume that the potential high-cost and complexity inherent to a novel technology developed for these tasks is counterbalanced by its outcomes.

In fact it is not just a question of efficiency, it is also a matter of safety. For example, vegetation cutting is considered as being one of the most boring/difficult tasks to be performed by a deminer (Cepolina, E. E. & Hemapala, M. U., 2007). Following the same line of thought, area reduction is also among the most dangerous tasks. Deminers usually perform it faster than when searching systematically for landmines (Colon, E. et al., 2007). Being of much less complexity than landmine detection, tackling these problems would produce faster effects in the mid term.

2.2 Risk Assessment

The reduced complexity of area reduction, terrain preparation, and post-clearance tasks when compared to the problem of systematic landmine detection and removal is mostly concerned with the difficulty in discriminating landmines from metal debris, natural clutters, and other objects without the need for vegetation cutting (Habib, M. K., 2007). This problem is being tackled by many research groups in sensor technology and sensor fusion techniques. But the fact is that despite all R&D efforts and improvements in multi-sensor fusion with all its advantages (e.g. false positives reduction), the detection and clearance process remains unsatisfactorily robust. In addition to these more related technological limitations, personnel in the field are conservative regarding these innovations. The general awareness of these limitations complicates the acceptance of novel technologies as alternative to metal detectors and manual prodding. This contention is reasonable due to the risky nature of the task, which makes procedural and conservative approaches preferable.

Surveying tasks have a different nature though. They are mostly probabilistic. *Impact surveys* are performed by interacting with population, governments, military forces, etc., in order to, among other goals, gather information about the most probable contaminated sites. During *technical surveys* more detailed information is obtained to make the detection and clearance process more accurately defined. A component of this phase is to define boundaries to the demining process by means of *area reduction*. To accurately define these boundaries, every patch should be thoroughly analysed. Since the goal of area reduction is exactly to avoid analysing the entire terrain, these requirements must be relaxed. Hence, *area reduction* can also be seen as a probabilistic process (i.e. risk assessment). *Post-clearance surveys* involve accreditation and monitoring of the demining organisation before and during operations (i.e. quality assurance) and inspection of cleared land before it is formally released to its owner (i.e. quality control). Once more, this process is also probabilistic. In fact, a more realistic goal than the UNMAS one of 100% clearance is the *zero-victim* target (EC, 2005). This means that land prioritisation, area reduction, and fast response to casualties are of utmost relevance.

The probabilistic and information-driven nature of these tasks suggests that any available technology providing additional data is beneficial. Thus, even though a novel product may not be able to provide a 100% sure output, as required for detecting landmines, it can be used as another knowledge source feeding the decision making process during a survey phase. Just as with complexity and cost criteria, technology developed for employment in survey phases is more likely to be accepted than for the detection and clearance phase.

2.3 Product's Life Cycle

Some market studies, e.g. (Newnham, P. & Daniels, D., 2001), concluded that the market of humanitarian demining is not active and wide. As a result, product's development usually requires direct or full funding. In addition, the technology buyers are mostly donors and not the end users. These factors endow the humanitarian demining market with complex (and sometimes hidden) dynamics, hindering the application of conventional product's life-cycle and return of investment strategies.

It is essential that developers design products capable of being transferred to other domains until they are accepted in the restricted humanitarian demining market. That is not to say that the developed technology should be general purpose. As pointed out in (Habib, M. K., 2007), technology should be developed with the special purpose of demining, otherwise it will most surely fail in coping with the hard requirements of real minefields. Although a reasonable trade-off between being general purpose to enable *transferability* and being optimised for the demining domain is surely difficult to achieve, being aware of it is already a good starting point.

2.4 Explosive Remnants of War (ERW)

Unfortunately, landmines are no longer alone in the top list of priorities in mine action programmes. Many other explosive remnants of war (ERW), such as cluster munitions, are becoming a bigger threat (Nema, M., 2007). These can be launched in air strikes covering larger and more indiscriminate areas than those affected by landmines deployment. Again, fast area reduction and risk assessment mechanisms appear as key mechanisms to help cover wider areas in a shorter period of time.

3. A “Business Model”

To cope with the presented technology development roadmap a business model has been devised (Santana, P. et al. 2005). It envisages a successful return of investment by guaranteeing a natural technology transfer to other domains, and also by covering aspects of the humanitarian demining process with recognised added-value. At a first sight, it may

seem heartless to talk about business and return of investment when human life is the centre of the question. However, these are essential factors in triggering the attention of rich countries' industry to this problem. If this goal is attained it will be much easier to develop better and cheaper technology for the humanitarian demining domain.
Restating the major conclusion obtained from the roadmap, area reduction is among the most demining-related activities prone to accept advanced technology. It can also be concluded that technology transfer should be favoured as much as possible. If area reduction is considered as an instance of a *generic remote monitoring toolkit*, solutions developed for it can also be applied to the domains of civil protection, surveillance, remote environmental monitoring, law enforcement, etc., emphasising the potential for technology transfer (see Fig. 1).

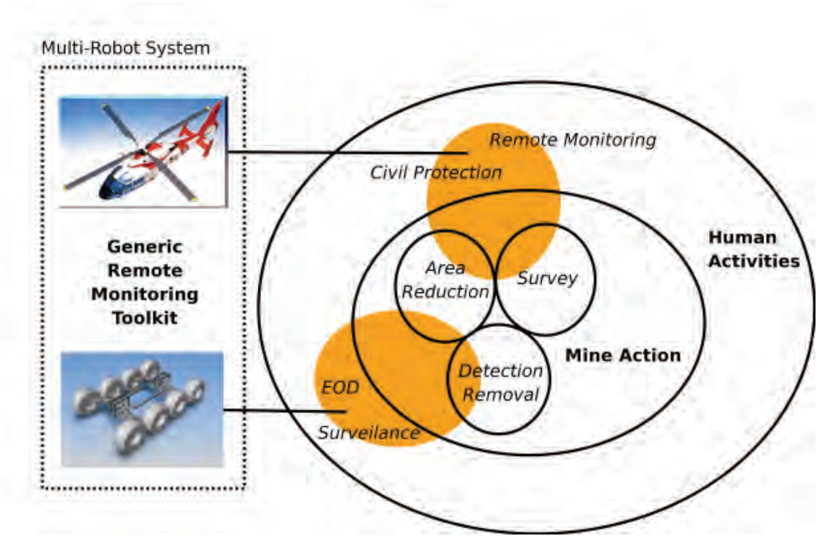


Fig. 1. The generic remote monitoring toolkit

3.1 A Portable Demining Kit

A particular component of the *generic remote monitoring toolkit*, a *portable kit* for rapid intervention in humanitarian demining emergencies, is the topic of this section. The idea is to have a low-cost, light, and simple maintenance robot fleet available in some hot spots of affected countries. Each time a landmine related accident is reported, a small team (e.g. one operator and one robot) is deployed to the affected area. Being small and light, the robot(s) can be carried in a common all-terrain vehicle, as well as being easily manipulated by the operator(s).
Once on site, the operator can perform area reduction and mapping in order to, for instance, provide information for risk assessment, delegating to others the full demining process. This can be extremely important as the field must be prioritised before being demined, and especially because locals may risk using the affected fields for agriculture or any other basic

survival activity. In fact, in many cases, populations start raising their crops in the minefields or start using mined roads as soon as a conflict finishes, which results in a high number of human casualties.
Therefore, this approach is intended to be a pragmatic way of reducing the number of casualties by providing the populations with immediate risk assessment information about the terrains they will be using. A set of design criteria for such a portable demining kit has been defined:

- **Field Applicability.** Due to the harsh, unstructured, and unpredictable nature of the application scenarios, designing a robotic system for landmine detection is a quite complex task. The following items should be taken into account when developing a mobile robot for humanitarian demining:
  - Locomotion capabilities. Landmine detection sensors are complex and usually require slow motion to perform properly. This sets up an upper limit to the robot's speed requirements. In fact, the true requirement for a demining robot is to be easily deployable (i.e. small and light), capable of traversing all-terrain, high slope, uneven, and densely vegetated terrains, while maintaining itself operational.
  - Accidental landmine triggering. The lighter the robot, the smaller the chances of triggering an undetected landmine. However, light robots are difficult to build, particularly if the goal is to make them autonomous. Autonomous robots require batteries, sensors, computational units, motors and respective drives, plus a robust mechanical platform with protective material against explosions. Therefore other strategies are required in addition to make robots as light as possible. One is the requirement for a safe lane in which the robot moves while scanning a potentially contaminated parallel lane. Another is to design the mechanical platform to be holed so that most of the explosion energy can pass through it. Making a breakable structure helps in isolating the damages.
  - Landmine detection & avoidance. Safe lanes not always exist. Picture for instance a cluttered environment or a situation where the robot must analyse an area between nearby trees. This issue can be tackled by scanning in real time the surface where the wheels/legs of the robot will move over. However, ground robots used for area reduction may not be equipped with landmine detection sensors. Rather they may be limited to lighter and cheaper chemical sensors, which can only be used to detect minefields and not particular landmines. This limitation stems from their high sensitivity to the chemical in question, but low spatial resolution. This is a big challenge that some have turned around by using unmanned aerial vehicles, such as (Eisl, M. M. & Khalili, M., 2003; Cramer, E. A., 2001). The challenge still remains though; aerial means can hardly operate in forest like environments, in which ground is not visible from above. Refer to (Santana, P. & Barata, J., 2005a) for a thorough analyses of the applicability of unmanned helicopters to the humanitarian demining domain.

   - Tripwires detection. Tripwires and other mechanisms to trigger landmines are very difficult to detect, especially in areas with dense vegetation. Nevertheless, some attempts have been reported (e.g. (Babey, S.K. et al., 2000)).

- **Ease of use.** A demining mission is much more efficient if robots are used as advanced devices to help experts and operators on the ground. It is widely accepted that such robotic systems to be successfully applied in the mine action domain must have a simple human-machine interface. Moreover, it is essential for the system to disturb as little as possible the operator. The operator must be focused on the landmine detection sensors output and not on the machine that carries them. This mainly requires the system to:
   - Be (semi-)autonomous. This is essential to reduce the operator's attention in all respects of the robot' activity. Since the operator will be immersed in the landmine detection sensors output, the robot's telemetry should operate on an event driven way, i.e. information should pop-up when it is meaningful. This requires the robot to self-diagnose, or at least to self-monitor. Obstacle avoidance, adaptation to terrain's roughness, sensor and actuator degradation are also essential features. Finally, the mission (i.e. tasks and interactions between robot(s) and operator(s)) should be stereotyped and automatically managed.
   - Be implemented with interoperability capabilities. Other experts, such as specific landmine experts not present on field, should be easily accessible when required. This feature is essential to motivate the distribution of portable kits throughout affected countries. Without remote access, experts would be required to be present in the minefield, which would hamper a fast deployment of the system. Interoperability also allows many operators, and even robots, to interact in a more transparent and harmonious way, in real team work.
   - Be mimicked in a realistic simulation-based training tool. Operators should be provided with a tool through which they could train in a simulated environment. This allows operators to train nominal and extreme situations, reducing the chances of erroneous behaviour in the real minefield. Thus, the simulator needs to model, to some extent, the robot's dynamics and kinematics, terrain, robot-terrain interactions, and landmine detection sensors.

- **Modularity.** Modularity is another essential criterion for a system to operate with so many and so demanding requirements. Being modular, the system is more easily extended and customised, reducing re-engineering costs. For instance, modular software allows an easier integration in an IT infrastructure while modular hardware allows an easier integration with custom made mechanical platforms for some special needs. A good (dis)assembly procedure reduces the transportation requirements, as well as the time and cost spent in maintenance tasks. Modular software, such as the one enabled by the multi-agent paradigm allows the scaling up/down of the system in the field as the number of operators and robots varies. Finally, training can also be improved by having a modular system, as it is possible to train for a specific component without requiring access to the whole system.

- **Affordability.** To be sustainable, the system must be affordable. Three major strategies have been considered to reduce the cost of the system:
  - Sensors reuse. Instead of considering high cost laser scanners for terrain perception, high cost navigation sensors (e.g. RTK-DGPS and inertial navigation systems) for localisation purposes, stereoscopic vision can be used for both. Since the number and diversity of parts to be maintained in stock is smaller, the logistic requirements are relaxed. In addition, the cost is reduced in about one order of magnitude when compared to conventional localisation+perception systems.
  - Compliant mechanical structures. By allowing the robot to adapt passively to the environment, the sensory requirements for terrain perception are reduced, and consequently their cost. Moreover, robustness increases when part of the robot's ability to safely traverse uneven terrain is decoupled from the control system.
  - General purpose properties. The system is more easily self-sustained if it can be exploited for other purposes. In addition, the more applicability it has, the more used it is, and consequently the better operators control it.

4. Towards the Implementation of a *Portable Demining Kit*

This section presents some conceptual and technical solutions that cope with the set of previously presented requirements for a *portable demining kit.* As mentioned, three sub-types of portable demining kits are being considered. Each of them is to be applied in different situations, which by their typical sequential nature can also be called of stages. The first stage refers to minefield detection, the second one to area reduction, and finally the third one to detection and clearance. As it will be shown, the three stages do not always follow each other in a pre-established sequence.

4.1 First Stage: Minefield Detection

Someone is aware of a previous conflict exactly on a location of particular importance for the local community. In this hypothetical scenario it would be extremely beneficial if the community could request a fast minefield risk assessment. For this purpose a team of small robots (~50 cm long) with poor localisation and terrain classification capabilities carrying a chemical sensor to minefield detection could be applied. Being extremely light, the probability of triggering a landmine is rather low. Even if that happens, their low cost and small dimensions makes their substitution easy. Therefore, there is no need to accurately detect landmines in order to avoid them. The chemical sensor does not provide high spatial resolution and therefore simple localisation capabilities suffice. The output of these robots operating autonomously and fast is a low resolution map of landmine explosive (e.g. TNT) in the potential minefield.

Bearing this in mind, i.e. low cost, simple, and small disposable robots, some biologically inspired models have been developed for terrain classification and reactive control. As concluded in (Santana, P. et al., 2007), biology is a good inspiration for building sustainable robots. Nature tends to evolve simple, efficient, and robust solutions, exactly what is required for such a team of small robots. The remainder of this section describes some of these biologically inspired models for the implementation of a small robotic team. These models have been tested in real robotic platforms, being a migration to small size robots scheduled for the mid-term.

4.1.1 Morphological Computation for Affordable All-terrain Piloting

Robots designed to operate autonomously in natural environments require a proper perception of their surroundings. Typically this problem is managed recurring to complex, expensive, and high consumption sensors, such as 3-D laser scanners and stereoscopic vision systems. These hard requirements are mostly necessary when robots have demanding dynamical and kinematic constraints, and their actions are intended to be optimal. However, a small and light robot operating in a natural environment is much less demanding in this respect. This vision lead to the development of a novel concept for *affordable embodied all-terrain locomotion* (Santana, P., 2005; Cruz, H. et al., 2005; Santana, P. et al., 2007).

The basic idea of this concept is to categorise the environment recurring to little computational power, by means of properly distributing simple sensors in key locations of the robot's body. The relative perspective these sensors have over the world makes them "tuned physical filters" to extract relevant environment's features. The output of the filters feed the control system allowing it to perform obstacle avoidance, speed control based on terrain's roughness, etc..

In order to test the method, some experiments have been carried out in a first version of the Ares robot (see Fig. 2). The Ares robot was equipped with a set of simple sensors utilising this approach so as to implement physical filters to distinguish *tall* from *low* objects, and *obstructive* from *non-obstructive* objects. Namely,

- An upper sonar set composed of eight sensors mounted on an elevated *pendular* platform allows the robot to detect *tall* objects (e.g. trees). The higher the platform is, the higher the objects must be in order to be detected by the sensors. Hence, specifying the height of the platform is like tuning a filter to reject *low* objects. Being *pendular*, the platform keeps its vertical position whatever the robot's roll angle. To reduce cost, the eight sonars can be substituted with a single one mounted on a servo.
- To detect *low* objects, a lower sonar set (a single sonar in this case) is used. Once again, this sonar set implements a physical filter to detect *low* objects.
- Two front bumpers attached to tunable springs detect *obstructive* objects (e.g. dense bushes). If a bumper is triggered, then it means that the robot touched an object that projects a force onto the robot greater than the one produced by the springs. Thus, specifying the strength of the springs is like tuning a filter to accept *non-obstructive* objects (e.g. weeds).

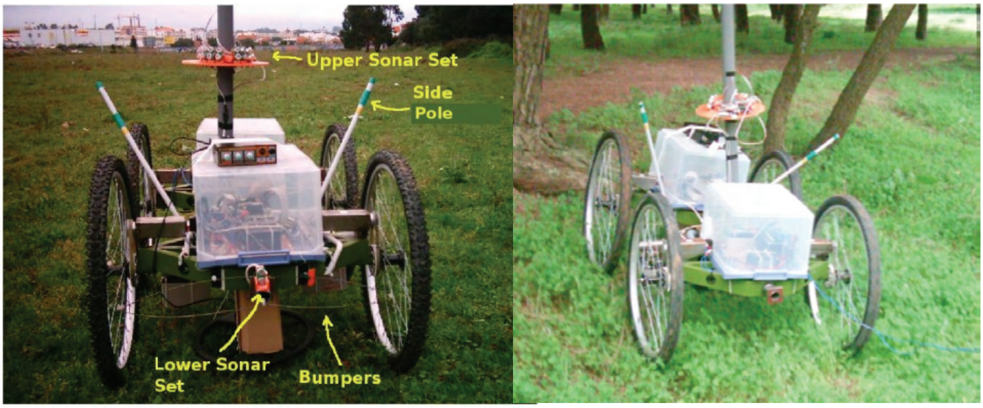


Fig. 2. The first Ares robot version

It is possible to react to all *obstacles* (i.e. *obstructive objects*) encountered by the robot using the bumpers alone. For a proper piloting of the robot, however, detecting *obstacles* before colliding with them is required. To do so, some heuristic knowledge about the environment can be used. A typical example of such knowledge is the fact that usually: weeds are *low* objects and *not obstacles* to the robot; trees are *tall* objects and *obstacles* to the robot; rocks are *low* objects and *obstacles* to the robot.

Based on these heuristics, the previously presented physical filters can be used to avoid *obstacles*. Since from the above facts it follows that *tall* objects are usually *obstacles,* each time a sensor in the upper sonar set detects something (i.e. a *tall* object) the robot should avoid it according to a given avoidance policy. However, some *low* objects are *obstacles* (see for instance the case of rocks). Therefore, each time an object is detected by the lower sonar set (i.e. a *low* object), the robot slows down its speed as it is not sure about the nature of the object. If a bumper is triggered afterwards, then the robot initiates an avoidance routine as it has detected an *obstructive* object, and consequently an *obstacle*.

This example illustrates how it is no longer possible to distinguish between software and hardware in terms of what takes control over what. Under this paradigm, the robot's body *is* part of the decision process, i.e. it is fully *embodied*. These ideas are closely related to the principles of *morphological computation* (Pfeifer, R. & Iida, F., 2005), in the sense that the body of the robot contributes greatly to the decision making process. In fact, some parameters of the robot's morphology (e.g. the height of the upper sonar set) can be used as constants in a *holistic embodied algorithm*. The absence of any central geometric representation of the environment results in low-cost and robust robots.

Despite its simplicity, this method is an interesting solution to the problem of making small and simple robots which perform well, perhaps not optimally, in complex environments. Next we present a behaviour-based control architecture developed to support control logic such as the one presented in this section.

4.1.2 The Survival Kit Architecture

Although a method to implement *embodied* all-terrain controllers was just presented, the underlying architecture was not covered therein. To close the gap this section briefly describes a behavioural architecture especially designed for disposable/affordable robots, the Survival Kit (SK) (Santana, P., 2005; Santana, P. & Correia, L., 2005; Santana, P. & Correia, L., 2006).

The SK architecture is the bottom layer of the robot control system, and it supplies the robot with safe local navigation capabilities. Thus, everything required to maintain the survival of the robot, in terms of immediate reactions, should be implemented within the SK architecture. Upper-layers are allowed to modulate the SK. Fig. 3 illustrates the main components of the SK architecture.

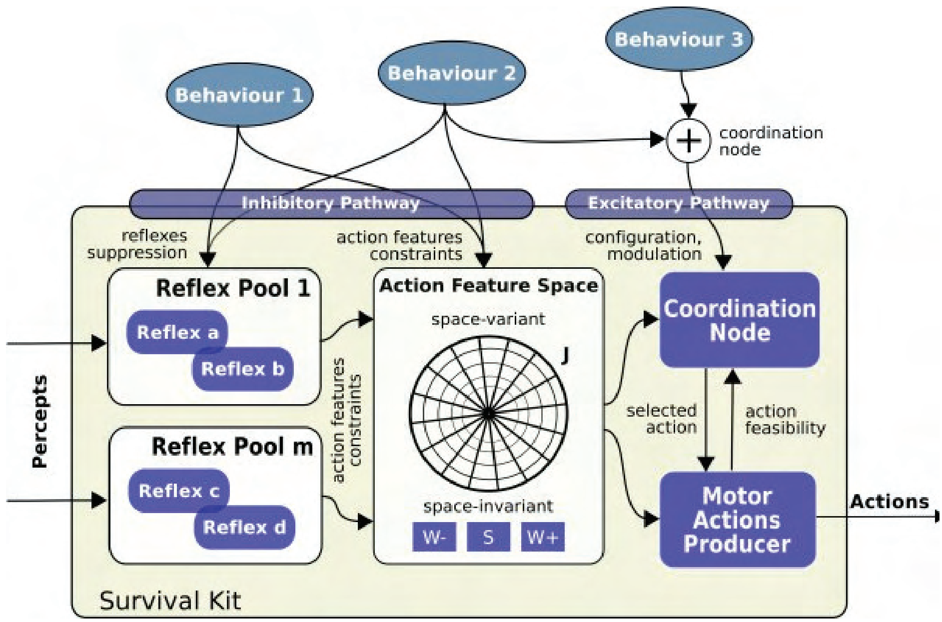


Fig. 3. The Survival Kit architecture

The core of the architecture is the *action feature space*, which indirectly describes all the robot available actions. An *action feature* is an attribute of the action, such as the *maximum allowed velocity* and the *maximum distance* the robot can travel in a given sector of the environment. This departs from the conventional *action space* (Rosenblatt, J. K., 1995; Pirjanian, P., 1998), in which actions are explicitly represented by tuples that are directly mapped to actuator commands, such as *linear and angular velocities.* The action feature space is composed of two sub-spaces: the *space-variant* and the *space-invariant*. The *space-variant action feature sub-space* is sectorial. Each sector corresponds to a region in the environment with the same shape. In each sector, associated to each action feature there are two slots, one for a constraint on the respective action feature, and another one for its temporal validity. A second action feature sub-space, the *space-invariant action feature sub-space*, is composed of action features without spatial relationship, such as *possibility of producing angular velocities*. These action features can also be temporarily constrained.

Reflexes are units responsible for constraining action features in order to implement a part of the survival policy, such as reacting to a collision. For the sake of clarity an example is given. Let us define the action feature v_{max}, as *the maximum linear velocity allowed in a given sector of the environment*, and a reflex *adapt_speed*, as the mechanism to set up the maximum speed the robot can travel in a given sector of the environment based on the terrain's roughness. This reflex can then add constraints to v_{max} so as to limit the robot's speed when the terrain's roughness increases. For instance, a constraint of $1\ ms^{-1}$ could be added to v_{max} in sector *0* for *100 ms.* In this way the reflex explicitly states what is the maximum speed the robot can have when travelling along sector *0,* if its mechanical structure is to be preserved.

A set of conditions must be met when accepting a new constraint. If a new constraint reduces the possible set of actions (e.g. if the new constraint is intended to reduce the value of v_{max} to $0.5\ ms^{-1}$), then it is immediately accepted. If the new constraint validity is greater than the current one, then the constraint validity is updated with the newer value. This approach guarantees that new constraints never relax previous ones, or their validity time. When its validity time expires a constraint is released.

Modulation comes in many forms. Upper layers can: constrain action features, suppress reflexes (e.g. docking requires to suppress reflexes sensible to bumpers), and provide a desired course of action (e.g. desired speed and direction). This plasticity is a must if the SK is to be embedded into a more complex system capable of producing complex adaptive behaviour.

The *coordination node* is the module responsible for selecting, from the actions still available, the one that better suits the modulatory signal provided by the upper layer. This is achieved by maximising an objective function that selects the best sector from the ones still available, and then builds up the commands that are immediately sent to the actuators. Among others, the objective function takes into account the free-space connectivity of the environment for a proper navigation through obstacles.

It is worth mentioning that the previously presented all-terrain piloting method is directly mapped into this architecture. Reflexes implement reactions to the *physical tuned filters* by specifying constraints, such as constraining v_{max} in the presence of *low objects.* Further details can be found in (Santana, P., 2005).

4.2 Second Stage: Minefield Area Reduction

If an explosion has already taken place, TNT and other compounds will be spread all around. In this case chemical sensors will always return a positive result, being of little use to determine if any other landmine is present in the field. Another technology, such as metal detectors or Ground Penetrating Radar (GPR), is therefore required. In addition, if after the first stage, i.e. minefield detection, the field is considered contaminated with TNT, a subsequent area reduction may be required so as to reduce as much as possible the amount of unusable land.

Hence, for the second stage, i.e. area reduction, robots should be able to transport other non-chemical sensors, such as GPR and metal detectors. These sensors are bulkier and require more energy to operate. Therefore the robot must be more powerful and consequently heavier. As a result the chances of triggering a landmine when stepping on it increase up to dangerous levels. Detecting the landmine in order to avoid it is then a must. This chapter being focused on the robotic platforms, this latter topic will not be covered.

4.2.1 The Ares Robot

The already presented Ares robot has been improved in a second version (Santana, P. et al., 2007) (see Fig. 4 and Fig. 5) for the second stage. Rather than developing a robot for planar and smooth outdoor environments, focus has been given to a platform able to traverse high slope uneven terrain. This way the robot can be used in cluttered areas where deminers usually have more difficulties in operating.

Fig. 4 illustrates the robot's mechanical structure, in which it is possible to see its four independently steered wheels in four different locomotion modes:

- **Double Ackerman mode.** This refers to a car-like locomotion method, but in this case the rear wheels also turn according to the double Ackerman geometry (Fig. 4 top-left). The Ackerman geometry must be continuously maintained. In this mode the robot is capable of producing a turning radius down to 80cm without lateral slippage.
- **Omnidirectional mode.** In this mode the four wheels are aligned to produce linear trajectories without rotation (Fig. 4 bottom-left).
- **Lateral mode.** This is a special instance of the previous mode, in which the four wheels are aligned and perpendicular to the main axis of the robot, allowing the robot to move sideways (Fig. 4 bottom-right).
- **Turning-Point mode.** In this mode the robot is able to rotate around its own geometrical centre without lateral slippage (Fig. 4 top-right).

This characteristic of high mobility enables low friction quasi-holonomic motions. In addition to its importance in the case of demining tasks, in which locomotion with lateral slippage is undesirable as it can trigger landmines by disturbing the ground, high manoeuvrability is also essential to make the robot get into highly cluttered environments.

The robot is implemented with low-cost, easily available components, like bicycle wheels. Besides being low cost and widely available, bicycle wheels also have the advantage of providing the robot with a considerable height from the ground (~40 cm). The upper bounds of the volume occupied by the robot are 1.51 m x 1.36 m x 1.50 m. The actual volume varies according to the selected locomotion mode. Both front and rear axes can freely and independently rotate around a longitudinal spinal axis (see Fig. 4 bottom-left). By having this passive joint, the robot is capable of being compliant with respect to uneven terrain.

The size of the wheels and the compliant body are extremely important features in reducing the sensorial and computational requirements of the robot, as they reduce the need for explicit handling of most natural obstacles (e.g. small rocks) present in the minefield. Less sensors and less computer power results in less energy consumption, less complexity, less cost, and consequently a more affordable and sustainable platform for mine action. By adapting the tyres to the nature of the terrain, it will be possible to cope with most environments where the system is to be applied. Fig. 5 illustrates the Ares robot performing in an all-terrain environment.

Fig. 4. The second Ares version mechanical platform (see text for details)

Fig. 5. The Ares robot in all-terrain

4.2.2 The Ares Robot's Locomotion Control System

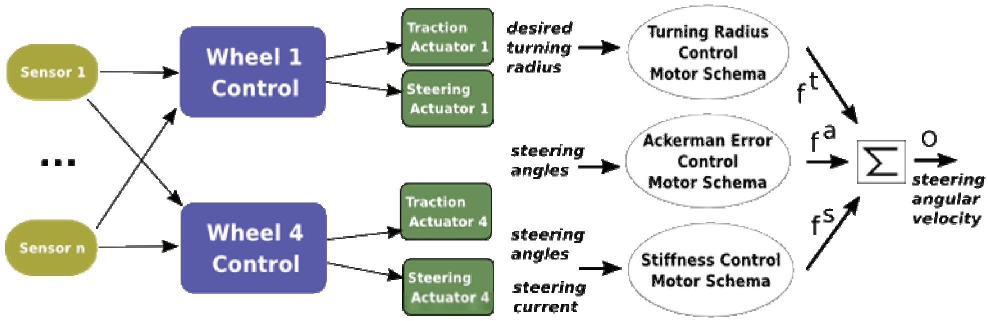
Among the most demanding challenges faced by a robot operating in a complex natural environment is the maintenance of a good performance in transient and extreme situations. This means that, more important than searching for optimal nominal behaviour, it is preferable to design the system to be endowed with graceful degradation. High slopes, loose terrains, fallen branches, etc., usually cause non-nominal states, such as significant lateral slippage and imminent turning over risk. To cope with these, a behaviour-based approach for the locomotion control system has been followed.

In these situations, to be more useful than behaviour-based solutions, model-based approaches require a complete model of the robot's dynamics, kinematics, and robot-terrain interactions. Such a model would be too complex to be used in real time. Rather, reflexive model-free approaches are fast at the expense of a more exhaustive trial and error design phase.

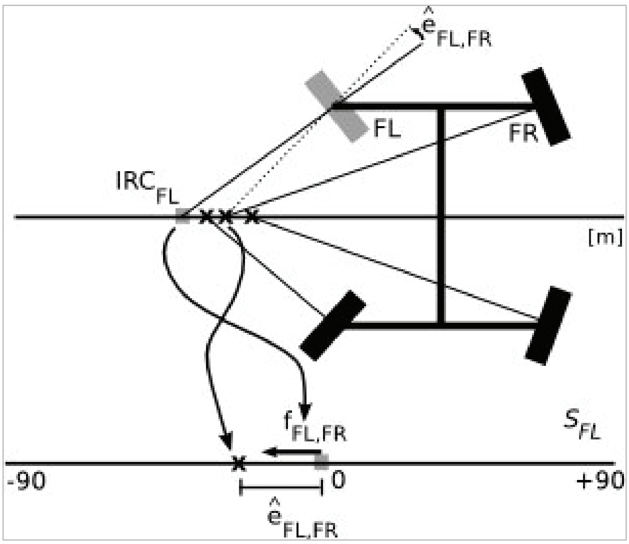
Fig. 6 illustrates part of an intuitive and biologically inspired approach to solve the locomotion control problem for the Ares robot (Santana, P. et al., 2006). The Ares robot, which is a Four-Wheel-Steering Robot (FWSR) encompasses several joints needing effective coordination. Failing to maintain a proper coordination results in wheel slippage, which usually induces mechanical stress, extra energy consumption, and ground disturbance.

Each wheel is seen as an independent entity with its own controller (see Fig. 6a). Each wheel controller is composed of a set of behaviours (see Fig. 6b), each responsible for a partial goal of the wheel, such as maintaining coordination with other wheels, responding to unexpected events (e.g. wheel blocking), or to maintain a target steering angle. A way of specifying each behaviour is by computing a resulting force vector that will be applied to the actuator according to a set of sensory inputs. In this case the behaviour is called motor-schema (Arkin, R. C., 1989).

Each motor-schema creates its own 1-D *potential field space*, designed to produce the desired behaviour. A point in the potential field space corresponds to an angular distance to be travelled by the steering actuator. According to sensory information, goals, etc., a motor-schema populates its potential field space with potential fields that can either attract or repel the steering actuator. The superposition of all potential fields over position zero in the potential field space, produces a "force" which will generate a proportional steering angular speed. As an example, the particular case of the Ackerman error control motor schema is analysed below (see Fig. 6c). First, the motor-schema determines the Ackerman error that the steering actuator *FL* (front-left) has relative to all other actuators. For instance, relative to *FR* (front right), the error is given by $\hat{e}_{FL,FR}$. This value refers to the number of degrees *FL* has to turn so as to guarantee that there is no Ackerman error between both steering actuators, i.e. $IRC_{FL}=IRC_{FR}$.



a) Locomotion control architecture b) Wheel controller



c) Ackerman Error Control behaviour

Fig. 6. Partial view of the behaviour-based locomotion control system

Then, an attractive potential field is added to the potential field space in the position defined by $\hat{e}_{FL,FR}$. This potential field induces an attractive force onto the steering actuator, in order to reduce the Ackerman error relative to *FR* (i.e. $\hat{e}_{FL,FR}=0$). The attraction to one of the steering actuators is then weighed against the attraction to the other steering actuators, following the procedure described above. Since all other wheel controllers are implemented likewise, steering actuators will cooperate implicitly.

Weights are defined empirically. However, their explicit semantic allows the designer to perfectly distinguish how each of them contributes to the intended displayed behaviour.

This is essential to promote fast and easy adaptations in the operations site. Motor-schemas are just a possible way of specifying behaviours. To better handle all types of exceptions, other methods for behaviour specification and coordination are being considered. Refer to (Pirjanian, P. , 1999; Arkin, R. C., 1998) for two thorough surveys on the field of behaviour-based robotics.

4.2.3 The Ares Robot's Perceptual and Localisation System

As mentioned earlier, sensor reuse is essential to reduce costs. With this in mind stereoscopic vision has been selected as the primary sensor to both localisation and environment perception. A 9 cm baseline Videre Design STOC is being used for both purposes. This device already comes calibrated and with enough computational power to provide range information up to 50 Hz. The device is mounted on the front of the robot at a height of 1.30 m (see Fig. 5).

An algorithm based on (Manduchi, R. et al., 2005) has been developed and can be briefly described as follows. A surface ramp is considered part of an obstacle if its slope is larger than a certain value, and if it spans a vertical interval larger than a given threshold. Closer obstacle points are then considered as part of the same object. This approach allows the determination of obstacles in slopped terrain without explicit ground plane extraction, which is a demanding computational task. With this information it is then possible to obtain data about obstacles, such as their approximate size and shape, and consequently reject those that are too small or too sparse. Fig. 7 illustrates the capabilities of such a system, motivating the use of stereo vision as the primary sensor in natural environments. In addition to obstacle detection, the very same sensor can be used for terrain classification and also for visual inspection of ERW.

Fig. 7. A typical result of obstacle detection with the stereo head

As aforementioned, stereo vision is also employed to enhance the localisation system. Two localisation accuracy levels have been defined for the humanitarian demining problem:

- **Accurate relative localisation.** Sensors' output (e.g. landmine and obstacle detectors) must be accurately fused to enable a proper operation of classification, identification, and mapping algorithms. This requires sequential sensory readings to be fused together with an accuracy in the order of one centimetre. Conventional localisation techniques based on relative motion estimation (e.g. dead-reckoning) can provide such accuracy.

- **Global convergence.** Even with one centimetre accuracy in relative motion estimation, the global localisation error grows unbounded when the estimation is integrated over time. Thus, although maintaining a good enough accuracy for landmine classification and identification is attainable with relative motion estimation techniques, geo-referencing each detected landmine requires a global localisation method. Painting the ground when a landmine is detected is an efficient mechanism to allow deminers to detect landmines by visual inspection, even without a proper geo-referencing. Hence, a low resolution (~1 m) global localisation suffices for the humanitarian demining domain.

These conclusions are essential for reducing costs. See for instance that a global localisation in the order of one centimetre accuracy can be achieved with high cost DGPS-RTK systems, which often fail nearby trees and buildings. In these cases it is necessary to estimate the robot's localisation by integrating relative motion and attitude changes. This procedure is commonly known as *dead reckoning*. For this purpose, typically high cost inertial navigation systems (INS) are employed. By relaxing global localisation requirements to one meter accuracy, the cost of a DGPS can be lowered by one order of magnitude. A Novatel EGM-333 has been selected for this. To fulfil the relative localisation role of expensive inertial systems, three low-cost systems are being used:

- A low cost Honeywell HMR 3000 compass is used to provide accurate robot's attitude information. Being based on accelerometer information to determine the pitch and roll of the robot, it is sensible to spurious accelerations.
- Wheel based odometry can be used in smooth terrains, and if carefully considered, can also provide valuable information in uneven terrains (Ojeda, L. et al., 2006).
- *Stereo based visual odometry* estimates the robot's displacement and attitude changes based on the relative motion of visual features perceived by the stereo head. This mechanism can be used in conjunction with the compass and wheel odometry mechanisms to provide accurate relative localisation in smooth, uneven, and sloped terrains.

We have developed an implementation of the stereo based visual odometry technique based on the work of (Agrawal, M. & Konolige, K., 2006). The method is composed of three main computational stages:

- **Feature selection.** The first step is to select landmarks from a 2D image for which the 3D position can be accurately measured.
- **Feature tracking.** In the second step landmarks from the current iteration are matched (i.e. tracked) against the landmarks from the previous iteration.
- **Motion estimation**. With the 3D position of a set of landmark pairs, the motion of the camera, and consequently of the robot, that better describes the relative position change of the landmarks is computed.

Fig. 8 illustrates the results of a typical run of the visual odometry algorithm filtered with compass information (for posture global convergence). The robot was tele-operated in Ackerman mode to perform a loop, i.e. to start and finish the run in the same location, with an average speed of 0.5 ms^{-1}. No special care has been taken in order to adapt the robot's speed to the terrain, which resulted in considerable oscillations felt by the stereo-head. Nevertheless, the positioning error, computed as the Euclidian distance between 'S' and 'E' (i.e. the starting and finishing positions of the robot in the map, respectively), was ~2.6 m, which in a ~50 m run results in an error of ~5%.

Fig. 8. A typical result of the visual-based dead-reckoning system. The estimated path on the left is superposed, with perspective correction, on a view of the terrain on the right. The superposing is illustrative only. The arrows represent the direction of motion, and the robot is on the starting position, represented by 'S' on the estimated path

4.3 Third Stage: Accurate Landmine Detection and Removal

The previously presented Ares robot may become a useful tool for area reduction, helping people to assess the risk when using land. However, it may be essential to clean some specific contaminated area, such as a narrow passage leading to an agriculture field. For this purpose, a machine able to perceive and manipulate the terrain in an accurate and stable way is paramount. Therefore, a robot such as Ares, whose main scanning capability is provided by its own motion, does not cope with these requirements. In addition, being light, the Ares robot is not adequate to transport a robotic arm for ground manipulation. Fig. 9 illustrates a 3D model of the Poseidon robot (Cruz, H. et al., 2005), a well adapted machine for accurate ground analyses and manipulation.

Although the Poseidon robot is still in design phase, its unique features deserve some especial attention. It will be made of aluminium and it has a squared shape with a 3 m^2 effective scanning area. In this area, a 3 DOF scanner will be handling any sort of landmine detection sensor or ground manipulation tool. The stabilization of the frame is ensured by the use of telescopic legs. A power screw and an electric motor actuate this device. These are attached to the structure through a spring which smooths the walking process. The walking movement of the structure is accomplished by means of a 2 DOF mechanism. A complete step can reach up to 3 m. This configuration only allows acting upon a DOF at a time, as illustrated in Fig. 9.

Since, the weight is an important asset, and the structure has large dimensions, the use of aluminium and polymeric material has been selected to reduce the structure weight. For the lateral beams a double "I" shape 190 mm wide, 80 mm high, 3200 mm long and 14 mm thick was chosen. Low cost and wide availability were the main concerns regarding the selection of this shape. These beams support the top scanner and the locomotion sliding structures. However, with such dimensions the beam is heavy, at about 18 kg/m. After a stress study, it was realized that drilling oval holes along the section could reduce the weight without a loss of rigidity. With this re-design, about 25% of its weight has been lost. An asymmetric "I" shape has been selected for the locomotion sliding beams. The use of aluminium provides a lightweight solution and reduces the electromagnetic influence on metal detectors.
The 3 DOF scanner is also built in aluminium whereas the sliding mechanism is made of polymeric material. The use of a polymeric material reduces the maintenance operation (because it does not require lubrication) and allows operation in dust conditions without further protective devices, which simplifies the design process. The sensors fitting zone is designed case by case to ensure a perfect assembly between the sensors and the scanner. The 3 DOF permits a perfect compliance between sensors and ground. Being able to move sensors and actuators in a 3 m x 3 m area without moving the legs makes it the ideal tool for accurate sensor fusion and ground manipulation. Despite being big, the robot will be easily disassembled so that it can occupy little space in an all-terrain vehicle.

Fig. 9. The 3D model of the Poseidon robot

This robot is an upgraded version of a 1 m² pneumatic frame-like robot (see Fig. 10). Being pneumatic, its control is much less precise than that of its electric counterpart, reducing its ability to cope with uneven terrain. In addition, the logistics associated with compressed air for the pneumatic system is much more complex than the one for the electric version.

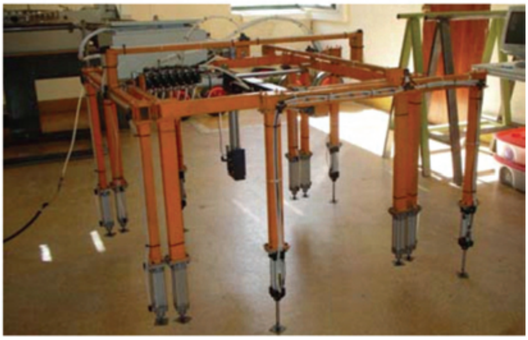


Fig. 10. The pneumatic version of the Poseidon robot

5. Human-Robot Teaming

A demining campaign is better achieved when multiple robots are employed, and in particular when these are low cost and light. However this requires them to be simple and therefore unable to fulfil the mission alone. A multi-robot approach is essential for the previously presented *first stage portable demining kit*, in which several small and simple robots scan wide areas searching for minefields. Consequently, as robots get damaged they must be replaced whenever possible. This requires the system to be highly flexible with scalability properties. It is also known that robotic systems performing complex tasks still require human intervention, or at least supervision. Since expert supervision may only be viable by remote interactions, the system should be *transparent* and *accessible* from any point in the internet.

All these requirements for inter-operability, modularity and scalability, make the use of the multi-agent paradigm a natural solution to the computational backbone of the architecture (Santana, P. & Barata, J., 2005b). Bearing this in mind, the Distributed Software Architecture for Autonomous Robots (DSAAR) (Santana, P. et al., 2006b; Santos, V. et al., 2007) has been devised. In DSAAR, robots and any other resource, are composed of two main layers: (1) the *social ability layer* and (2) the *individual control layer* (see Fig. 11).

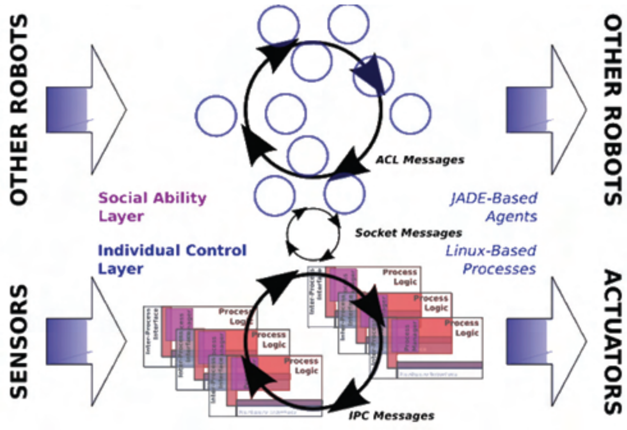


Fig. 11. A robot control system under DSAAR

A set of Jade[1] agents (blue circles in Fig. 11) is responsible for implementing the robot's *social skills*. Hence, these Java agents interface with other agents representing other robots in order to act cooperatively. They also interact with *mission support agents* so that operators can interact with the system. All agents in the system communicate with FIPA-ACL[2] (FIPA compliant Agent Communication Language) messages, according to an ontology specified in Protégé[3].

Ontologies are not just vocabularies, they may represent complex relationships between concepts. A general ontology serves as backbone for the whole system. Then, concepts

1 http://jade.tilab.com/
2 http://www.fipa.org/
3 http://protege.stanford.edu/

maintained in the general ontology are used to build up new concepts, these specialised and therefore useful for specific purposes. An example is the case of the concepts used in tele-operation agent-based communications. Being stripped down versions of more complex concepts, these communication oriented concepts can help in reducing the bandwidth requirements. Nevertheless, all being concepts in the system related to each other through a general ontology, it is possible to maintain a common language throughout the system.
In the bottom of Fig. 11 it is possible to depict a set of entities responsible for the control of the robot's autonomous behaviour. These entities are implemented as Linux processes following an appropriate control model. The previously presented Survival Kit architecture and locomotion control method are implemented at this level.

5.2 Mission Support Agents

To allow an intuitive interaction between operator(s) and robot(s), a set of agent-based tools has been developed. These tools are supported by *mission support agents* which interact with the *social ability agents* present in each resource (e.g. robot). The following text briefly describes two of them, viz. tele-operation and 2D map tools.
The tele-operation tool (Santos, V. et al., 2007) (see Fig. 12) allows the user to control the robot, a camera or both by using a generic USB gamepad. Via the gamepad, the operator can select the robot's locomotion mode, lock either the direction axis or the speed axis while controlling the robot, inspecting the pitch, twist, heading, wheel angle, wheel speed, battery status, and localisation information. All this information is supplied by the robot's *image agent* through ACL messages.
Also fed by the robot's *image agent, t*he 2D map tool (Santos, V. et al., 2007) (see Fig. 12) provides the user with a map along with all its common functionalities, such as zoom in, zoom out and map navigation.

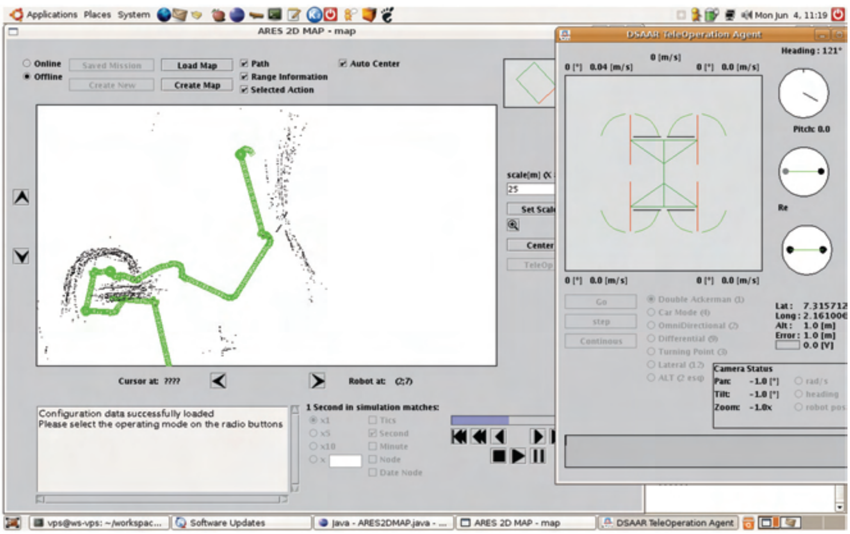


Fig. 12.The 2D map (on the left) and the tele-operation (on the right) tools

The tool provides information in both *off-line* and *on-line* modes. In the former case, the tool can be used to navigate in a previous mission object created with log files produced by the robot. Therefore, it is possible to know what has been done by the robot in a previous mission up to a millisecond resolution. Obstacles and robot localisation/path can be inspected directly in the tool, whereas detailed information about past wheel angles, currents, etc., are provided to the user through the tele-operation tool. The 2D map sends messages to the tele-operation tool as the robot's *image agent*, allowing the operator, in this way, to perceive past and present information through the same interface.
The on-line mode allows the user to see what is actually happening in the the current mission. The obstacles are just low resolution representations of the real world, and are simply superposed in the map as they are detected. Refined occupancy maps are produced on-board the robot, and then provided as bitmaps to populate the 2D map tool's background. This way the communication bandwidth is kept under reasonable levels.

6. Conclusions

This chapter presented some guidelines to build a *portable demining kit*, which is intended to be a fast deployable and affordable robotic system to aid in emergency situations. Since the logistics of a *portable demining kit* are less demanding when compared to a regular demining campaign, local mine action centres, provided with such a tool, will be able to be more responsive to emergency situations, reducing the chances of further victims.
It has been shown that to be successful, these kits must also be self-sustainable. This ranges from requiring simple maintenance, to the fact that they should be usable in other domains. If that is the case, then the owners, local governments for example, can exploit the devices for other purposes.
Several aspects of a sustainable robot capable of coping with the requirements of the mine action domain have been covered. The most important one is related to cost. The robot should be as cheap as possible. For that purpose a solution whose main sensor is stereo imaging has been proposed. This is used for localisation and perception. The localisation system is about one order of magnitude cheaper than conventional localisation systems.
Other essential topics are modularity and interoperability. These two basic engineering principles are paramount in making the system scalable. Scalability refers to the ability to allow elements of the system to be added and removed without inflicting dramatic effects on the system's performance. These elements can be robots and operators. Remote experts should be enabled to be integrated to the system as complications emerge. Modularity and interoperability is handled under the multi-agent paradigm. Furthermore, scalability must also be seen under the light of re-engineering. Add-ons, adaptations, and vertical developments are fostered having a system complying to the multi-agent paradigm.
The major cornerstone for the future work is the testing of the system in an actual demining scenario.

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12

Some Robotic Approaches and Technologies for Humanitarian Demining

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1. Introduction

Landmines, especially anti-personnel, are more-less psychological weapons. The advantages that result from their deployment for one side of the conflict should be eliminated by the availability of fast and reliable detection and neutralization technologies. Then, reasons for their use could be reduced.

Classic methods for detection and removing mines, used at present, are dangerous, too costly and considering the number of mines, are very slow. Within technologies for cleaning most frequently used are mechanical systems (Habib, M.K. 2002). Main drawback of these purely mechanical techniques is that they should mechanically effect on large areas, frequently, without any occurrence of mines. More, no such system can satisfy desired 100% reliability and frequently manual verification of yet cleaned area is required. It should be said that the key problem of demining lies and will be solved if mines are reliably detected and localized. Then the neutralization procedure is directly addressed to this place of mine occurrence.

The overviews of existing research projects, techniques and equipment have been developed for performing particular tasks are listed in several databases (www.gichd.ch; GICHD, 2006; www.hdic.jmu.edu; www.eudem.vub.ac.be) and in several conference proceedings.

The demining tasks represent dangerous works in hazardous environments the safety of human beings and / or valuable equipment then, the emergency management application should takes place. As human safety is the highest priority, the interest is to remove the operator from the hazardous scene and / or either totally to substitute him by an onboard "intelligent" agent - which is expected to provide the same or similar functionality. The first step is to provide the operator by such means that would enable him to perform the same mission safely, i.e. without direct entrance on dangerous terrain and contacts with explosives.

Considering large polluted areas and drawbacks of actual demining technologies main contributions by using robotic technologies are expected in following topics:

- Searching large areas and localization of mines and any explosives (UXO) by fast and reliable way.
- Fast and reliable neutralization/destruction of mines without the need of personal assistance to be inside, or close, to dangerous places.

Performing these tasks by a "robot" is a big challenge for research in all domains of robotics. Oriented research is especially desired in the following domains (Ide et al., 2004; Wetzel & Smith, 2003; Mori et al. 2005; Hae et al. 2005). There are especially:
- *Mobile robotics.* Such a robot should be autonomous or semi-autonomous vehicle, easily transportable, and cheap. It should be able to move in various terrains (holes, slopes, stones, etc.) with possible obstacles (trees, weed coppice, wickets, waters, etc.) and to resist accidental explosions of mines. For neutralization of mines it is equipped by one or several appropriate mine removing or / and explosion activating systems.
- *Sensing technology.* Detection and localization of mines in terrain has a crucial importance in demining operations. Considering great number of types of produced mines (different forms, plastic materials, colors, etc.), variety of terrain as well as possibilities of hiding mines in various terrains the reliable detection equipment is highly desirable. Such a detection system should perform using more sensing principles and fusing sensory information. This naturally includes elaboration of reliable recognition algorithms.
- *Control and communication system.* The perception and information system includes several smart sensors need for the mobility control, searching dangerous terrain, localizations of targets, obstacle avoidance and navigation. All these functions suppose large amount of transferred data via wireless communication.
Much research work has been yet done in the domain of detection and localization of mines. Beside known methods new sophisticated sensing principles able to detect and recognize mines, as hidden objects, are under development. This is the most crucial task in the whole process. Because of automatic demining process is based on using special robotic vehicles / agents further research is oriented to the development mobile agents able to operate in, or, above the dangerous and partially unknown terrain as porters of detection systems and other tools used for preparing place of occurrence of mines and their neutralization, as well. Some robotic concepts and problems related to terrestrial demining are discussed below.

2. General Considerations

2.1. Robotic Approaches

Many research projects and lot of research work has resulted in design of several concepts of demining technologies as well as development new machines and especially detection systems. But, despite this effort and promising performances in laboratories, several sophisticated solutions and systems did not find such acceptance in practical use as was expected.
Designing a robotic technology the first idea is to construct the universal all terrain robotic system, highly mobile, lightweight, that could be immediately set to demining works all around the globe. Although such an idea could be realizable, when one considers the current state of technology, there is no reason to spend so much money and enormous human effort to develop such a complicated high-tech and enormously expensive system. Any robotic system should satisfy specific conditions directly related to its local application (Antinić, et al., 2001). Let us mention some reasons that directly influence the choice and use the adequate technology:

Principal requirements
When analyze actual situation in technology for humanitarian demining and compare its application one can deduce some principles:
Mechanics and mechanisms. Reliability and light-weight robust mechanics is preferred and desirable. The equipment should be easy, or, self – deployable directly on the minefields.
Electronics. HW and SW parts need not to be built on the most sophisticated technology. More important is that all systems should resist any possible actions due to errors of operators, shocks during transport, etc.
Sensors/detection systems. Development and availability of cheap, light-weight and reliable sensors can certainly solve the majority of searching problems.
Control. Remote or semi-autonomous control that reduces the risk of human operator is desired. The complexity and level of training for local operators should correspond to their local talent and technical education. An understandable and robust system with minimum training effort is preferred.
It is obvious that all parts of the system should be adequately robust to sustain not only harsh working and climatic conditions but some possible accidental explosions too. It should be said that any complex repair to be made on place is very limited. Beside acceptable performance parameters the robotic system should exhibit a "self- recovery" capability. This means that it could be removed from the minefield without access or interventions of humans.

Economy.
Mines are deployed in post – battle regions where mainly local materials, local manufacturing and local manpower should be used to perform demining operation and to maintain all technology. Technical knowledge of people is very limited and access to high-technology components is almost absent. Usually the economy of such regions does not work, or, it is totally destroyed. Demining operations are then usually financed by donor organizations. It is obvious that under such conditions using low-cost demining equipment, including standard hand searching and neutralization technologies are more preferred.

Psychological aspects.
Humanitarian demining requires the high level of confidence that all mines have been detected and neutralized. This naturally results that any technology should guarantee practically 100% reliability of cleaning. When consider that deminers (professionals or locally engaged) doing this dangerous task are always under psychological pressure. They are usually not able to master a complex robotic system including its operation, maintenance and possible repairs. Otherwise specialists should be trained what considerably increases cost of demining woks. It should be said that the confidence of demining personals to the technique plays an important role otherwise it can be hardy accepted.

2.2. Main Rules and Criteria

Before consideration about a robotic system to be in use on the minefields there are some main rules have to be respected yet in conceptual design. Let us mention some main rules that should be taken into account before starting a new development of any equipment:

- **Minefields are not laboratories.** Robust and reliable constructions as well as control techniques should correspond to harsh working conditions and environment. This includes solving so called "self-recovery strategies" in most crucial situations that could arise (occasional explosions, errors in systems / operators, lost of communication, etc.).

- **The cost and availability of detection as well as neutralization technologies** is a very important factor that could limit their mass use in post conflict areas. Robotic cleaning should be faster (as to productivity in m^2/hour), cheaper (as to total cost/m^2) comparing to standard hand methods, reliable and safe.
- **Any new demining technology should be easily accepted by local authorities and people.** The robotic system should satisfy specific conditions related to its local application demands (country people and their education experiences, infected terrains, climatic conditions, type of mines, maintenance, etc).
- **There are no universal solutions.** Robotic technology cannot totally replace humans in all phases of demining process. Some robotic approaches should replace some most dangerous searching / neutralization methods. Automatic ways are especially suited for primary detection and cleaning large areas under some homogenous conditions (obstacles, mines, vegetation, etc.).
- **The reliable detection and localization of mines** (UXO) as targets is the task of primary importance. It can be said: "As soon as the mine is found and localized more then 90% of problem is solved".
- **Any new solution should minimize risks for people**, as well as for the damage of relatively expensive technology. This risk of the damage, or, the lifetime by using new technology should be calculated in expected comparable total cost for demininig the unit of surface.

2.3. Requirements on a Robotic System

The demining equipment beside maximal reliability, should guarantee some standards given for particular devices. The effort for standardization of main functional characteristics resulted in CEN workshop agreement "Test and evaluation of demining machines" (CEN 2004). Similarly, when consider a new robotic system there are several criteria should be taken into account. There are as follows:

Operational criteria

- Working efficiency / neutralization capability
- Reliability of cleaning
- Self-recovery capabilities
- Working time to change and repairs, availability of spare parts
- Diagnostics and maintenance
- Way of the operation / control and level of autonomy

Technical parameters

- Performance characteristics of the mobility / positioning systems (positioning accuracy, speed, allowable slopes, payloads, masses, maneuvering capabilities, etc.)
- Characteristics of detection systems (detectors and reliability of recognition)
- Neutralization and cleaning tools (reliability of cleaning)
- Control and communication systems (distance, data transmission, etc.)
- Mines and protection against explosions
- etc.

Applicability

- Working conditions (environment, terrain, types of mines could be destroyed, etc.)

- Transport to minefields
- Technical level / skills of operators
- Integration with respect to other technologies
- Additional attachment / auxiliary equipment (the set of exchangeable tools could be used not only in demining process)
- Acceptability (friendly) by local people / operators

Cost and economy

- Total cost of the system (including services)
- Working costs (price / working hour, price / m^2 of cleaned area, etc.)

2.4. Some Specific Features

When characterize main functions of a robotic system for demining: it should be a remotely / programmable controlled general porter of several detection systems able to perform searching dangerous terrain, localize and neutralize dangerous targets. It should exhibit excellent mobility and maneuvering capabilities in various terrains. General demand is for such an agent working in risky environment is that it should exhibit three following features: self-recovery capability, minimal risk assessment and maximal reliability in all actions.

The self-recovery performance is an important and specific feature directly related to particular tasks. Its main purpose is to prevent / to avoid loses or self-destruction of the agent and to finish a given action in risky environment without serious damages. The self-recovery strategies should start especially in unwanted situations as follows:

- In cases of any failure of technique (communication, engine, control system, sensory system, etc.). The problem is to remove it from the dangerous terrain without any risk for persons. One of the simplest ways how to solve such situation is using a cable and to pull it out by the winch mechanisms. The other possibility enables using another vehicle, which helps to remove the first one from the minefield.
- There are no / not enough information for further action. It seems to be risky situation to continue any motion; otherwise there is a probability that it could be destroyed. Solving such situation brings for operator / operation system the decision problem: to decide for the next action if any unexpected situation arose. The general rule is: the operator decides for the next paths of the agent in order to minimize any risk of damages for the agent itself. Naturally he should use all available sensor readings and information. This procedure represents the standard decision algorithms according to the scheme for risk assessment in Fig. 1.

It is obvious that some decisions can be represented by relatively simple routines working over a given set of options: Action : <STOP / GO BACK / … > if .< CONDITION: SENSOR ->. On the other hand, other operator’s decisions require much more complex assessment of possible risks with respect to given criteria. Such a typical situation arises during automatic demining operation when using mine detection systems give not reliable information about the presence of mines and there is only a suspicion if “something is inside”. In such cases the general rule is usually adopted: “the risk is minimized if one considers that there are always expected some mines”.

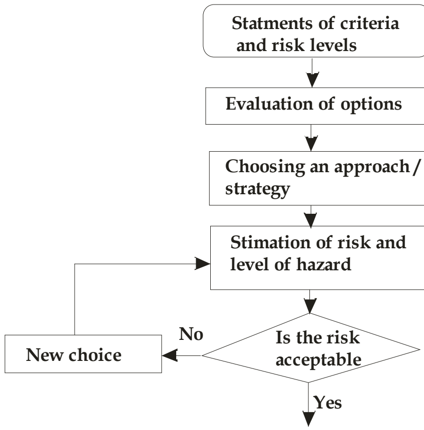


Fig. 1. The general risk assessment and decision procedure

3. Approach to Robotic Demining

3.1. Desired Performance

In general, the mine cleaning procedure consists of two main tasks:

- Detection and localization of land mines.
- Neutralization i.e. removing or destruction of mines on place.

These both tasks are usually directly related to the common problem and third important task:

- Preparing infected terrain for reliable detection as well as for neutralization procedures, i.e. removing vegetation and any obstacles that could prevent detection or safe neutralization.

Considering large polluted areas and drawbacks of actual demining technologies main contributions by using robotic technologies are expected in following topics:

– Searching large areas and localization of mines and any explosives (UXO) by fast and reliable way.
– Fast and reliable neutralization/destruction of mines without the need of personal assistance to be inside or close to dangerous places.

As obvious, any robotic system can effectively work under some standard and expected conditions / environment. Performing demining activity this means that there are given some standard working environment and its capability as to maneuvering of the mobility system, reliable detection of mines and desired confidence level of neutralization equipment. This practically results in fact that automatic demining technology will be preferably used for cleaning large homogenous terrains without complex obstacles (vegetation, terrain, trenches, etc.). Beside such complex automatic equipments several task oriented semi - automatic, or remotely controlled devices can effectively take place. There are especially robotic vehicles and tools for searching dangerous terrains, robotic tools for neutralization of explosives / mines and tools for preparing terrain for demining. Naturally, a principal role in the whole demining process is given to the development of reliable detections techniques and technology.

3.2. Parts of the Global Robotic System

When consider a most general robotic mine clearance technology an advanced system consists of following parts. See Fig.2. (Havlik, 2004)

Mobility system. It is represented by remotely controlled / autonomous / semiautonomous mobile (robotic) vehicle, as general porter of sensory platforms and other manipulation systems for performing three principal tasks: detection, preparing terrain and neutralization. In principle, there are following possibilities:

- Free flying vehicles with suspended platform i.e. airborne mission mainly for searching especially large areas.
- Ground vehicles (wheeled / belt or walking / legged machines)
- Cable suspended platforms moving over the dangerous terrain

Multi-sensorial system for detection and recognition of mines. As to sensing principles automatic detection techniques should satisfy reliable detection / recognition of mines and to mark them into maps (assign them coordinates) as targets. In principle, the sensory systems can be situated on a special platform of a mobile vehicle performing scanning dangerous terrain or on the end of a robotic arm.

As obvious, some principles are more suited for searching large areas to detect the existence of minefields (infrared, chemical, bacteria) and the others should enable precise localizations of particular targets.

Tools for neutralization / destruction of mines. Beside mechanical systems as for instance: rollers, ploughs, flails, rakes, hammers, …etc, other principles that activate explosion of mines can be used. There are: explosive hoses, fuel air mixture, directed energy systems, laser, microwave sources or sniper rifle. For the mine removal tasks there are special end-effectors in forms of double shovels, diggers, etc. Input data for these systems are positions / coordinates of mine targets as well as actual sensory information (vision, tactile, force and other available sensors).

Tools for removing obstacles / vegetation and preparing terrain. Mines after some years of deployment are covered by sand (in desert conditions), ground, vegetation, masking means, etc. For removing these obstacles different remotely operated tools with sensory feedback should be developed. There are: sand suckers, cutters, shovels, special grippers, diggers and probes, etc.

Control and communication systems. Principal requirement is that the system should operate in remote control mode, or, semi-autonomously. As to the control a general system includes: mobility navigation / control, target positioning for detection, as well as neutralization systems.

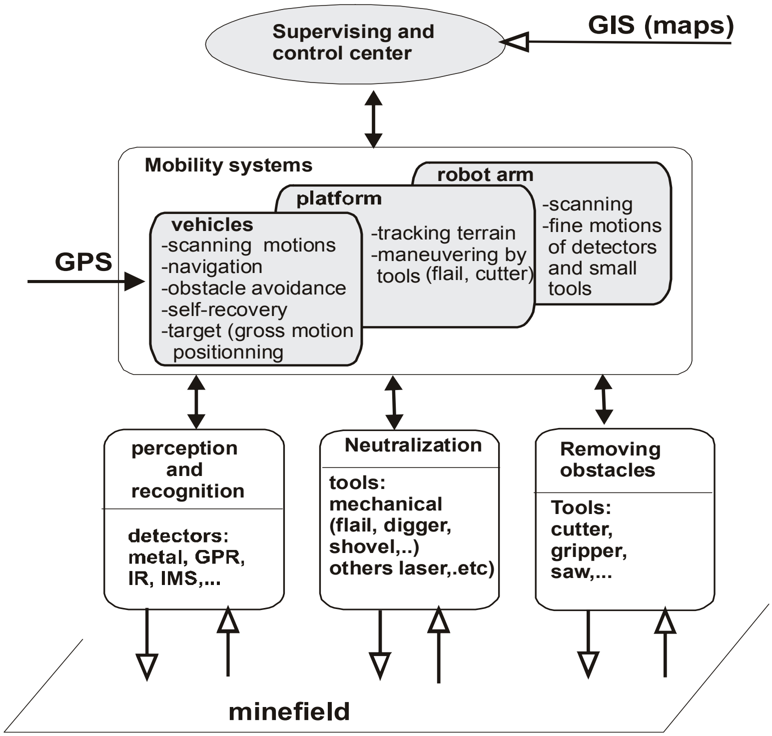


Fig. 2 Parts of the robotic demining system

3.3. Analysis of Motions and Functionality

When analyze main tasks of the demining process from the position / motion control point of view, positions are related to the base – field reference coordinates. Then, for displacements, two characteristic categories of motions can be distinguished. There are:

Gross motions, of the vehicle usually measured by GPS or other measuring system; for instance laser. As to the accuracy of positioning, as well as recording targets into digital maps it should correspond to the resolution of positional measurement.

Fine motions are performed by any of on/board tools (robot arm, platform). These motions are related to the vehicle reference system.

Some characteristic features of particular motions are in next table.

	Gross motions	Fine motions
Tasks	- Global positioning - searching/scanning motions - mapping targets - marking - flailing	- Fine motions scanning - removing mines /obstacles
Mechanisms	vehicles	- on-board robot arm and tools, - sensory platform
Desired positional resolution	< 10 m for aerial vehicle 0,3 - 0,5 m for ground vehicles (in global references)	< 2-5 mm (relative coordinates)
Sensing - primary positional control - adaptive positional control	GPS, laser, camera, etc. Sensors for vehicle-environment interaction: (mine detectors, obstacle detectors, etc..)	Internal sensor in joints of mechanisms. Sensors for tool-environment interaction (hand-held mine detectors, hand camera, force-tactile sensors, etc.).

Table 1. Motion characteristics of robotic systems

It should be noted that some operations procedures require more precise positioning of tools, then the others. For instance: the flailing destruction techniques must not so exact coordinates of targets for successful function. On the other hand removing mines requires relatively much more precise positional information for any control action.

Compare now some different performance requirements between particular tasks and classic robots used in manufacturing (see table 2). Let the characteristic measure be *m* - meter.

	Manufacturing	Demining
Range of the operation space	m	m. 10^2 ($\div 10^3$)
Positioning Accuracy / Accepted resolution	m. 10^{-4}	m.10^{-3}
Order difference	4	5 (6)

Table 2.

Because of there are considered two dependent positioning mechanisms, obviously, it is not possible to reach such an accuracy under all possible errors that could arise. For this reason the approach that includes elimination of possible uncertainties should be applied in control. Some robotic concepts some principal motion routines for control of robotic vehicle are given below.

4. The Global Concept "ANGEL"

One of the most general concepts "ANGEL" considers activity of two missions: aerial and ground, having a common operation / information center (ANGEL, 1998). . Main function

of this operation center is to collect information, planning activities and evaluation of actual situations as well as controlling agents for detection and neutralization. The system operates with GPS data over digital GIS maps.
The agents for performing these tasks can be, in principle, aerial or ground vehicles that satisfy desired mobility features and are provided by adequate technology equipment, depicted in Fig.3.
Flying vehicle. Aerial searching is especially suited for first scan of large areas. Unmanned flying vehicle – small helicopter for this purpose is equipped by a special platform with several detection systems. The helicopter performs scanning motions over the terrain and as soon as any suspicion on mine (UXO) will arise coordinates of this place are saved into operation map. More precise localization of particular mines is doing by ground detection vehicle in next searching.

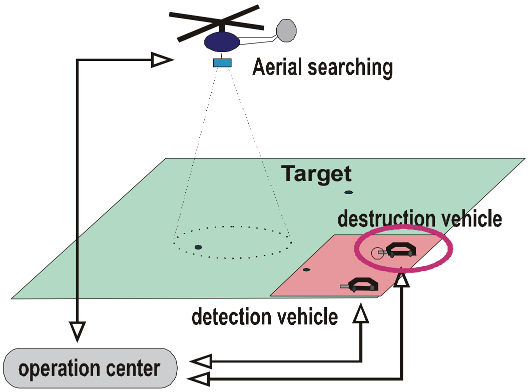


Fig. 3. The global concept of demining

Land vehicle for detection. The vehicle automatically moves to address coordinates according digital map where an explosive was observed / detected by aerial searching. Its task is to localize exact position of targets, and / or to mark them by a visible color. The vehicle as porter of multi-sensorial system should exhibit very good maneuvering and control capability in various terrains as well as autonomy features that enables to avoid obstacles, using remote vision system, etc. To prevent any accidental explosion of mines automatic stop and further searching procedure are activated. From the point of view mechanical performance there are some several specific requirements that such a vehicle should satisfy (maximal pressure on the ground, velocity related to speed of detection systems, noise and temperature limitation, reliable power and communication systems, self recovery capabilities, etc).
Neutralization – mine destruction land vehicle. This vehicle with similar maneuvering and control capabilities has to approach to the position of a detected mine and to neutralize it by activation or removing procedure. For this reason it has to be protected against explosions of mines not only antipersonnel but anti-tanks too.
Functional part of both above vehicles is the robotic arm with a set of tools for removing obstacles / vegetation or for neutralization procedure.

5. The Cable Suspended Searching Platform (Conceptual Study and Analysis)

5.1 The Principle and Main Parts

For searching dangerous terrain and relatively large operation space the concept of the cable suspended robotic platform was designed (Havlik, 1993, Havlik & Licko 1998).
In principle the system, as schematically illustrated in Fig.4, consists of three cable winches fixed on mobile columns. The ends of cables from particular winches are connected on the platform moving above the working place. Each winch mechanism is equipped by the cable length measuring sensor and the position / velocity control system. Thus for such a parallel mechanical structure any actual position of the moving platform determine three distances i.e. measured lengths of cables between the platform and end pulleys of winch mechanisms. The central control system performs transformations and coordinated motion control of the platform with respect to a world reference frame defined on place. Principal functional parts of the whole system are depicted in Fig. 5.

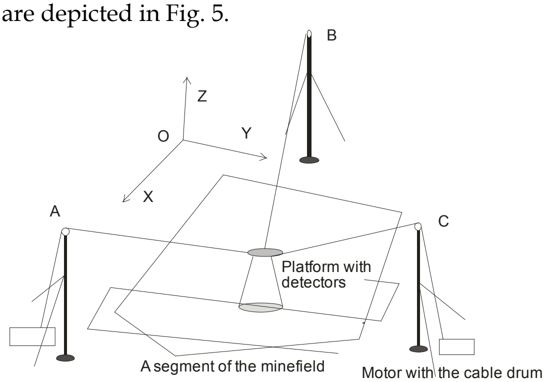


Fig. 4. Concept of searching dangerous terrain

This concept of scanning dangerous terrain by the suspended platform with detectors exhibits some advantageous features as follows:
Large workspace of operation which is reconfigurable according to actual terrain conditions
Low weight and simple transport
Fast and simple installation on place
Operation / control in Cartesian coordinates defined directly on place.
Using joystick, or programmable control it is possible to move the platform in a given scanning distance over the terrain. The Cartesian positions, i.e. x, y coordinates of any target are set into map, or, can be directly marked by colors. It is obvious that the operation space is given by the triangle created by the fixation positions of the end pulleys. It is approximately above the ground projection of this fixation triangle. As can be seen later, the upper boundary surface is given by the limit force in particular cables / fixations.

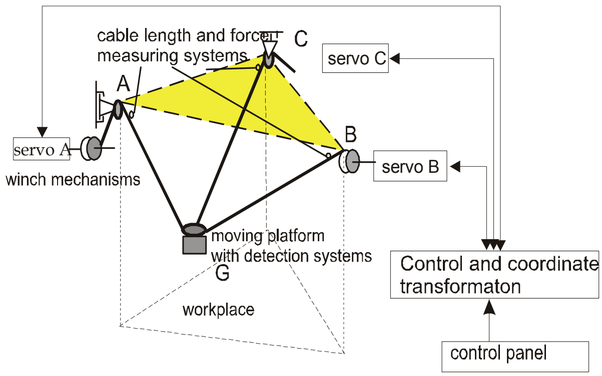


Fig. 5. Principal functional parts

5.2 Analysis of Motions and Control

Four main problems have been solved for this system. There are:

- ***Kinematic and force analysis.*** The task is to derive relations for motion and force transformation i.e. functions that relate actual motion and load values expressed in world reference coordinates and internal representation of control parameters i.e. cable length and internal forces.
- ***Coordinated motion control*** in world coordinates. This is a principal requirement to control and monitor scanning motions of the platform in Cartesian references mutually related to world references. Then, positions of targets are directly localized.
- ***Dynamic analysis and control***. As follows from principal configuration the cable system exhibits limits that should be automatically adjusted.
- ***Calibration,*** i.e. to actualization of parameters in relations for motion and force transformations according to real configuration of the system and its spatial geometry.

Let us briefly explain solutions of these problems.

For the purpose of analysis following reference systems are stated on the geometrical scheme in Fig.6):

- O(x,y,z) the Cartesian world coordinate system of global positioning, Denote the fixation points A,B,C that create the triangle ΔABC above the working area. Each point of this triangle is given by three global coordinates $A(x_A,y_A,z_A)$, $B(x_B,y_B,z_B)$ and $C(x_C,y_C,z_C)$.
- A(x',y',z') the auxiliary Cartesian reference system where x',y' axes lie in the plane given by triangle ΔABC

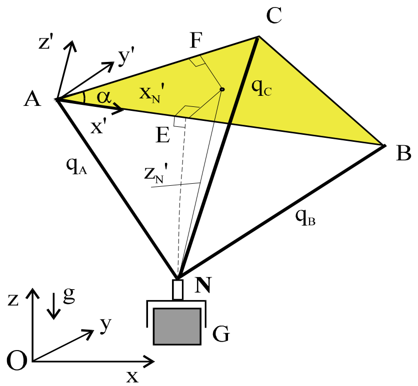


Fig. 6. Geometry of the cable support

Let point N be the reference on the moving platform. Its position gives the vector $\boldsymbol{p'}_N = [x'_N, y'_N, z'_N]^T$ in the A(x',y',z') local coordinate system or $\boldsymbol{p}_N = [x_N, y_N, z_N]^T$ in the global Cartesian references. These position vectors are mutually related using transformation

$$\boldsymbol{p}_N = \boldsymbol{p}_A + \boldsymbol{S}.\boldsymbol{p}'_N \tag{1}$$

where $\boldsymbol{S}$ is the 3x3 rotation matrix of local coordinates into global references..
Denote by symbols: q_A, q_B, q_C ; the lengths of cables as controllable values. For the simplicity of calculations we will consider dimensions of the moving platform with respect to triangle ABC to be relatively small and negligible. Then, for such an actual tetrahedron ABCN one can write

$$\begin{aligned} q_A^2 &= (x'_N - x'_A)^2 + (y'_N - y'_A)^2 + (z'_N - z'_A)^2 \\ q_B^2 &= (x'_N - x'_B)^2 + (y'_N - y'_B)^2 + (z'_N - z'_B)^2 \\ q_C^2 &= (x'_N - x'_C)^2 + (y'_N - y'_C)^2 + (z'_N - z'_C)^2 \end{aligned} \tag{2}$$

Express now the actual position of the platform in global world coordinates for any combination of three controlled lengths of cables. Solving the above relations we have a unique solution for the Cartesian position $\boldsymbol{p'}_N$, when a combination of cable lengths q_A, q_B, q_C is given.

$$\begin{aligned} x'_N &= \frac{1}{2.\overline{AB}}(q_A^2 + \overline{AB}^2 - q_B^2) \\ y'_N &= -\frac{1}{tga}x'_N + \frac{1}{sina}\cdot\overline{AF} \\ z'_N &= (-)\sqrt{q_A^2 - x'^2_N - y'^2_N} \end{aligned} \tag{3}$$

where according to Fig.6

$$\overline{AB}^2 = (x_A - x_B)^2 + (y_A - y_B)^2 + (z_A - z_B)^2$$
$$\overline{AC}^2 = (x_A - x_C)^2 + (y_A - y_C)^2 + (z_A - z_C)^2$$
$$\overline{BC}^2 = (x_B - x_C)^2 + (y_B - y_C)^2 + (z_B - z_C)^2$$
$$\overline{AF} = \frac{1}{2.\overline{AC}}(q_A^2 + \overline{AC}^2 - q_C^2)$$
$$\alpha = arccos(\frac{\overline{AB}^2 + \overline{AC}^2 - \overline{BC}^2}{2.\overline{AB}.\overline{AC}})$$

Direct task of kinematics

The position and motion of the platform is specified by three control parameters arranged into vector $\boldsymbol{q} = [q_A, q_B, q_C]^T$. The task is to express the motion in the global references. As derived above we calculate the actual global position is given by transformation (1).
Applying the time differentiation we have for velocities

$$\dot{\boldsymbol{p}} = \boldsymbol{J}_0 . \dot{\boldsymbol{q}} \tag{4}$$

and because of the Jacobi matrices $\boldsymbol{J}_A$ and $\boldsymbol{J}_0$ for incremental motion/velocity in local and global reference frames are related $\boldsymbol{J}_0 = \boldsymbol{S}.\boldsymbol{J}_A$ one get

$$\dot{\boldsymbol{p}} = \boldsymbol{S}.\boldsymbol{J}_A . \dot{\boldsymbol{q}} \tag{5}$$

Inverse task

For a given global position $\boldsymbol{p}$ we are looking for control parameters in the vector $\boldsymbol{q}$. Considering (2, 4) one can directly write for cable velocity and acceleration

$$\dot{\boldsymbol{q}} = \boldsymbol{J}_0^{-1}.\dot{\boldsymbol{p}}$$
$$\ddot{\boldsymbol{q}} = \boldsymbol{J}_0^{-1}(\ddot{\boldsymbol{p}} - \boldsymbol{J}_0\dot{\boldsymbol{q}}) \tag{6}$$

where inverted Jacobi matrix is in form

$$\boldsymbol{J}_0^{-1} = \begin{bmatrix} 1/q_A & 0 & 0 \\ 0 & 1/q_B & 0 \\ 0 & 0 & 1/q_C \end{bmatrix} * \begin{bmatrix} x_N - x_A & y_N - y_A & z_N - z_A \\ x_N - x_B & y_N - y_B & z_N - z_B \\ x_N - x_C & y_N - y_C & z_N - z_C \end{bmatrix} \tag{7}$$

Force analysis

Denote by Q_A, Q_B, Q_C cable forces in tension and define the vector $\boldsymbol{Q} = [Q_A, Q_B, Q_C]^T$. Considering a possible external force $\boldsymbol{P} = [P_x, P_y, P_z]^T$ the load on the platform will be $\boldsymbol{F} = \boldsymbol{G} + \boldsymbol{P}$. Applying principle of virtual works one can write

$$\boldsymbol{Q}^{T}.\Delta\boldsymbol{q} = \boldsymbol{F}^{T}.\Delta\boldsymbol{p} \tag{8}$$

Solving this relation the forces in cables and external load are related

$$\boldsymbol{Q} = \boldsymbol{J}_{0}^{T}.\boldsymbol{F} \tag{9}$$

As follows from decomposition of an external load the values of three cable forces will increase with increasing *z*-coordinate of the platform position.
Naturally, in order to avoid an overload condition and to protect the system all cable forces should be supervised on maximal their values. These maximal cable forces give the upper boundary surface that limits the workspace. An example of the workspace analysis for a real geometry is given below. The upper limit surface of the operation workspace is given by boundary conditions

$$Q_{i} \leq Q_{lim} \tag{10}$$

<u>Dynamics</u>
The system dynamics in Cartesian space is described by equations

$$m\,\ddot{\boldsymbol{p}} + \boldsymbol{G} + \boldsymbol{P} = \boldsymbol{J}^{-T}.\boldsymbol{Q} \tag{11}$$

As follows from principle each cable force should be non-negative ($Q_i > 0$). This fact states the limit condition for maximal acceleration of the desired trajectory of the moving platform. Thus from (10, 11) it should be satisfied

$$\ddot{\boldsymbol{p}} \geq \boldsymbol{g} \tag{12}$$

where $\boldsymbol{g} = [0 \;\; 0 \;\; -g]^{T}$
<u>Control</u>
In general, the dynamics of the system with rigid cables is described in cable coordinates as follows

$$\boldsymbol{M(q)}\,\ddot{\boldsymbol{q}} + \boldsymbol{C(q,\, \dot{q})}\dot{\boldsymbol{q}} + \boldsymbol{D(q)q} \;= \boldsymbol{Q} \tag{13}$$

where ***M, C, D*** are (3x3) matrices that represent terms for inertia (**D**), Coriolis, centrifugal and friction forces **(C)** and gravity forces (**D**).
Rewriting equation (11) into this form the system has to be controlled will be

$$m\,.\boldsymbol{J}^{T}.\boldsymbol{J}\;\;^{1}(\ddot{\boldsymbol{p}}\quad \dot{\boldsymbol{J}}\dot{\boldsymbol{q}}) + \boldsymbol{J}^{T}(\boldsymbol{G} + \boldsymbol{P}) = \boldsymbol{Q} \tag{14}$$

where

$$u = \ddot{p} = A.K_v(\dot{p} - \dot{p}_d) + K_p(p - p_d) - \ddot{p}_d \tag{15}$$

is the control vector, K_v, K_p are positive definite matrices and index d denotes desired values. Rem.: The choice of these matrices in some optimal sense is not the objective of this paper.

5.3 Calibration procedure

As soon as all three winch mechanisms with end pulleys have been installed on place we do not know the coordinates of the fixation points vectors $p_i = [x_i, y_i, z_i]^T$, i = A, B, C ; need for kinematic and force transformations. There is an initial problem: we have to execute calibration i.e. to actualize the parameters in relations for motion and force transformations for a real arrangement of the whole system. Principal requirement is to perform this calibration without any additional equipment.
In order to find the unknown coordinates of the A, B, C points the following calibration procedure is proposed in four steps:

a) Let us stake out three points M, N, and P on the ground x-y plane. These points create a triangle with known geometry. Although, in principle, this triangle could be chosen quite arbitrarily, it is more advantageous will be to construct it equilateral, as depicted in Fig.7.

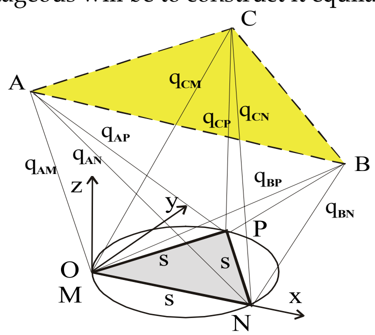


Fig. 7. Geometry for calibration

b) Using individual command of particular servos we perform positioning of the platform sequentially into points M, N and P. Denote by symbols: q_{AM}, q_{BM}, q_{CM}, q_{AN}, q_{BN}, q_{CN} and q_{AP}, q_{BP}, q_{CP} all measured lengths of cables that correspond to particular positions according to Fig.7.

c) Solving three tetrahedrons MNPA; MNPB and MNPC, the coordinates x,y,z of A,B,C points are calculated.

Consider now the equilateral triangle MNP; (MN = NP = PM = s; $s = R\sqrt{3}$). The position vectors and coordinates of these points are

$$\begin{aligned} \boldsymbol{p}_{N1} &= [\boldsymbol{0} \quad \boldsymbol{0} \quad \boldsymbol{0}]^T \\ \boldsymbol{p}_{N2} &= \left[R\sqrt{\boldsymbol{3}} \quad \boldsymbol{0} \quad \boldsymbol{0}\right]^T \\ \boldsymbol{p}_{N3} &= \left[\tfrac{1}{2}R\sqrt{\boldsymbol{3}} \quad \tfrac{3}{2}R\sqrt{\boldsymbol{3}} \quad \boldsymbol{0}\right]^T \end{aligned} \tag{16}$$

Then, after substitution into (3) solutions for i = A,B,C will be

$$\begin{aligned} x_i &= \frac{1}{2R.\sqrt{3}}\left[q_{i1}^2 + (R.\sqrt{3})^2 \quad q_{i2}^2\right] \\ y_i &= \frac{1}{6R}\left[q_{i1}^2 + q_{i2}^2 \quad 2q_{i3}^2 + (R.\sqrt{3})^2\right] \\ z_i &= \sqrt{q_{i1}^2 \quad x_i^2 \quad y_i^2} \end{aligned} \tag{17}$$

d) Actualize the transformation matrix $\boldsymbol{S_{0A}}$ in (1) that relates actual configuration of fixation points A,B,C with respect to a given ground reference system O(x,y,z). Let us denote the elements of this transformation matrix

$$S_{0A} = \begin{vmatrix} s_{11} & s_{12} & s_{13} \\ s_{21} & s_{22} & s_{23} \\ s_{31} & s_{32} & s_{33} \end{vmatrix} \tag{18}$$

In order to calculate particular elements that express rotation of two reference systems one can write

$$s_{11} = \cos a_1 = \frac{x_B - x_A}{|AB|}\;; \qquad s_{21} = \cos\beta_1 = \frac{y_B - y_A}{|AB|}\;; \qquad s_{31} = \cos\gamma_1 = \frac{z_B - z_A}{|AB|}$$

$$|AB| = \sqrt{(x_B - x_A)^2 + (y_B - y_A)^2 + (z_B - z_A)^2} \tag{24}$$

and

$$s_{13} = \cos a_3 = \frac{n_x}{|\boldsymbol{n}|}\;; \qquad s_{23} = \cos\beta_3 = \frac{n_y}{|\boldsymbol{n}|}\;; \qquad s_{33} = \cos\gamma_3 = \frac{n_z}{|\boldsymbol{n}|}$$

$$\boldsymbol{n} = \overrightarrow{\boldsymbol{AB}} \times \overrightarrow{\boldsymbol{AC}} \tag{25}$$

where $\boldsymbol{n}$ is the vector perpendicular to the plane given by triangle ABC. It is calculated as the cross product of multiplication of two vectors $\overrightarrow{AB}$ and $\overrightarrow{AC}$ and $|\boldsymbol{n}|$ is its absolute value.

$$s_{21} = \cos a_2 = \frac{r_x}{|\boldsymbol{r}|}\;; \qquad s_{22} = \cos\beta_2 = \frac{r_y}{|\boldsymbol{r}|}\;; \qquad s_{23} = \cos\gamma_2 = \frac{r_z}{|\boldsymbol{r}|}$$

$$\boldsymbol{r} = \boldsymbol{n} \times \overrightarrow{\boldsymbol{AB}} \tag{26}$$

Similarly $\boldsymbol{r}$ is the vector that complements the orthogonal reference frame $\overrightarrow{\boldsymbol{AB}}$, $\boldsymbol{n}$, $\boldsymbol{r}$.

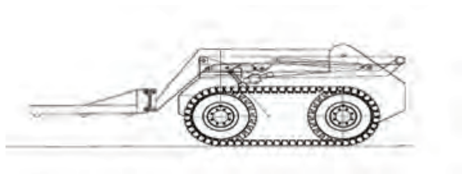
Each new installation of this mechanical system requires adaptation of all transformations with respect to real configuration. The procedure includes mathematical model of the system that consists of following basic programs:

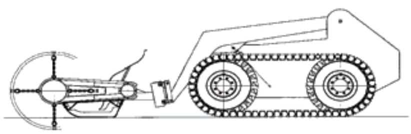
- Calibration according to the described procedure.
- Solving the direct and inverse tasks of kinematics
- Calculation of Jacobi matrices
- Force analysis for quasi static and dynamic cases.

6. Land Robotic Vehicles

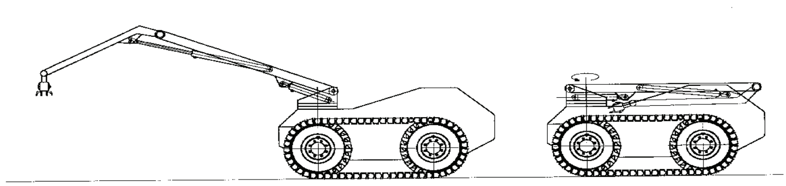
6.1 A Modular Concept

The vehicle for demining process can be characterized as follows: It is a remotely / programmable controlled general porter of several detection systems able to perform searching dangerous terrain, localize and neutralize mines. It exhibits excellent mobility and maneuvering capabilities in various terrains. It should be noted that destination of the vehicle to work in dangerous environment requires some specific systems and protection equipment. Then the unified concept of robotic vehicles that enables to combine several functional equipments can be adopted, as depicted in Fig. 8. (Havlik, 2002, 2003, 2005).





a) The vehicle with sensory platform b) The vehicle with flailing activation mechanism



c) The long reach robot arm

Fig. 8. Possible concepts of robotic vehicles

6.2 Functional parts

Taking into account possible situations that could arise in demining process a most general solution of the ground vehicle could include following functional parts:

– ***The vehicle and its mobility system.*** The vehicle and its mobility system should provide desired good maneuvering capability in various terrains. Following this requirement that enables to combine wheels and belts seems to be the best solution.

– ***The heavy manipulator.*** The 2 or 3 d.o.f. manipulator enables to fix various soil tools as well as special demining equipment: flailing mechanisms, saws or cutters of vegetation, removing shovels, etc. The sensory platform, as depicted in Fig. 3a, exhibit possibility to install a set of appropriate detection systems can be fixed on the end flange. It is equipped by distance sensor what enables tracking terrain at a given vertical distance as well as collision protection range detectors.

– ***The long reach robotic arm*** The on-board robot arm, as depicted in Fig. 3c, performs some specific tasks especially in situations as follows:
  - Targets are not exactly localized and further – more precise searching / detection procedures using hand held detectors should be made.
  - Targets are hidden by vegetation / stones, or, targets are in inaccessible positions for removing or other way of neutralization. In these cases special demining procedures and tools have to be applied.

The 6 d.o.f. remotely controlled robot hand can exhibit the payload capacity about 20 kg with the reach 3m. It could be controlled in Cartesian hand references as well as the vehicle reference coordinates related to camera systems. It is supposed that the vehicle is equipped by a set of exchangeable tools for performing fine operations. One of desired tasks can be laying additional explosives beside mines in situations when other neutralization procedure seems to be not reliable, or could be too dangerous.

- ***Mine detection system and on-board sensory equipment.*** The vehicle, as a complex robotic system, works in partially unknown, or, not exactly structured environment. To perform main demining tasks it should be equipped by large variety of sensors and detection systems that, beside functionally of particular mechanisms, will satisfy reliability and safety of the whole process. Categories of sensors and detection systems with respect to functions and mechanisms brings next table.

Task	Places and Outputs	Sensors / detection systems
Mine detection and recognition systems	Operation center (localization of targets) Vehicle (security control) Marking system	Metal detectors, ground penetration radar (GPR), IR camera, Gamma detector, vapor detectors, etc.
Navigation (gross motion control)	Operation center Vehicle (control system)	GPS, compass, camera, range finder,
Fine operations by on board tools (fine motion control)	Robot arm, manipulator Grippers, marking system, tools for preparing activation of mines, etc.	Hand held camera, tactile / force sensors, position and proximity sensors, … Hand held detectors for explosives
Monitoring / reliable functioning	Engine, power sources, communication, etc.	Temperature, pressure, tension (V) / current (A), switches, …

Table 3. Categories of sensors

– ***Tools for removing obstacles / vegetation and preparing terrain.*** For removing obstacles many different remotely operated tools with sensory feedback should be developed. There are: cutters, shovels, special grippers, sand suckers, probes, etc.
– ***Neutralization / mine-destruction tools.*** Referring to possible techniques of neutralization, i.e., removing or destruction, the set of exchangeable tools in a magazine is considered. When compare existing techniques from the safety point of view, the flailing technique seems to be a single way which relatively safe, fast and reliable. It can be used especially in cases when coordinates of targets are not exactly known and terrain is covered by vegetation. The verified configuration: the vehicle with flailing activating mechanism on the heavy manipulator is depicted in Fig. 8.

In principle, explosions of mines are activated by the beating force of hammers on the ends of rotating chains. On order to satisfy reliability of the cleaning procedure this force should be keep above some given limit and every point of the terrain should be bit several times. Naturally, the rotation speed (rpm) of the flailing shaft and advance speed of the vehicle are mutually related and depend on several factors, as shown in Figure 8 (left). This dependence was experimentally tested and the simple mathematical model was built. The output of this model, partially integrated into control system, is desired value of advance speed during operation.

Practically, the control system for the flail should guarantee that every local place of the terrain that corresponds to diameter of mines to be struck more then five times by a minimal force / energy.

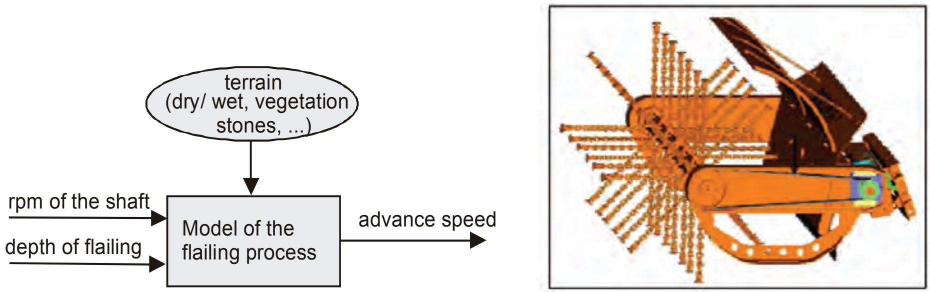


Fig. 8. Model of the flailing process and the flailing mechanisms

– ***Covers for protection the vehicle in cases of explosions.*** Any explosion (activated or accidental) can seriously damage equipments, or destroy the whole vehicle. For this reason it should exhibit adequate mass and armored protection covers. One of ways that minimizes effect of explosion during flailing is using the formed cover in front of the vehicle which changes direction of the pressure wave.

– ***Navigation, control and communication systems.*** The communication system transmits large amount of sensory and control data between the vehicle and the control station. For this reason maximal reliability of transmission should be guaranteed. As discussed above it is not expected that the system could work automatically. Nevertheless, searching and neutralization procedures made by mobile robotic vehicles should exhibit some level of autonomy. This fact naturally requires some unified approach to navigation and control. The general scheme of the control system in Fig. 9 shows some main components arranged in four control loops: global positioning, steering control loop, motor control loop and loops for control of various on board equipments (robot arm, manipulator, tools).

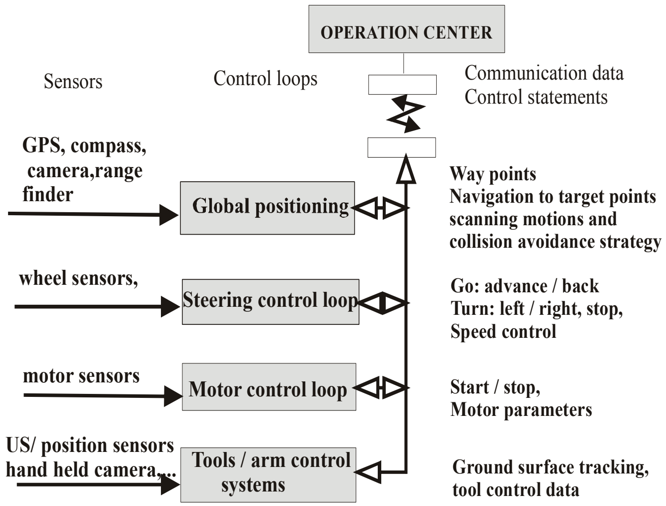


Fig. 9. Components of the vehicle control system

Specific working conditions for vehicles and robotic tools and security reason require that the control system to work in two independent modes:

- ***Automatic / programmable control*** mode through communication with operation center. This mode supposes normal operation of all systems as included scheme in Figure 5. Communication system for automatic modes transmit control and sensory data: way-points / trajectory, control statements for vehicle and motor, images from camera (remote vision), vehicle and motor states, warning error situations, etc.

- ***Manual control*** using joystick / control panel / keyboard that allows maneuvering the vehicle without operation center. Manual control is used in cases as follows: removing the vehicle from the minefield and recovery if any situation due to failure of any other system (programs, communication, etc.), loading / unloading the vehicles during transport, testing. This control mode directly operates steering and motor control loops. Communication is limited and corresponds to main statements for limited maneuvering motions.

6.3 Principal Control Routines

In general, any demining procedure consists of many specific tasks and some general control routines that can be performed automatically. Within general routines there are especially 3 positioning tasks:

Task 1. Position and orientation of the vehicle.

Altitude and longitude of the vehicle is directly measured by on board GPS unit. The accuracy and resolution of measurements should correspond to accuracy of digital maps where all targets are recorded. As to orientation angle (azimuth φ) can be directly measured by digital compass. Then, three variables (x_V, y_V, φ_V) are controlled coordinates of the vehicle as can be seen in Figure 10.

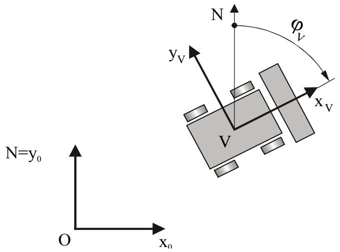


Fig. 10. Position and orientation of the vehicle

Task 2. Maneuvering to a given target. (Direct task)

The vehicle should move to a given target coordinates in order to localize its position more precisely, or, to destroy it. For the security reason we state around the target the security measure ρ and the approach angle φ_{ap}. These parameters should guarantee that the first "contact" of the vehicle with an expected dangerous target be by a detection system, or, by the destruction system. The approach angle φ_{ap} denotes the direction of movement of vehicle from an actual to a specified vicinity of the expected target position. The security measure ρ represents the uncertainty of recording targets into digital map as result of a limited accuracy of localization during aerial / terrestrial searching. Considering this uncertainty or security measure it is expected that the target be situated inside the circle given by coordinates in digital map. Then, the searching strategy of goal position depends on φ_{ap} and ρ parameters. Such a situation when the goal position is reached and next operation could start is depicted in Figure 11.

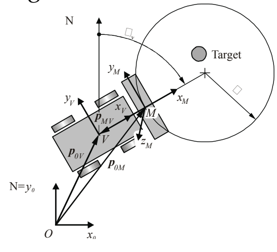


Fig. 11. Approach to the target

Task 3. Precise localization of target positions. (Inverse task)

The vehicle is in a position and the target is detected by some of detection systems. The exact position of the target should be stated and recorded. Practically the vehicle stops in some sensing position and performs searching dangerous terrain according to a given searching strategy, which corresponds to detection system just used for searching. (see Figure 12.)

There are, in principle, two possibilities:

- Detectors are on the sensory platform in front of the vehicle
- Detectors are in the robot hand.

The task is then to ascertain positions of targets using transformations that relate to particular detection system. Fusing sensory information it is possible to repeat detection procedure by using different sensing technologies including camera in the hand. Performing this task the vehicle is then maneuvered to this goal position specified by three variables x_V, y_V, φ_{ap}.

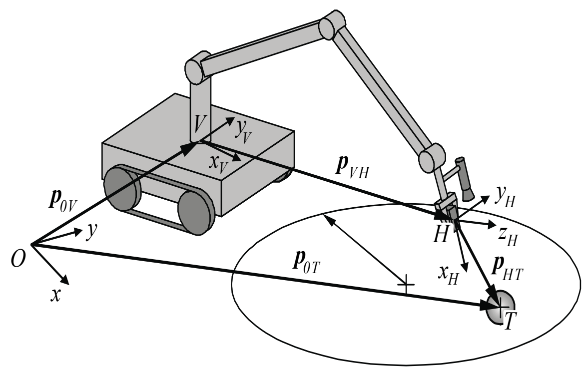


Fig. 12. Precise localization of the target by detectors in robot hand

Let us describe now the procedure for calculation of position of targets in all principal tasks. Considering reference coordinate systems, as specified above global position of the target detected by the sensor can be expressed using transformation

$$\boldsymbol{p}_{0T} = \boldsymbol{A}_{0H} \cdot \boldsymbol{p}_{HT} \tag{18}$$

where symbols $\boldsymbol{p}$ denote positional vectors related to particular reference systems and $\boldsymbol{A}$ represent transformation matrices between these systems. Thus, for instance

$$\boldsymbol{p}_{VH} = [x_H, y_H, z_H, 0]^T \tag{19}$$

$$\boldsymbol{A}_{VH} = \begin{bmatrix} \boldsymbol{R}_{VH} & \boldsymbol{p}_{VH} \\ \boldsymbol{0} & 1 \end{bmatrix} \tag{20}$$

and $\boldsymbol{R}_{VH}$ is the 3x3 rotation matrix of the *H* reference system into *V* system and $\boldsymbol{p}_{VH}$ is the positional vector of the *H* system with respect to *V*.

Then, considering introduced reference systems it is obviously

$$\boldsymbol{A}_{\boldsymbol{0}H} = \boldsymbol{A}_{\boldsymbol{0}V} \cdot \boldsymbol{A}_{VM} \cdot \boldsymbol{A}_{MH} \tag{21}$$

Because of positions of targets are given by two coordinates in global – world references particular transformation matrices can be simplified as follows

$$\boldsymbol{A}_{\boldsymbol{0}V} = \begin{bmatrix} \sin\varphi_V & -\cos\varphi_V & 0 & x_v \\ \cos\varphi_V & \sin\varphi_V & 0 & y_v \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{22}$$

where x_v, y_v, and φ_v are three measured variables that determine position and orientation of the vehicle.

Rem. Accurate calculation of target position requires that the inclination angle of the vehicle be considered. Although the actual inclination of the vehicle can be measured by a two-axis inclinometer following maximal simplicity of sensory equipment it is reasonable to neglect errors due to inclination. Anyway, when consider maximal allowable inclination angles in terrain this error will be within the range of the accuracy of GPS measurements.

Further more sophisticated control routines can be programmed. Then, the level of autonomy, provided to the vehicle will naturally relate to additional sensory equipment. There are for instance:

- Obstacle avoidance algorithms. In general, as obstacles can be considered all unexpected objects that prevent to continue in desired activities; motion for the vehicle, or robot / manipulator. Some typical obstacles are: stones, trenches, trees, positions of mines, etc. If any obstacle is detected, the motion should stop and situation will be evaluated. Automatic avoidance will be primary solved for some class of obstacles.
- Scanning motion strategies. Automatic performing scanning motions will help to reduce number of actions that the operator should carefully control.
- Self-recovery strategies. This is an important and specific feature directly related to particular tasks. Its main purpose is to prevent / to avoid loses or self-destruction of the vehicle. The self-recovery starts especially in unwanted situations as follows: any failure of technique due to explosion (communication, engine, control system, sensory system, etc…), fault decision made by the operator, or, there are no / not enough information for further action and the vehicle it could be destroyed. It is very risky for service persons to interact directly in place. The primary task is to remove it from the dangerous terrain without any risk for persons. There are, basically, two simplest ways how to solve such situation. The first one is using a cable and to pull it out. The other possibility is using another vehicle, which helps to remove the first one from that dangerous place.

7. Conclusion

Some conceptual considerations in designing robotic systems for detection, localization neutralization of mines, especially anti-personnel are presented. As discussed any robotic system for performing dangerous works under harsh working conditions should satisfy

several criteria and performance requirements. Crucial importance is given to security and reliability.
In general, it is considered that demining operations are performed by unmanned vehicles with special on-board equipment and the whole process is monitored from the operation center. The operation center is working with digital maps and GPS sensory data that enables to localize any objects and to control mobile vehicles in global or locally stated coordinates. It is expected that robotic vehicles are provided by some degree of autonomy in performing particular actions. Dangerous terrain and avoiding unexpected explosions of mines result in applying the specific approach to searching with precise localization of targets and neutralization. Both operations closely correspond to sensory equipment for detection as well as destruction technology.

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13

Land Robotic Vehicles for Demining

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1. Introduction

The idea of using mechanical equipments and vehicles for demining operations is dated since the First World War. At the same time several explosion activating mechanisms, including flails, were designed and tested. There were two main reasons. Preferably, it was the military demand to perform demining operation by a faster way in order to protect passage of army troops. The development of the demining technology for cleaning the post battle fields and protection of civilians was the interest of second order, only. This opinion was continuing during the Second war, practically till the end of 1970s. During this period no important progress and principal changes as to demining technology were observed. It was more-less standard concept: a roller, tiller or a rotating flail shaft pushing if front of a heavy vehicle, most frequently the tank. After this period, further development and mass production of cheap mines as well as they deployment have resulted in fact that mines became the real psychological weapon witch suffer mainly civilians. Unfortunately, the large amount of mines, especially anti/personnel, are still deployed and still used in some conflict areas. This fact confirms number of victims and injuries due to accidental explosions of mines abandoned on post-battle fields.
Classic methods for detection and removing mines are dangerous, too costly and considering the number of abandoned mines, are very slow. Within technologies for demining large mine polluted areas most frequently used are mechanical systems. Usually a pressure is acting on the ground by rollers pushed ahead of a tank or rotary flails beating the ground, or, the mines are dug out and pressed by a rake. Main drawback of this purely mechanical demining is that no system can satisfy the desired 100% reliability of humanitarian mine cleaning. For this reason manual verification of cleaned area is required.
Following the development of vehicles for demining, especially humanitarian, the acceleration and progress can be seen after 1980s. This was naturally influenced by development and progress in robotics, detection systems, computing, communication and control, as well as related technological domains. Some available technologies that can be used for demining are more exactly elaborated and, beside yet known techniques, new principles are designed and widely studied. Despite this effort concepts of remotely operated vehicles combining mechanical activation techniques are most widely used (Habib, 2002; Licko & Havlik, 1997; GICHD, 2004; Lindman & Watts, 2003; Ide et al., 2004; Kaminski et al., 2003; Stilling et al., 2003). Actually, there are more then 30 manufacturers of machines for this purpose listed in catalogue (GICHD, 2006). For performance evaluation of particular

machines the common criteria and test conditions were accepted on the international level (CEN, 2004). According to these standards it is possible to compare machines available on market (Proc, 2007).
When we talk about robotic vehicles we have in mind some principal features that such a robotic vehicle for demining should exhibit. There are:
- It is unmanned vehicle which moves and works in the minefield automatically, or, remotely controlled.
- The vehicle is equipped by on board manipulation systems (robot arm, manipulator).
- Using detection systems and sets of special tools for manipulation systems enable to perform three principal tasks of the demining process: searching / detection, preparing terrain, neutralization.

As obvious, the vehicle should be provided by sensory equipment that enables some level of autonomy in performing particular tasks. Keeping the reality and in order to show the development of such kind of vehicles the „Božena" family machines will be followed; as one example for the purpose of this article.

2. History and Experiences

The development and building unmanned vehicles that could replace humans in making such dangerous works, as demining operations, was one of the first fields of interest since the beginning of advanced robotics. As proved the robotic demining technology can be successfully applied in searching process, as well as neutralization of mines. After more then twenty years of development, production and using flailing vehicles in many regions lot of experiences, as regards to their further development, have been gained. First vehicles "Božena 1" developed before 1995 and produced within next five years were verified in real conditions and have been used by demining companies and military peace forces for cleaning the post battle minefields in several countries (Ličko & Havlík, 1997).
The primary concept of the vehicle, in Fig. 1, represents a modification of the small loader i.e. machine for manipulation with loose materials, terrain works, etc. The flailing activation mechanism based on rotating chains with hammers on their ends is fixed on the end flange of the hydraulically powered mechanism. The radio communication system enables remote mobility control, manipulation with activating mechanisms as well as monitoring relevant parameters of the whole system.

Fig. 1. The remotely operated flailing vehicle "Božena 1"

Next generations of these mini-flail machines “Božena 2 and 3“, as shown in Fig. 2 have been produced within 2000-2002. They exhibit more powerful driving unit, better maneuvering and control capabilities and, due to more available power, more reliable activation by flailing was reached.

Fig. 2. The mini-flail vehicles “Božena 2 and 3”

Further development of these machines represents important design changes, improvement of their performances and more operation applicability as well. The latest generations of these machines and more detailed description of is given in next section.
As confirmed experience the remotely operated flailing vehicles exhibit some important advantages. There are:

- Fast speed and high productivity in performing cleaning operation. Comparing to classical hand demining procedures the system based on mechanical flailing technology is minimally 10 times faster.
- Low cost and high efficiency of the system especially when infected terrain is covered by grass or small vegetation. Flailing technology is especially suited for cleaning large areas where mines can be hardly detected due to terrain and vegetation.
- Universal technical solution of the system based on multipurpose soil machines, as small loaders. The loader and maneuvering unit can be combined with several additional attachments can be used for demining process. Such concept guarantees availability of spare parts, verified reliability and good maintenance.
- Relatively low weight, fast and low cost transport to the place of use is highly required.

Results from more then fifteen years experience of using similar machines can be summarized into statements as follows:

- Application of purely mechanical destruction techniques and the flailing technique, as well, can not guarantee 100% reliability of cleaning terrain from mines and any explosives. Despite this fact the vehicle with flailing mechanisms is an effective tool especially in all cases when positions of mines are not exactly known, if the terrain is covered by vegetation, or, if there is another suspicion or some uncertainty. To satisfy maximal reliability the post verification of the cleaning process can be realized using vehicles equipped by mine detection systems.
- Using remotely operated vehicles minimizes psychological pressure and improves safety of persons. The useful help for operator is, if some functions are performed automatically,

as for instance: flailing process with respect to advance speed, or, straight line control routines.

– The efficiency of the whole demining process will be improved if mines are previously detected and localized. Then, the destruction vehicle could be directly navigated to these positions where mines are expected.

To document and compare the productivity in performing cleaning of various terrains classified on three categories the verified parameters of the real mini-flail vehicle "Bozena 4" (WAY Industry, 2006) are given in Table 1.

Category A 	Cleaned area: 2500 m^2 / hour (12500 m^2 / 5 hour day) Soil and Ground: dry topsoil, not too hard, without stones and boulders Terrain: flat or with gentle slopes only Vegetation: scarce, wet with max. 3 cm thick stems not higher than 1 m Obstacles: no trees, razor fences and no large refuse pile, other obstacles classified as "moderate"
Category B 	Cleaned area: 1100 m^2/ hour (5500 m^2 / day) Soil and Ground: hard soil, partially stony or wet with scarce boulders Terrain: flat or with moderate slopes up to 15° Vegetation: moderate, wet (max. 10 cm thick stems not higher than 1.5 m Obstacles: not too many trees, gaps between trees not less then 10 m, not too many razor fences and refuse piles, other obstacles classified as "difficult"
Category C 	Cleaned area 520 m^2/ hour (2600 m^2 / day) Soil and Ground: muddy and marshy, or very stony with large boulders Terrain: very uneven surface with slopes over 20°, the machine stuck in mud at least once per day Vegetation: dense and hard bushes higher than 1.5m, not higher than 1 m, over 60% of cleared area, gaps between trees not less then 5 m, not too many razor fences and refuse piles, other obstacles classified as "very difficult"

Table 1. Productivity of flailing vehicles

As follows from experiences the vehicle should be constructed as a "multi purpose" machine able to perform various activities. Such approach could minimize cost of the vehicle and the whole system, as well.

3. A Modular Concept

The multi purpose remotely operated machine should able to perform beside demining tasks some other activities, as for instance: disaster rescue and anti-terrorist operations, or, several civil engineering works. This is the concept of the remotely operated vehicle with on board manipulation robotic mechanisms and sets of task oriented tools for performing particular tasks.
When analyze available demining technologies and technical possibilities one can relate functional requirements to on-board vehicle equipment and tools, as given in the next table.

Task and minefield activities	Equipment / Tools	Robotic equipment
Searching dangerous terrain	Mine detection systems on platform (mainly Ground penetration radar – GPR) Detectors on the end flange of the long reach arm Marking system of targets	Heavy manipulator Robot arm
Neutralization by flailing	Flailing mechanism	Heavy manipulator
Post – cleaning verification, removing metal parts, …	Detection systems Strong magnets	Heavy manipulator
Cleaning vegetation	Cutters, saws, …	Heavy manipulator, Robot arm
Removing mines, obstacles, …	Grippers, suckers,	Robot arm
Neutralization by using specific techniques: posing explosives, burning and others.	Grippers – special tools	Robot arm
Manipulation with soil and loose materials: transport, loading, digging, drilling,	Additional accessories / tools	Heavy manipulator

Table 2. Tasks and on board vehicle equipment and tools

As could be deduced from the above analysis and considering actually real possibilities these functional requirements can satisfy the common modular concept of mobile robotic system with as shown in Figs. 3 and 4 (Havlík, 2007).

- An all-terrain unmanned vehicle moving on wheels / belts with the maneuvering capability that corresponds to terrain conditions. The vehicle as porter of multi-sensorial system should exhibit very good maneuvering and control capability in various terrain as well as autonomy features, as collision avoidance, automatic stop in cases of detected mine, remote vision, etc. In case of the neutralization vehicle with similar maneuvering and control capabilities it has to approach to the position of a detected mine and to neutralize it by activation or removing. For this reason it has to be protected against explosions of mines (not only antipersonnel but anti-tanks too). One of successful solution seems to be flailing activation system and formed protection cover against pressure waves due to explosions. From the point of view mechanical performance there are several specific requirements that both vehicles should satisfy (maximal pressure on the ground, velocity related to speed of detection systems, noise and temperature limitation, reliable power and communication systems, self recovery capabilities, etc).

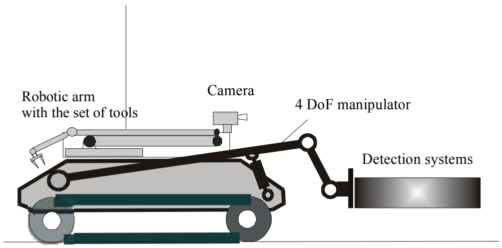

Fig. 3. A concept of the robotic vehicle for detection landmines

- A heavy 3 - 4 d.o.f. manipulator in front of the vehicle with about 1000 - 1200 kg payload capacity. The heavy weight manipulator is the main porter of heavy sensory systems as well as equipment for neutralization of mines (flail with protective cover), tools for cutting vegetation, etc.
- A long reach 6 d.o.f. robot arm: payload about 20 kg and reach distance approx. 3 m. The long reach arm will be used for fine works as follows: removing / deployment neutralization explosives, probing, fine cutting the vegetation, localization of mines using additional detectors, etc.
- Sets of exchangeable tools and attachment for performing particular tasks. The set of tools consists of probes, cutters, various grippers, additional sensors for detecting explosives, etc. On the end of arm will be small camera what will allow detailed views on the mine and place of its vicinity.

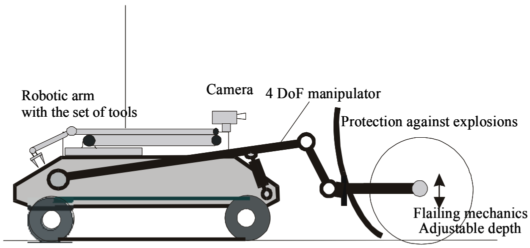

Fig. 4. The robotic flailing vehicle for destruction of mines

- Internal sensors for state monitoring and control of the vehicle and manipulation devices. There are sensors for sensing: pressures, positions of mechanisms, velocities, etc.

- External detection and sensory systems for sensing / monitoring environment (global position sensing – GPS, multi- sensorial mine detection / recognition systems, vehicle navigation, obstacles, etc.)
- Sophisticated communication and control systems. The vehicle control system includes navigation and mobility control. As regards to navigation the vehicle operates within the global world coordinates measured by GPS or within local references defined on place. Control of robot arm is considered to be in local world or tool reference coordinates. Global control scheme of the system shows Fig.5.
- An operation / control center with monitoring devices.

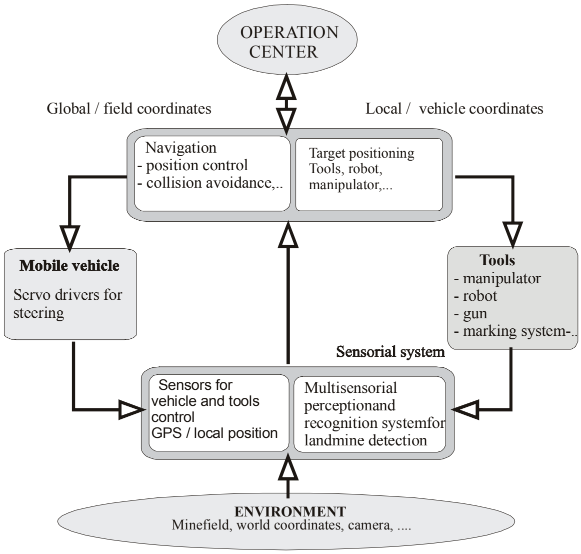

Fig. 5 . Global control scheme of the robotic vehicle for demining operations

4. Further Development of Demining Machines

4.1 Design and System Description

As discussed in (Havlik, 2007) there are several criteria should be taken into account and standards (CEN, 2004) that any vehicle for mechanical demining should satisfy. On the example of Božena machines further research and development of vehicles with mechanical activation technology is shown.

“Božena 4” in Fig. 6, is the fourth generation of the mini-flail vehicles mainly oriented for clearing large areas from antipersonnel mines (AP) as well as from anti-tank (AT) mines up to 9 kg of TNT equivalent.

The last generation machine of this family, “Božena 5”, belongs to category of midi-flail systems. This much more powerful machine exhibits about two-times higher productivity of cleaning comparable terrains. To reach a good maneuvering capability in various terrains the solution that enables to combine wheels and belts was adopted.

Fig. 6. Božena 4 (left) and Božena 5 (right) in demining action

Control of all mechanisms is realized from the cabin where all data and information about the machine and its environment are transmitted. The operator can use the special portable control box with keyboard and joystick. Some principal control routines are pre-programmed.

To improve controllability of vehicle actions the on-board remote vision system has been developed and can be installed. In the most complex configuration it consists of two stable cameras for observation the environment in front and in rear of the vehicle and one camera fixed on the 2 d.o.f. mechanism, in Fig. 7., which enables adjustable possibility of observation within the whole area 360^0 around the vehicle and +/- 20^0 tilting. Pictures from cameras are digitally transmitted on screens into the operation center. Thus, combining the visual pictures with GPS data it is possible to recognize actual situation on the minefield (terrain, obstacles, trenches, trees, etc.) and to make correct decisions.

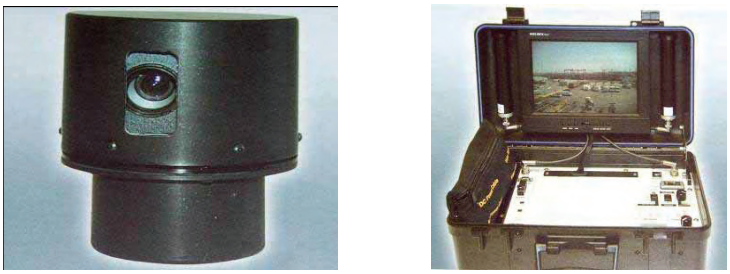

Fig. 7. The robust camera and monitor box of the vision system

In cases when the vehicle can not move due to any serious failures (engine, communication, etc.) it should be removed from the minefield. For this purpose it is equipped by the hydraulic winch - cable mechanism. This simple recovery system enables the machine to be pulled back from a dangerous place.

4.2 Tools and Attachments

Concept of the multi-purpose machine includes two categories of tools and attachments. There are:

- Equipment directly related to the demining process: platform for detection systems, flailing mechanism, target marking system, saw / cutter of vegetation, system for removing metal parts, grippers, etc.
- Equipment for engineering works as digging, drilling, loading and transport of soil or loose materials, removing obstacles, etc.

Some examples of these accessories have been developed for Božena machines are given in next.

Flailing Mechanism

The well known flailing principle consists of the rotating shaft with set of chains and hammers on their ends. The crucial problem is to design such a flailing system which keeps maximal efficiency and quality together with high productivity of cleaning process. To achieve this performance many parameters and characteristics should be studied and experimentally verified. Some of them are: length of chains, forms and material of hammers, positions of chains on the shaft, speed of rotation, impact energy of hammers, advance speed with respect to depth of penetration, soil, etc. Beside technical criteria, the mechanism should be very robust to resist explosions of AP mines and possible AT mines too.

The flailing mechanism in Fig. 8 is designed as an independent system powered by two hydro-motors with reverse rotation possibility. The flailing process, including advance speed, shaft rotation speed, depth, copying the terrain, is fully controlled by pre programmed routines.

Fig. 8. Flailing mechanism

Collector of Magnetic Parts

After cleaning process on each minefield are usually spread great numbers of metal parts, such as shells, ammunition cartridges, mine fragments, or other ferromagnetic parts such as wires, screws, etc. Obviously, these spread parts result in false signals of metal detectors when the verification procedure is doing. To pick up all small ferromagnetic parts the special attachment -magnetic collector, in Fig.9, is designed.

Fig. 9. Magnetic collector

Soil Separator

Another useful attachment is the mechanism for sifting and recycling soils where AP mines and UXO are expected. This attachment enables to take up the material (soil, waste) and, after closing the drum, by turning motion the content is sifted. The objects, as AP mines, remain inside the drum and may be dumped afterwards after opening the jaw. Grated form of jaws is as well the best solution enables to spread the blast wave in case explosions inside the drum. As the procedure is remotely controlled the safety for operator is provided.

Fig. 10. Separator for sifting and recycling soil

Other Attachments

Beside direct demining process, there are many dangerous works should be made in remote operation mode. Main reason is to protect persons if any suspicion on explosion or other possible hazard situation could arise. There are several useful accessories that can be directly attached on the end flange of the heavy load manipulator. Some of them frequently applied for most principal works are in Fig.11.

Fig. 11. Some accessories for remotely operated machines

5. Conclusion

Considering large polluted areas and drawbacks of actual demining technologies main contributions of using robotic vehicles are expected in following topics:

– Searching large areas and localization of mines and any explosives (UXO) by fast and reliable way.
– Fast and reliable neutralization/destruction of mines without the need of personal assistance to be inside, or close to dangerous places.

Demining process remains and will be still one of the most dangerous operations. For this reason new robotic technologies and detection principles should be applied.
The paper presents a modular concept and on examples describes the robotic vehicles equipped by the flailing activation mechanism and other accessories used in demining process and other civil engineering works.
All activities in dangerous terrains, as minefields, require applying specific approaches to searching, precise localization of single targets, neutralization process and other works, as well. Operations of unmanned vehicles in such terrains suppose that they have some level of autonomy to solve especially critical situations. This is the task for research in the future.

Acknowledgment

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14

PEACE: An Excavation-Type Demining Robot for Anti-Personnel Mines

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1. Introduction

We propose an excavation-type demining robot *PEACE* for farmland aiming at "complete removal" and "automation."(Mori et al., 2003, Mori et al., 2005) The reason why we choose farmland as the demining area is as follows: farmland is such an area where local people cannot help entering to live, so it should be given the highest priority (Jimbo, 1997).
PEACE is designed to clear APMs (anti-personnel mines) after disposing ATMs (anti-tank mines) and UXOs (unexploded ordnances). Needless to say, the first keyword "complete removal" is inevitable and is the most important. The second one "automation" has two meanings, that is, safety and efficiency. In the conventional research, detection and removal of mines are considered as different works, and the removal is after the detection. However, in the case of the excavation-type demining robot, detecting work will be omitted because the robot disposes of all mines in the target area. As the result, no error caused in the detecting work brings the demining rate near to 100%.
Currently, the demining work mainly depends on hazardous manual removal by humans; it presents serious safety and efficiency issues. For increased safety and efficiency, some large-sized machines have been developed. For example, the German *MgM Rotar* rotates a cylindrical cage attached in front of the body and separates mines from soil (see Fig. 1, Geneva International Centre for Humanitarian Demining, 2002; Shibata, 2001). The *RHINO Earth Tiller*, also made in Germany, has a large-sized rotor in front of the body; it crushes mines while tilling soil (see Fig. 2, Geneva International Centre for Humanitarian Demining, 2006). The advantages of *MgM Rotar* and *RHINO* are a high clearance capability (99%) and high efficiency respectively.
In Japan, Yamanashi Hitachi Construction Machinery Co., Ltd. has developed a demining machine based on a hydraulic shovel. A rotary cutter attached to the end of the arm destroys mines; the cutter is also used for cutting grasses and bushes. Although many machines with various techniques have been developed, a comprehensive solution that is superior to human manual removal remains elusive. Salient problems are the demining rate, limitation of demining area (*MgM Rotar*), prohibitive weight and limitation of mine type (*RHINO Earth Tiller*), and demining efficiency (*MgM Rotar, and the demining machine made by Yamanashi Hitachi Construction Machinery Co., Ltd.*). Because those machines are operated manually or

Fig. 1. MgM Rotar Mk-I

Fig. 2. RHINO Earth Tiller

by remote control, expert operators are required for each machine. Also, working hours are limited.

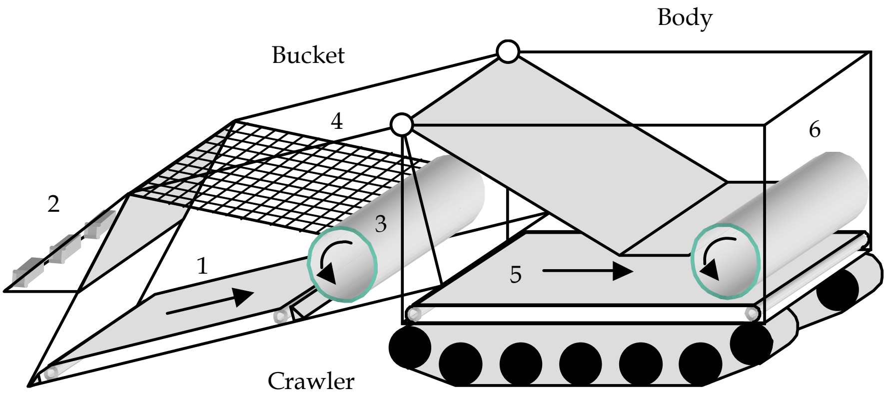
Recently, various demining robots have been developing mainly at universities. Hirose *et al*. have developed a probe-type mine detecting sensor that replaces a conventional prod (Kama et al., 2000). It increases safety and reliability. They have also developed a quadruped walking robot *TITAN*, some snake-type robots, mechanical master-slave hands to remove landmines *Mine Hand*, and robotic system with pantograph manipulator *Gryphon* (Hirose et al., 2001a; Hirose et al., 2001b; Furihata et al., 2005; Tojo et al., 2004). Nonami *et al*. have developed a locomotion robot with six legs for mine detection *COMET* (Shiraishi et al., 2002). A highly sensitive metal detector installed on the bottom of each foot detects mines and marks the ground. Ushijima *et al*. proposes a mine detecting system using an airship (Ushijima, 2001). On this system, the airship has a control system and a detecting system for mines using electromagnetic waves; it flies over the minefield autonomously. These studies mainly address mine detection; it is difficult to infer that they effectively consider all processes from detection to disposal.

This study proposes an excavation-type demining robot *PEACE* and presents the possibility of its realization. The robot has a large bucket in front of the body and can travel while maintaining a target depth by tilting the bucket. The robot takes soil into the body and crushes the soil, which includes mines. It then removes broken mine fragments and restores

the soil, previously polluted by mines, to a clean condition. In the process, the soil is cultivated, so the land is available for farm use immediately. Expert robot operators are not required; the robot works all day long because it can be controlled autonomously.
Section 2 presents the conceptual design of the excavation-type demining robot *PEACE*. Section 3 describes robot kinematics and trajectory planning. In Section 4, the optimal depth of the excavation is discussed. Section 5 shows experimental results of traveling with digging soil by a scale model of the robot. In Section 6, the structure of the crusher and parameters for crush process are discussed through several experiments. Finally, Section 7 contains summary and future works.

2. Conceptual Design of *PEACE*

The conceptual design of the robot is shown in Fig. 3. The robot uses crawlers for the transfer mechanism because of their high ground-adaptability. The robot has a large bucket on its front. A mine crusher is inside the bucket, and a metal separator is in its body. The first process of demining is to take soil into the body using the bucket. Figure 4 shows the excavating force on the contact point between the bucket and ground. Torque T is generated at the base of the bucket when the bucket rotates. The torque T generates force F_t against the ground. The body generates propelling force F_v. As the result, contact force F is generated as the resultant force. The rotational direction of the bucket decides the direction of the contact force F. Therefore, the robot can realize both upward motion and downward motion by adjusting the bucket torque T and the propelling force F_v. Furthermore, the robot can advance while maintaining a target depth by using some sensors. The next process is to crush mines. The soil is conveyed into the bucket by the conveyor belt 1 in Fig. 3. As the soil is immediately carried, the strong propelling force of the body is not



1. Conveyor belt 1
2. Sensors for ATM
3. Crusher
4. Lattice
5. Conveyor belt 2
6. Metal separator

Fig. 3. Conceptual design of the robot

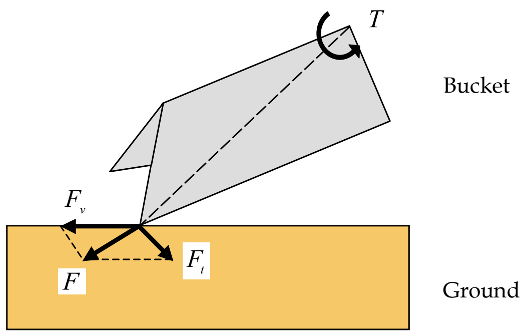


Fig. 4. Excavating force on the contact point

required. The soil, which includes mines, is crushed by the crusher. Most of the blast with the crush escapes from the lattice 4 because the fore of the bucket is underground when demining. The crusher and the bucket are hardly damaged because the explosive power of APMs is so weak to the metal. The sufficient thickness of the steel plate is about 1 cm (Geneva International Centre for Humanitarian Demining, 2002, 2006).
The last process is to separate metal splinters of mines from the soil using a metal separator. Crushed debris are conveyed by the conveyer belt 2 in Fig. 3. The metal splinters, which are used for recycling, can be selected by an electromagnet. The rest are discharged from the rear.

Fig. 5. Aardvark Mk IV

Fig. 6. Armtrac 100

The merits and some supplementary explanations of this mechanism are as follows:

1. This mechanism can cope with all types of mines irrespective of the size, form, and material of the mine.
2. After a series of processes, the area is available for farm use immediately as the soil becomes clean and tilled.
3. If the size of the lattice 4 is proper, uncrushed mines cannot go outside through the lattice. The uncrushed mines escaped from the bucket will be few because the clearance between the bucket and the ground is narrow and the blast will brow through the lattice. The mines will not scatter in the distance, and they will be taken into the bucket again in a short time.
4. *PEACE* is designed to work after clearing ATMs and UXOs. In order to clear them, chain flail type demining machine, e.g. Aardvark Mk IV or Armtrac 100 would be suitable in terms of the mobility, the simplicity and the maintenance (see Figs. 5 and 6, Geneva International Centre for Humanitarian Demining, 2002, 2006). If the robot should detect ATMs by using sensors for ATM 2, it would stop before them, and the work would be restarted after disposing the ATMs.

3. Kinematics and Trajectory Planning

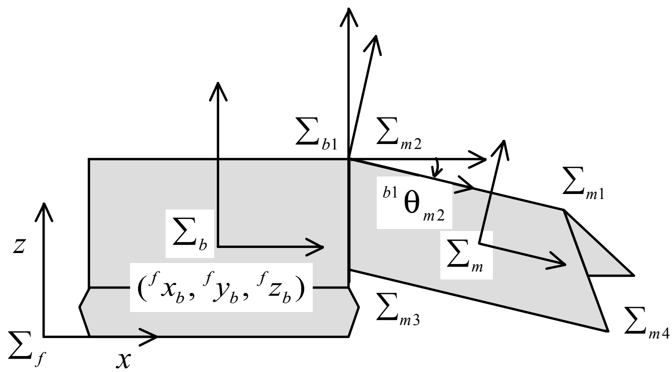


Fig. 7. Coordinate system and parameters

The coordinate system of the robot is shown in Fig. 7. The origins of the coordinate system Σ_{b1} and Σ_{m2} are the same.

Σ_f : Coordinate system relative to the ground,

Σ_b : Coordinate system relative to the body,

Σ_{bi} : Coordinate systems relative to each corner of the body,

Σ_m : Coordinate system relative to the bucket,

Σ_{mi} : Coordinate systems relative to each corner of the bucket,

for $i = 1,2,\cdots,4$.

Each variable and constant are as follows:

${}^{*1}P_{*2} = ({}^{*1}x_{*2}, {}^{*1}y_{*2}, {}^{*1}z_{*2})$: Vector from the origin in coordinate system Σ_{*1} to that in coordinate system Σ_{*2} .

${}^{*1}\theta_{*2}$: Angle from the x-axis in coordinate system Σ_{*1} to that in coordinate system Σ_{*2} .

${}^{*1}L_{*2}^{*3}$: Constant length from the origin in coordinate system Σ_{*1} to that in coordinate system Σ_{*2} . The length is the value of *3 -axis, that is x or z , in coordinate system Σ_{*1} .

The following coordinates are derived by calculating the homogeneous transform from coordinate system Σ_f to coordinate system Σ_{m4} .

$$ {}^f x_{m4} = {}^{m2}L_{m4}^x \cos({}^f\theta_b + {}^{b1}\theta_{m2}) - {}^{m2}L_{m4}^z \sin({}^f\theta_b + {}^{b1}\theta_{m2}) + {}^bL_{b1}^x \cos {}^f\theta_b - {}^bL_{b1}^z \sin {}^f\theta_b + {}^f x_b , \quad (1) $$

$$ {}^f z_{m4} = {}^{m2}L_{m4}^x \sin({}^f\theta_b + {}^{b1}\theta_{m2}) + {}^{m2}L_{m4}^z \cos({}^f\theta_b + {}^{b1}\theta_{m2}) + {}^bL_{b1}^x \sin {}^f\theta_b + {}^bL_{b1}^z \cos {}^f\theta_b + {}^f z_b . \quad (2) $$

From eq. (2), the control angle of the bucket ${}^{b1}\theta_{m2}$ is derived as eq. (3), where the height of the robot ${}^f z_b$ can be measured by using some sensors like GPS and the inclinational angle of the body ${}^f\theta_b$ can be measured by using a clinometer. Therefore, the target angle of ${}^{b1}\theta_{m2}$ can be calculated if the height of the end of the bucket ${}^f z_{m4}$ is given as the target value. For example, at the beginning of digging, the sign of ${}^f z_{m4}$ is minus, and it is constant when the robot advances while maintaining a target depth. The body position ${}^f x_b$ can be derived as eq. (4) by substituting ${}^{b1}\theta_{m2}$ in eq. (3) for eq. (1). The traveling body velocity ${}^f \dot{x}_b$ is the derivation in time of eq. (4) and the velocity can be calculated if the bucket velocity ${}^f \dot{x}_{m4}$ is given as the target value.

$$ {}^{b1}\theta_{m2} = \sin^{-1}\left\{ \frac{{}^f z_{m4} - {}^bL_{b1}^x \sin {}^f\theta_b - {}^bL_{b1}^z \cos {}^f\theta_b - {}^f z_b}{\sqrt{({}^{m2}L_{m4}^x)^2 + ({}^{m2}L_{m4}^z)^2}} \right\} - \tan^{-1} \frac{{}^{m2}L_{m4}^z}{{}^{m2}L_{m4}^x} - {}^f\theta_b , \quad (3) $$

$$ {}^f x_b = -{}^{m2}L_{m4}^x \cos({}^f\theta_b + {}^{b1}\theta_{m2}) + {}^{m2}L_{m4}^z \sin({}^f\theta_b + {}^{b1}\theta_{m2}) - {}^bL_{b1}^x \cos {}^f\theta_b + {}^bL_{b1}^z \sin {}^f\theta_b + {}^f x_{m4} . \quad (4) $$

Next, the trajectory of the bucket is discussed. The robot starts to dig by lowering its bucket while proceeding, and it descends the slope that is made by the bucket. The target shape of

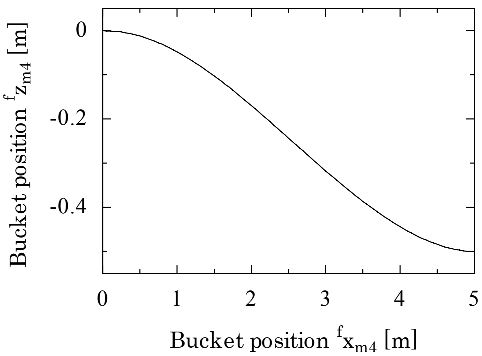


Fig. 8. Trajectory of the bucket position

the slope based on a cubic polynomial is shown in Fig. 8. That is the trajectory of the end of the bucket. The target depth was 50 cm and the slope was generated for 20 s, and then it went ahead while maintaining a target depth. The simulation result of the whole process is shown in Fig. 9, and the time response of the bucket angle ${}^{b1}\theta_{m2}$ is shown in Fig. 10. The bucket angle does not change smoothly after about 12 s because the body tilts while it descends the slope.

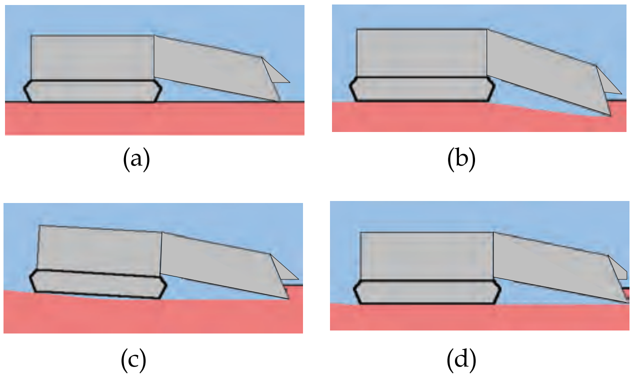


Fig. 9. Sequence of the excavation motion

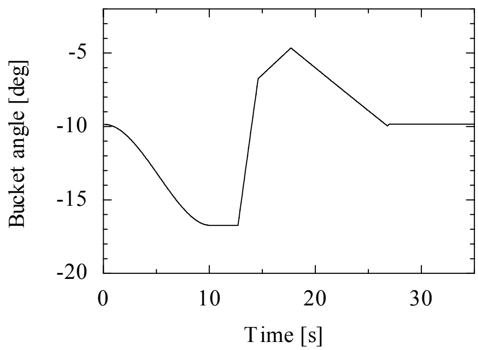


Fig. 10. Simulation of the excavation motion

4. Optimal Depth of Excavation

Generally, APMs are laid on the surface of the ground from 1 cm to 2 cm in depth (Shimoi, 2002). However, it is possible that they are buried in the ground by deposits. It is true that deep excavation leads to safety, but the depth beyond necessity is not realistic from the aspect of working hours and cost. In this section, we discuss which depth is appropriate.

We assumed the following: The ground is an elastic plate of the semi-infinite. Uniformly distributed load q is taken on a rectangular plate that is put on the surface of the ground. Then normal stress to vertical direction σ_z, which passes through the center of the plate, is calculated using the theoretical formula of *Fröhlich* ,

$$\sigma_z = \frac{\nu q z^{\nu}}{2\pi} \int_{x=\frac{-L}{2}}^{\frac{L}{2}} \int_{y=\frac{-B}{2}}^{\frac{B}{2}} (x^2 + y^2 + z^2)^{-\frac{\nu}{2}-1} dxdy \qquad (5)$$

where ν is the stress concentration factor, z is the depth from the surface of the ground, L and B are the length and width of the rectangular plate respectively. The value of ν depends on the elastic property of the soil, and it is appropriate that $\nu = 3$ is for clay soil and $\nu = 4\text{-}5$ is for sand deposit.

In this study, we examined the earth load in the ground to verify eq. (5). At first, standard sand, of which particle size was about 0.2 mm, was put into a poly container by 20 cm in depth. The capacity of the container was 300 l, and the diameter and the height were 87 cm and 70.5 cm respectively. Then the earth pressure gauge was put on the center of the surface of the soil. The maximum load of the gauge was 2 kgf/cm^2. Next, some soil was deposited on it and was hardened softly and evenly, and then the earth load was measured when a test subject put weight quietly on the rectangular plate in his one foot. The test subject was a man whose weight was 60 kg. The rectangular plate was wooden, and the size was 9 cm × 22.6 cm and the thickness was 1.2 cm. The area of the plate was based on that of the shoe of 26 cm. We measured the earth load each five times about 10 cm, 20 cm, 30 cm, 40 cm and 47.7 cm in depth, and regarded each average as the representative value.

The result was shown in Fig. 11. The closed circle in Fig. 11 represents the earth load without additional weight, while the open circle represents the earth load when the test subject put weight on the surface. The dashed line was based on the least squares approximation of the earth load without additional weight, while the continuous line was calculated by the theoretical formula of *Fröhlich* eq. (5) when ν equals 5. The dotted line represents the ignition pressure of PMN, Type72, MD82B and PMN2, which are the representative APMs.

In Fig. 11, for example, a straight line that passes through the point of 30 cm in depth crosses with a line and a curve at about 0.1 and 0.15 kgf/cm^2 respectively. In this case, the pressure only of the soil is 0.1 kgf/cm^2, and it changes to 0.15 kgf/cm^2 when the test subject puts weight on the surface. The mines of which ignition pressure is less than 0.1 kgf/cm^2 hardly remain unexploded because almost all of them explode under the earth load. The mine of which ignition pressure is from 0.1 kgf/cm^2 to 0.15 kgf/cm^2 explodes when the test subject puts on it. The mine of which ignition pressure is more than 0.15 kgf/cm^2, however, does not explode with the test subject who weighs 60 kg because the ignition pressure is over the total load of the soil and him. Summarizing the above, there are few mines in the area of 1. Mines are not active in the area of 2. Mines will explode if the test subject steps into the area of 3. It is desirable that the area between 1 and 2 is narrow. However, deep excavation results in high cost. In addition, a certain amount of overburden will contribute to

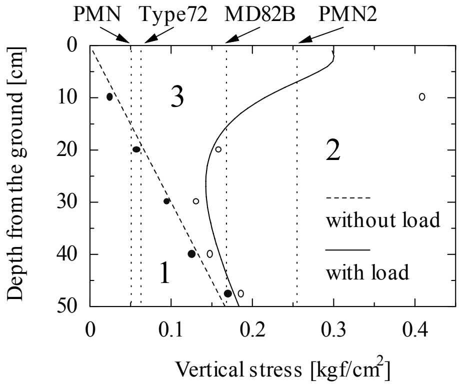


Fig. 11. Soil pressure (ν =5)

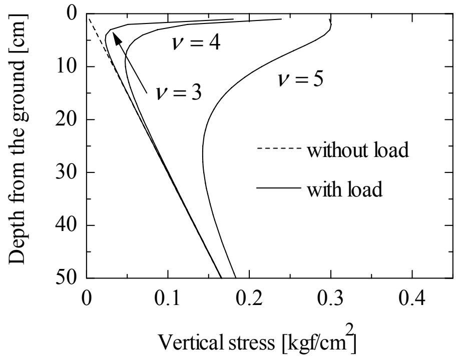


Fig. 12. Relationship between the vertical stress and ν

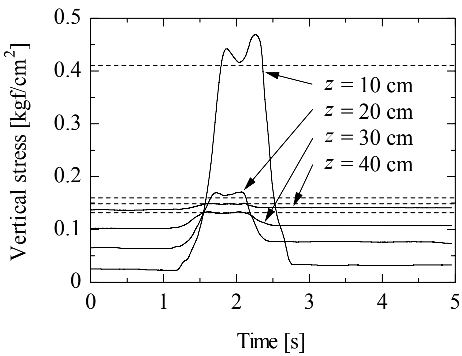


Fig. 13. Time response of the soil pressure when walking

preventing the immense damage. Figure 12 shows the result to various stress concentration factors ν . In case of sand: $\nu = 5$ or in case of Fig. 11, vertical stress σ_z was highest on a

certain depth. That means the environment of sand is the most dangerous because the area of 3 in Fig. 11 is widest. Therefore, it was confirmed that 40 cm was proper depth.
Next, we discuss the dynamic load. The continuous line in Fig. 13 shows the experimental results when the test subject walked on the surface of the soil. The depths of the soil were from 10 cm to 40 cm. The dashed lines show the experimental results for the static loads. From this result, we can see that the load on the surface did not influence the underground so much when the depth was over 30 cm.
In conclusion, we propose 40 cm as the best excavation depth. This depth is also valid for farmland. In case mines are buried in a leaning position or that the soil has solidified with passing years, the mines become difficult to explode. Therefore, the proposed excavation depth is safer.

5. Hardware of the Scale Model

In order to control the robot autonomously, it is necessary to measure the position of the robot (${}^f x_b , {}^f y_b , {}^f z_b$). In the actual robot, it is measured by using GPS. High-precision GPS (RTK-GPS) is, however, expensive and difficult to use indoors, so a high-precision and inexpensive positioning sensor was produced in this study.

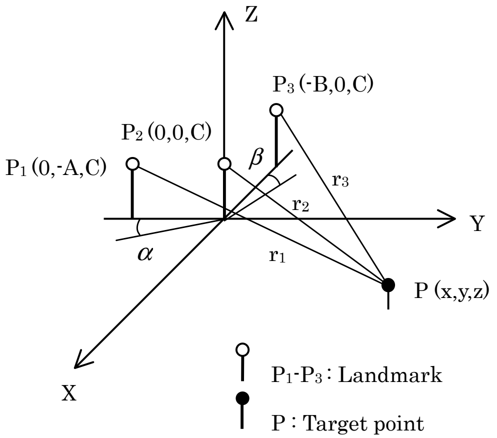


Fig. 14. Position identification

The positioning sensor is a landmark system. Three landmarks P_1, P_2, P_3 are set above the y-axis (0, $-A$, C), origin (0,0, C), x-axis ($-B$, 0, C) respectively as Fig. 14, and the heights of them are the same. Each distance from the robot is r_i (i =1,2,3). The angles α and β are the angular errors that are caused when installing the positioning sensor units. The position of the robot P (x , y , z) is derived as follows:

$$\begin{bmatrix} x \\ y \end{bmatrix} = \frac{1}{\eta} \begin{bmatrix} \sin\beta & \cos\alpha \\ \cos\beta & \sin\alpha \end{bmatrix} \begin{bmatrix} B\,(r_1^2 - r_2^2 - A^2) \\ A\,(r_3^2 - r_2^2 - B^2) \end{bmatrix}, \tag{6}$$

$$z = C - \sqrt{r_2^{\,2} - x^2 - y^2} \tag{7}$$

where

$$\eta = 2AB\cos(\alpha + \beta)\,. \tag{8}$$

The sign before the root in eq. (7) is negative if the landmark is above the robot.

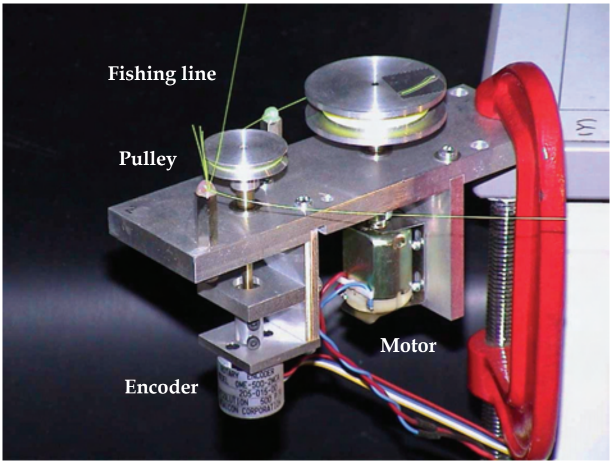


Fig. 15. Positioning sensor unit

Figure 15 shows a photograph of one positioning sensor unit. A fishing line is wound round a pulley connected to an encoder. The line is stretched tight because a fixed voltage is applied on a motor that winds the line. It is possible to measure the position P (x, y, z) by

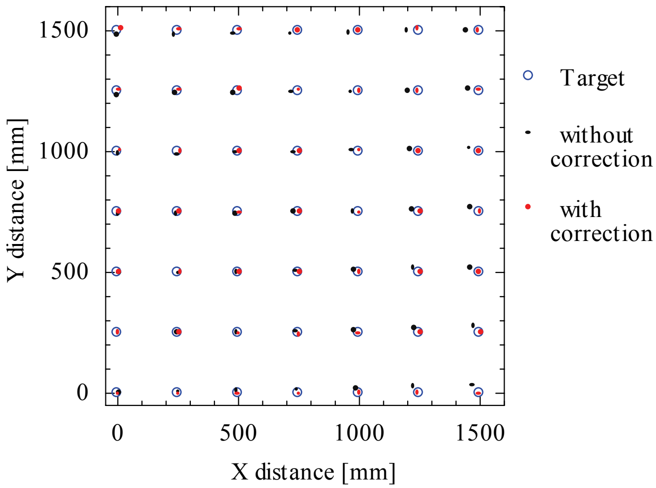


Fig. 16. Result of the position measurement

using three sensor units in theory. In that case, however, it was clarified that large errors on z-axis occurred through experiments. The measure for that is to attach one more sensor unit on z-axis.

To estimate the accuracy of the positioning sensor on the x-y plane, positions of lattice points in the area of 1.5 m square were measured in every 0.25 m. The result is shown in Fig. 16. The maximum error was approximately 5.56 cm. After corrections about α , β and the diameter of the pulley connected to each encoder, the maximum error was approximately 0.69 cm.

The model of the excavation-type demining robot has a scale of 1 to 10. The dimensions of the robot are 0.36 m × 0.84 m × 0.217 m in height. The photograph is shown in Fig. 17. The crawlers for the transfer mechanism are the parts of a model tank. Each crawler can be rotated independently by a motor with an encoder. The inclinational angle of the body was measured by a fiber optical gyroscope (JG-108FD1, Resolution < 0.01 deg, Frequency response 20 Hz; Japan Aviation Electronics Industry, Ltd.). The bucket angle was measured by a clinometer (NG3, Resolution < 0.003 deg, Frequency response > 3.3 Hz; SEIKA Mikrosystemtechnik GmbH) and a potentiometer; the former was used for monitoring the bucket angle and the latter was for control. The soil in the bucket was carried by a conveyor belt to the body and discharged backward of the body without being crushed. The robot was controlled by a PD controller.

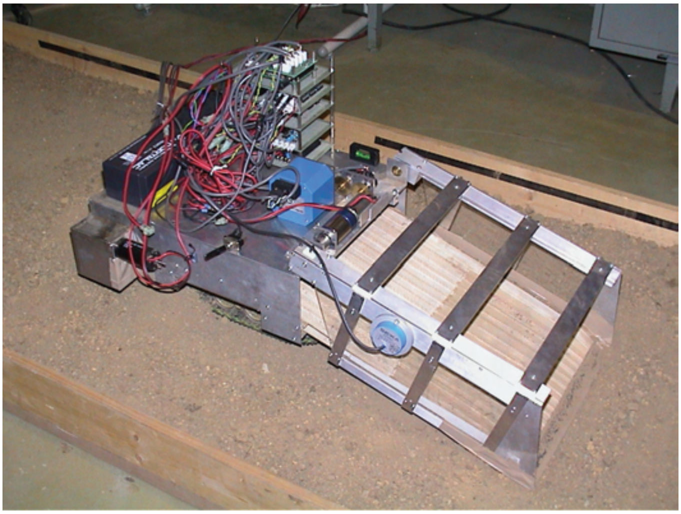


Fig. 17. Excavation type mine removal robot

Figures 18-21 show the experimental results. The robot went through 50 cm distance in 20 s. The bucket reached the target depth of 3 cm in 10 s and kept it afterward. The measured data of the wheel angle almost agreed with the target. Figure 18 shows the time response of the wheel angle. Figure 19 shows the position of the robot (${}^{f}x_b$, ${}^{f}z_b$) that was measured by using three positioning sensor units shown in Fig. 15 installed with tilting 90 deg. The errors

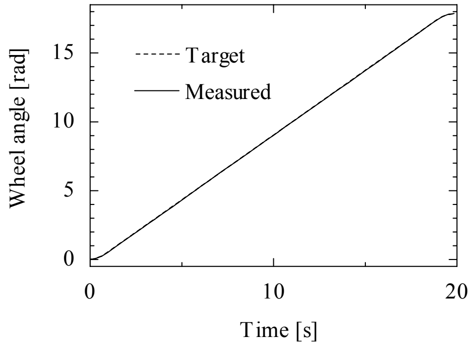


Fig. 18. Time response of the wheel angle

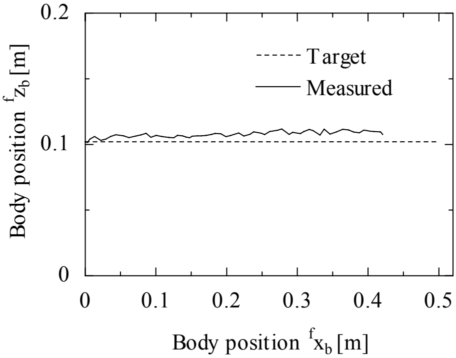


Fig. 19. Body position

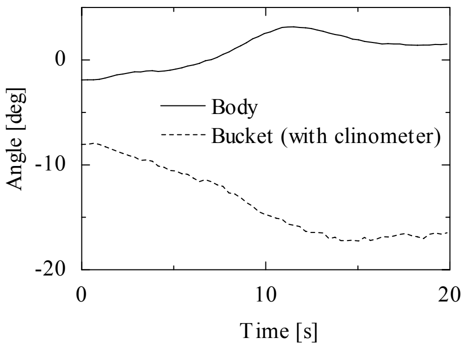


Fig. 20. Time response of the body angle and bucket angle

were mainly caused by the unevenness of the ground and the slippage of the crawler. Those errors can be reduced if the measured position of the robot is programmed in the feedback

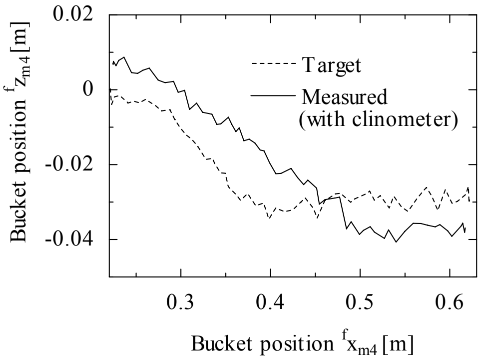


Fig. 21. Time response of the bucket position

control loop. Figure 20 shows the time response of the bucket angle measured with the clinometer and the inclinational angle of the body. The body was lifted slightly by the drag from the bucket. Figure 21 shows the bucket position ($^f x_{m4}$, $^f z_{m4}$) that was calculated from eqs. (1) and (2) based on the bucket angle measured with the clinometer. The shape of it resembled Fig. 8. The vibration of the target trajectory was caused by the measured position and inclinational angle of the body. The bucket followed the trajectory and dug to near the goal depth.

6. Crush Process

The processing reliability of demining machines or robots is the most important to humanitarian demining. The main point is the crush process. Most conventional rotor-type demining machines have rotor bits that are larger than mines. Therefore, it is possible that the mines do not touch the bits and they are left unprocessed. In addition, high reliability cannot be realized without the sifting process. Almost all of conventional machines, however, have no such process. Although MgM Rotar has this process, the demining efficiency is not so high (Geneva International Centre for Humanitarian Demining, 2002). We discuss the structure of the crusher. We made the test equipment shown in Figs. 22 and 23 in order to examine the validity of it and the improved points. The characteristics are as follows:

1. The rotational frequency of the rotor is rapid so that the debris may become small.
2. Small rotor bits are mounted around the rotor in small intervals, and every line is mutually different.
3. The plate shown in Fig. 22 is installed under the rotor of which direction of rotation is anticlockwise.

Because of the characteristics 2 and 3, sifting process is realized.

The width of the test equipment was 554 mm, the length was 450 mm, and the height was 280 mm. The diameter of the rotor was 100 mm without bits, and its width was 207 mm. Setscrews of M5 were used for the bits. Each lateral interval of bits was 10 mm, and twenty-four bits were mounted around the circumference of the rotor. The rotor was driven by DC motor of 250 W, and its rotational frequency was measured by an encoder. The electric current supplied to the motor was also measured. A box made of the acrylic covered the equipment and was used to prevent some debris from being scattered. A wheeled mobile robot shown in Fig. 23 carried the experimental samples on the plate to the rotor that was fixed on the base.

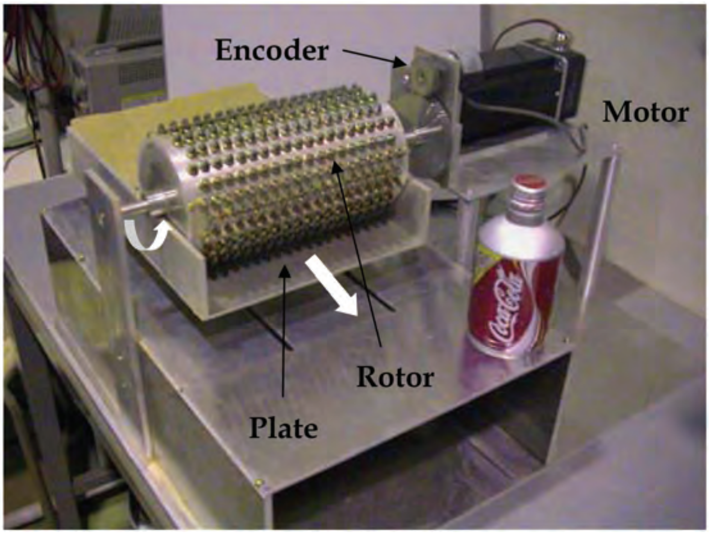


Fig. 22. Test equipment for crush (top view)

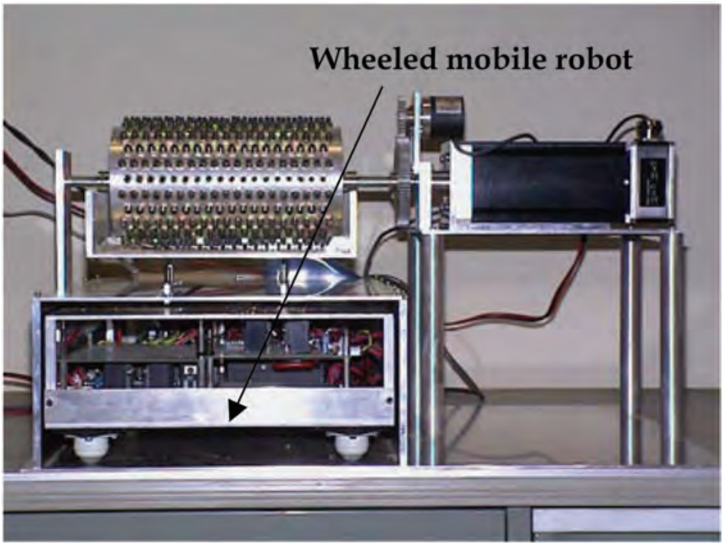
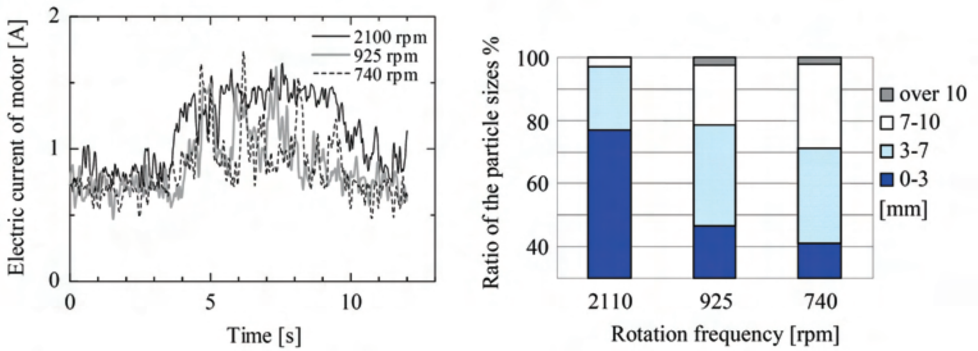


Fig. 23. Test equipment for crush (side view)

As the experiment samples, we used clods of the loam layer, in which there is nothing explodable. The amount of the clods for one experiment was 160 g. It is true that the samples were more easily broken than the real earth but they were enough to examine the phenomena. The electric current and particle sizes of the samples after the crush were measured according to various conditions: the rotational frequency of the rotor, the length of the bits, the gap between the tip of the bits and the plate fixed under the rotor, and the traveling speed of the robot. They were varied on condition that each standard value was 2100 rpm, 5 mm, 2 mm and 10 mm/s respectively. The particle sizes of the samples after the crush were sorted out at four groups: 0-3 mm, 3-7 mm, 7-10 mm, and over 10 mm. The lengths of 3 mm, 7 mm and 10 mm correspond to the hole size of the square lattice plates used for sorting.

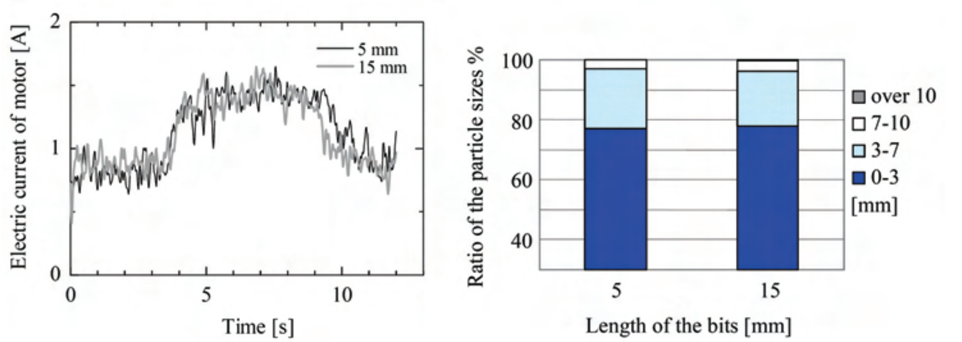
Figure 24 shows the experimental results to each rotational frequency of the rotor: 2100 rpm, 925 rpm and 740 rpm, which was changed by speed reducers. The voltage supplied to the rotor motor was constant. In the conventional demining machines, the frequency is at most as 700 rpm (Geneva International Centre for Humanitarian Demining, 2002, 2006). Figure 24 (a) shows that high rotational frequency leads to continuous crush. Figure 24 (b) shows that high rotational frequency is related to fineness of the particle sizes of the samples after the crush, that is, high processing reliability.



(a) Time response of the electric current of motor

(b) Relationship between rotation frequency and ratio of the particle sizes

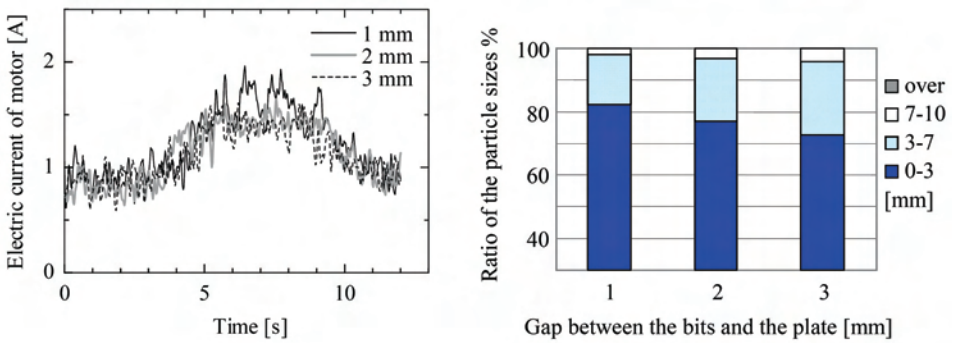
Fig. 24. Comparison for the rotational frequencies



(a) Time response of the electric current of motor

(b) Relationship between length of the bits and ratio of the particle sizes

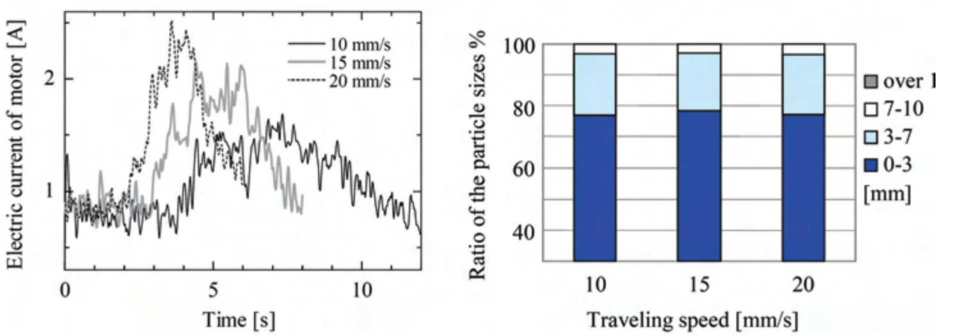
Fig. 25. Comparison for the lengths of bits



(a) Time response of the electric current of motor

(b) Relationship between gap and ratio of the particle sizes

Fig. 26. Comparison for the gaps



(a) Time response of the electric current of motor

(b) Relationship between traveling speed and ratio of the particle sizes

Fig. 27. Comparison for the traveling speeds

Figure 25 shows the experimental results to the length of the bits. Each length of the bits was 5 mm and 15 mm except for the length of the mounting parts that was about 5 mm. Both results were almost equal because of the high rotational frequency of the rotor. In case of 15 mm bits, however, there were some debris that passed through the 10 mm square lattice. While, in case of 5 mm bits, no such debris were left.
Figure 26 shows the experimental results to the gap between the tip of the bits and the plate fixed under the rotor. Three kinds of gaps were examined: 1 mm, 2 mm and 3 mm. The smaller the gap became, the smaller the samples were crushed and the electric current of the motor slightly increased. Therefore, it was confirmed that small distance is desirable for humanitarian demining operation.
Figure 27 shows the experimental results to the three kinds of traveling speeds of the robot: 10 mm/s, 15 mm/s and 20 mm/s. As the robot traveled faster, the maximum value of the electric current of the motor increased. However, there is little difference to the particle sizes of the samples after the crush. Therefore, in respect of time efficiency, it is desirable that the robot travels fast within the limits of keeping the rotational frequency of the rotor.

7. Summary and Future Works

In this study, we proposed a novel excavation-type demining robot that worked autonomously. The advantages of the robot are a high clearance capability and high efficiency. The crusher inside of the robot plays two roles: crushing the mines and sifting soil. Therefore, the robot has a high clearance capability. It also has a mechanism for separating metal splinters of mines inside. In addition, the robot can perform a series of those operations continuously. So it has high efficiency.
However, this robot is not all-powerful for all environments. The main target area for our robot is the place that becomes the farmland after demining. For example, the areas are plains or past farmland. The reason why we choose farmland as the demining area is that farmland is such an area where local people cannot help entering to live, and so it should be given the highest priority. For severe conditions, it will be necessary to cooperate with other types of machines, robots and some sensors systems.
The kinematics and motion planning for the robot were discussed. The possibility of demining was verified by a scale model of the robot. It was confirmed that 40 cm was the proper depth of excavation through experiments. The crush process that had high reliability was also discussed.
The implementation of a prototype is as follows: the power source for the robot is hydraulic, the required minimum shielding is 10 mm steel plate, and the approximate size and weight are $3.6 \times 8.4 \times 3.0$ m in height and 50 t respectively. We assume that the maximum crushable rock size is about $20 \times 20 \times 20$ cm. If a bigger and sturdy rock comes into the bucket, the rotor may stop. In this case, the robot will have to stop the operation and to remove the rock. This is our future work. For the navigation system, we use some sensors as follows: the global position of the robot is measured with RTK-GPS. The tilt angles of the body (roll and pitch angles) are measured with clinometers. The orientation angle of the body (yaw angle) is measured with a gyroscope. Stereo video cameras are necessary to measure the corrugation of the ground and to monitor the ground. Laser range finders and ultrasonic sensors are necessary to find the obstacles.

It will need a lot of money to develop and maintain the robot. However, we are convinced that our robot is one of the best solutions concerning a clearance capacity and efficiency. We wish the robot would be provided by an advanced nation as a part of a national contribution.

8. Acknowledgments

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15

A Human-Animal-Robot Cooperative System for Anti-Personal Mine Detection

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Abstract

This chapter reports the latest results of an attempt made in Sri Lanka to develop a human-animal-robot integrated system to detect anti-personal landmines. In this study, a mongoose was trained to sniff for landmines. It was attached to a semi-autonomous legged mobile robot. The robot could sense the direction of movement of the mongoose. The robot used this direction information along with commands sent by a remote human operator to modify its own semi-autonomous behaviors. The human operator gave overall commands as to which direction the robot should move. The robot took care of detailed tasks such as obstacle avoidance, monitoring the environment immediately in front of it, and guiding the mongoose. The mobile robot was a laboratory made fully embedded platform with simple sensors such as bumper switches and a sonar sensor. Experiments were carried out in typical environments where anti-personal landmines are buried in Sri Lanka.

1. Introduction

One of the most significant challenges faced by any post war human re-settlement program is to cover a vast unstructured land of minefields as fast as possible with a guarantee of safety for civilians. For most of the developing countries, landmine removal is a pre-requisite to economic development. Apparently, demining is an operation accompanied with a lot of risk to human deminers. Therefore, manual deminers move slowly. Analysis of the movements of the human deminers shows that the mobility part can be easily and safely performed by robotic systems. Then the challenge is reduced to sensing the landmines.

1.1 Landmine and Explosive Detection Technologies

A survey has been done to categorize different technologies available for landmine detection into 9 classes (Brian, M. & Barratt J., 2002). Class-1 is for those technologies with only basic principle observed and reported, class-2 is for those with technology concept and/or application formulated, class-3 for those with analytical and experimental critical function and/or characteristic proof of concept is given, class-4 is for those with technology component and/or basic technology sub-system validation in laboratory environment has been done, class-5 is for those with technology component and/or basic sub-system validation in relevant environment, Class-6 is for those with technology system/subsystem model or prototype demonstration in a relevant environment has been done, Class-7 is for those with technology system prototype demonstration in an operational environment, Class-8 is for those with actual technology system completed and qualified through test and demonstration, and Class-9 is for those with technology system "accredited" through successful mission operations.

1.1.1 Metal Detectors (Electromagnetic Induction Devices)

A time varying current in a transmitting coil induces an "eddy" current in nearby metallic objects. The magnetic field created by this induced current induces a Voltage in a receiving coil of the metal detector. This signal is filtered and amplified to generate an acoustic signal that works as the alarm (Collins L., et al, 2002). The major limitations of this technology are: It gives a lot of false alarms for shell fragments, bullet cases, and other metal debris usually found in mine fields, it is difficult to tune in laterite rich soil or conductive soil (red soil, sea beaches etc.), it is difficult to detect mines with more than 1 feet soil deposits over it, and there can be false alarms due to electromagnetic interference.

1.1.2 Ground Penetrating Radar (GPR)

GPR works by emitting a microwave signal into the soil. If an object such as a landmine that has a different dielectric property than the surrounding soil is present, the sensor can use the reflected signal to differentiate the object and the soil (Sun Y. & Li J., 2003; Savelyev T.G., et al, 2007). Therefore, GPR does not look for the small metal parts in the landmine like in metal detectors. The major limitations are: It is an expensive technology. Therefore it is very seldom used in the affected regions in the world; Microwaves attenuate in conductive and wet soils. It gives false alarms for roots, rocks, water pockets etc., there is a need to compromise between the resolution and penetration. Resolution is high at elevated frequencies, and penetration is high at low frequencies. In (Sun Y. & Li J., 2003), experiments have been done using a GPR detector mounted in front of a field vehicle so that the GPR detector is directed forward. When the vehicle moves forward, the data is collected in time domain. The frequency analysis of these data has been done. 2-D images have been obtained by plotting the real part of the Fourier transformed data on the X-axis and the frequency spectrum on the Y-axis. The corresponding image gives different patterns for different mines buried at different depths. This could be considered an effective method to detect suspicious items by visual inspection. Yet, how this method will perform when the sensor array vibrates due to the jolt of the vehicle when it moves in a rough terrain is questionable.

1.1.3 Multisensor Systems Using GPR and Metal Detectors

1. Hand Held Standoff Mine Detection System (HSTAMIDS or acronym AN/PSS-14) (Xu X., et al, 2002): This US army project has developed a multi-sensor system that contains a GPR and a Metal Detector that is used by a sensor fusion algorithm for feature extraction.
2. MINEHOUND (Doheny R.C., et al, 2005) is claimed to be simple and effective compared to other GPR based technologies. The project is sponsored by the UK Department for International Development and developed by ERA Technology.

3. ALIS (Advanced Landmine Detection System) (Daniels D.J., et al, 2005) similar to HSTAMIDS, this uses GPR and Pulse Induced Metal Detectors. The limitations are: it is very expensive for normal use, and need a large platform to carry it, that may cause problems in a tropical minefield.

There has been considerable amount of effort given to improve the sensor fusion algorithms (Sato M., et al, 2005; Ferrari S. & Vaghi A., 2006). In (Sato M., et al, 2005), a sensor fusion technique based on Bayesian networks is proposed. The method is tested on a system of GPR, electromagnetic induction, and infra-red sensors. The data have been processed as batches. Therefore, there is no guarantee that this method can be deployed in an unstructured environment with no prior information to detect landmines on line.

1.1.4 Trace Explosive Detection Systems

Samples of the environment have to be obtained and the detection of explosives is done based on a chemical reaction or a mass-spectroscopy measurement (Perrin S., et al, 2004; George V., et al, 1999; Cumming C., et al, 2001). For instance, one technology is to use Amplifying Fluorescent Polymers (AFPs) (George V., et al, 1999). In the absence of explosive agents, the polymer fluoresces when exposed to light. With the presence of nitro-aromatic compounds, the fluorescence decreases. The limitations are: Slow to respond, expensive, requires samples of the environment and therefore not efficient to detect on the move.

1.1.5 Biosensors

These use a Quartz crystal microbalance (QCM) together with antibody (Ab) and Antigens (Ag). A sample collector sucks in the vapor. If there are substrates of TNT/DNT, RDX, PETN and tetryl, the oscillating frequency of the QCM changes due to the migration of the micro-organisms (Fisher M.E. & Sikes J., 2003; Crabbe S., 2005; BIOSENS Consortium, 2004). This change in the frequency is detected to give an alarm. Limitations: Slow response, can have a drift due to population changes, very expensive.

1.1.6 Magnetic Quadrupole Resonance

A method is proposed to observe the quadrupole resonance signals of explosives that are often interfered by background radio signals (Crabbe S., et al, 2003). For instance in TNT, there are 18 resonant frequencies 12 of which are between 700 - 900 kHz that is susceptible to interference from AM radio. Since the resonant signal is weak, filtering and observation is necessary. This method proposes to use the noise as the state and the signal as the measurement noise of the Kalman filter. If the interference from AM radio is handled with improved signal processing methods, this method can be useful as a remote sensing technique. However, the technology is not yet mature.

1.1.7 Seismo-Acoustic Methods

Seismic waves are generated from one end and from the other end, a non-contact (acoustic) transducer and a contact (seismic) transducer picks up the signal (Tan Y., et al, 2005; Xiang N. & Sabatier J., 2004; Scott W.R., et al, 2001]. If there are hollow objects like landmines, it will be reflected in the received signal because of its difference with the mechanical properties of the surrounding soil. Attempts have been taken to identify the vibration

signature of a mine. However, ageing and changes in the mechanical properties of the mine may lead to false alarms.
In essence, given the scale of the need to have a technology to detect landmines and explosives, the current state of the art is very expensive, computationally cumbersome, and gives high false alarm rates. Therefore, there is an open need to have a simple, cost effective, and powerful technique that can be applied in most practical cases. We believe the answer lies in a system that combines the strengths of animals to detect chemical agents, semi-autonomous robots that can navigate in a cluttered environment to guide the animal, and a human's ability to control a robot and to analyze the visual feedback of an animal's behavior.

1.2 The Proposed Method to Use a Rodent

The most common animal used for explosive detection all around the world is the dog. In addition to dogs there are situations where rats and bees have been used for this kind of purposes. Although these animals are used today, there are certain drawbacks and limitations of them. Dogs' sniffing capability is powerful in downward direction and not that strong upwards like in searching a vehicle. In addition they are not much suitable for work in crowded places. Rats have been used to sniff and detect Tuberculosis Bacteria in human sputum samples. Yet, due to limited stamina, they can not cover large areas and work continuously. The primary sensing system in our approach is a trained mongoose. It's said to have the third most sniffing ability among animals, only being less than that of elephant and pig. Furthermore unlike dogs, it has a powerful sniffing ability in upward direction. The rodent is attached to a semi-autonomous field robot through an elastic cord with an angle sensor at the robot's end. The angle sensor will provide information about the rodent's wondering behaviors.

2. Training a Mongoose to Detect Landmines

2.1 Animal-robot Interaction

Experiments have been done to observe how chicken behaves when a robot elicits different behaviors in the same cage (Bohlen M., 1999). It has been found that the chicken reacts to the relative velocities and accelerations of the robot, the sounds it generate, and how close it comes to them. Sometimes, animals attach value to colors. Experiments done on male Sticklebacks have shown that any odd shaped thing with a red bottom will make them think that it is a threat to them, because stickleback males show a red belly during courtship season to differentiate them from females (De Schutter G., et al, 2001). Experimentsconducted on miniature robots working in societies of cockroaches show that once the insects accept the robot to be part of their society, the robot can influence some of the collective behaviors of the animals such as foraging under a shade, moving as a group etc. (Caprari G., et al, 2005). An algorithm to accelerate reward based training of rats is proposed in (Ishii H., et al, 2005), where a rat learns to press levers of a robot to obtain food and water. It is found that the training process should be phased out in order to accelerate training. In this case, the first phase was to remove the anxiety of the rat to face the robot, the next phase was to reward the robot for coming closer the robot, the last phase was to motivate the robot to press the appropriate levers of the robot to get food and water. Based on the work done so far on understanding how different animals react to the presence of robots, and how an animal can be trained to interact with a robot, we expect to investigate the features of the robot's appearance and the behaviors in order to make the best use of the animal's natural sensory system. A major novelty of the proposed study is that the robot does not duplicate any hardware needed to sense the environment wherever the animal can do it better. Hence the robot becomes simpler and cheaper. Furthermore, the robot learns from the animal how to move in a cluttered environment while restricting the animal's movements to a given area of interest.

In the area of forcing an animal to behave in a given way, some work has been done on invasive techniques such as invoking behaviors through artificial stimulation of the animal's nervous system. A Bio-robotic system has been explained where a cockroach is electrically stimulated to turn left and right to keep it on a black strip (Holzer R. & Shimoyama I, 1997). A similar attempt to guide a rat along a desired path is described in (Talwar S.K., et al, 2002), where electrodes were planted in the rat's somatosensory cortical whisker representations to give sensory cues, and the Medial forebrain bundles to give the rewards. The rat has been guided along a given path using a wireless data communication system between a backpack mounted on the rat and a remote supervisor. However, it is our belief that invasive techniques should be avoided wherever possible in order to make the best use out of the animal's natural sensory system.

Monitoring of animal's behaviors from a remote place or directly monitoring the activities of the brain is of paramount importance in the proposed study. The advances in PET technology have been very useful in brain imaging of animals (Vaska P., et al, 2004; Ziegler S.I., 2005). This could open up future opportunities to trace the activity of the olfactory system of the animals and match it against a template for a particular type of explosive. Yet, this remains a remote possibility given the current state of the art. Some work has been done to model animal behavior using 3-D video images (Ramanan D., et al, 2006; Girard M., 1987). A possible extension is to capture a particular behavior that the animal might elicit in response to hazardous objects. Yet, in the proposed study, a human in a remote control room will do the behavior tracking of the animal. This method will render itself to be robust with minimum errors.

2.2 Swarm Robots

Swarm robotics is a related area of research where a complex collective behavior is emerged in a group of relatively simple robots through inter-robot and robot-environment interactions (Goldberg D. & Mataric M., 1997; Hayes A, 2002; Johns C. & Mataric M., 2003; Krieger M. & Billeter J.B., 2003). A given robot is generally very simple and inexpensive, capable of eliciting a limited array of primitive behaviors, and equipped with a limited number of sensors and actuators. Given a task to be accomplished such as walking over a gap that none of the individual robots can not accomplish, the simple robots may share their diverse sensor information, actively support each other by joining hands, and coordinate movements to achieve the common goal. This concept can be useful in a task to find a hazardous object in a cluttered environment where one robot can not carry all the required sensors. Yet in that case, there is nothing that improves the behavior of an individual robot. The focus is to emerge a collective behavior based on the rules that apply to each robot to interact with other robots and the environment, and not to improve individual robotic behaviors through peer interaction. To the best of our knowledge there has been no work done to study a scenario where each robot is directly influenced by a real animal as a peer who can sniff for the target objects and at the same time support the robot to learn how to navigate in a cluttered environment.

2.3 Characterizing the Environment

Experiments have been done in Sri Lanka where a robot navigates in a vegetated tropical minefield using a single sonar sensor (Nanayakkara T., et al, 2006). The sonar scans the environment to derive statistics of the distances between the robot and the trees. In one scan, it collects 10 readings of the distances to the trees. Based on the variance and the mean of the distances to the trees obtained in one scan, the robot classifies the environment into one of a given number of known environments. An image based 3-D map building approach for forest environments has been proposed in (Forsman P. & Halme A., 1998). Yet, how far this can be applied in a minefield is questionable, because the robot has to recognize the environment in the first trial. The sonar and laser range finder based map building and robot localization has been studied extensively in the recent history especially in indoor environments (Thrun S., et al, 1998; Burgard W., et al, 1998; Ayache N. & Faugeras O.D., 1989; Bozma O. & Kuc R., 1991; Chong K.S. & Kleeman L., 1996; Dudek G., et al, 1996;). In most cases, a sonar sensor is used to alert the laser range finder to look for finer details. In a forest or a densely wooded environment or in a highly congested area, the sonar will always give alerts. Therefore, these methods may not be as good as having an animal to signal the robot to change the path to avoid an obstacle.

2.4 Advantages of Using a Mongoose

- Mongooses have a highly developed sense of smell;
- Mongooses are easy to tame and train;
- Mongooses are small, cheap and easy to maintain and transport;
- Once taught, the animals love performing repetitive tasks;
- It has found that the mongoose can exceed the sensitivity of dogs appear to be well founded;
- Mongooses are widespread and easily adapt to all environments.

2.5 Biological Facts about the Mongoose

The mongoose belongs to Herpestidae family. They can be found in Asia, Africa, the Caribbean and southern Europe. There are more than thirty species, ranging between one and four feet in length.

Mongoosesare mostly carnivores, feeding on insects, crabs, earthworms, lizards, snakes, rodents and other small creatures.

They will also consume eggs, carrion and sometimes fruit. Some species, such as the Indian mongoose, are popularly known for their ability tofight and kill venomous snakes such as cobras. They are able to do this because of their speed, agility and cunning properties.

Herpestidae family

- Subfamily Herpestinae
  - Genus *Atilax*
    - Marsh Mongoose
  - Genus *Bdeogale*
    - Bushy-tailed Mongoose
    - Jackson's Mongoose
    - Black-footed Mongoose
  - Genus *Crossarchus*
    - Alexander's Cusimanse
    - Ansorge's Cusimanse
    - Long-nosed Cusimanse
    - Flat-headed Cusimanse
  - Genus *Cynictis*
    - Yellow Mongoose
  - Genus *Dologale*
    - Pousargues' Mongoose
  - Genus *Galerella*
    - Black Slender Mongoose
    - Cape Grey Mongoose
    - Slender Mongoose
    - Namaqua Slender Mongoose
  - Genus *Helogale*
    - Desert Dwarf Mongoose
    - Dwarf Mongoose
  - Genus *Herpestes*
    - Short-tailed Mongoose
    - Indian Gray Mongoose
    - Indian Brown Mongoose
    - Egyptian Mongoose
    - Indian Mongoose
    - Long-nosed Mongoose
    - Bengal Mongoose
    - Collared Mongoose
    - Ruddy Mongoose
    - Crab-eating Mongoose
    - Striped-necked Mongoose
  - Genus *Ichneumia*
    - White-tailed Mongoose
  - Genus *Liberiictus*
    - Liberian Mongoose
  - Genus *Mungos*
    - Gambian Mongoose
    - Banded Mongoose
  - Genus *Mungotictis*
    - Narrow-striped Mongoose
  - Genus *Paracynictis*
    - Selous' Mongoose
  - Genus *Rhynchogale*
    - Meller's Mongoose
  - Genus *Suricata*
    - Meerkat, Suricata suricatta

Among those species what we find here in Sri Lanka mostly is Dwarf Mongoose.

2.6 Reward Based Learning of Mongooses to Detect Explosives

The plasticity of an animal's brain can be effectively used to develop a motivation to carry out tasks that it did not use to enjoy. Basically the animal is repeatedly given a reward whenever it carries out a desired task. This type of learning is known as reward based learning or reinforcement based learning (Schultz W., et al, 1997; Dayan P. & Balleine B., 2002; Montague P. & Berns G., 2002; Hollerman J.R., et al, 1998; German P.W. & Fields H.L., 2007). Experimental results on how the activity of the Dopamine neurons in the brain is related to reward based learning suggests that the brain tries to give priority to actions that maximize the total expected rewards given by equation (1), where $V(t)$ is the total expected reward, $E(\bullet)$ is the expectation function, $r(t)$ is the reward at time t, and γ is the discounting rate.

$$V(t) = E\left(r(t) + \gamma r(t+1) + \gamma^2 r(t+2) + \cdots\right) \quad (1)$$

However, mathematical models developed so far in the machine learning literature suggest that the learning speed largely depends on the shape of the reward function (Sutton R.S. & Barto A.G., 1998; Watkins C.J.C.H, 1989; Mataric M.J., 1994; Mataric M.J., 2000; Ng A.Y., et al, 1999). In machine learning, a control policy π is updated using a critic that estimates $V(t)$ given a situation s and a policy π. The policy is defined as $\pi : s \rightarrow a$, where s is the situation and a is the action. Therefore, it is clear that the speed and accuracy of the process of improving the control policy depends on the accuracy of the critic that estimates $V(t)$ given in equation (1).

Work done on motor memory consolidation using human subjects suggest that learning in distinctive episodes leads to the formation of robust modular internal representations that can be combined to form complex skills (Shadmehr R. & Holcomb H.H., 1997; Brushers-Krug T., et al, 1996; Thoroughman K. & Shadmehr R., 2000). A salient feature of these modules of internal representations is that they are less prone to interference from others. In other words, the parameter changes in one module have less influence on the performance of another module. Therefore, we expect the proposed learning method to simplify the cost landscape in the learning parameter space, thus accelerating convergence of parameters towards a global optimum.

Based on the above scientific background, we started our experiments with two mongooses. They were of the dwarf mongoose type. The first step was to train the wild mongooses that are sensitive to even the slightest disturbance in the environment to interact with humans and be impartial to sudden disturbances in the environment. In the initial phases fish and meat were tested as a medium for rewards. Yet, we soon realized that the traces of raw fish and meat emanated a strong smell that overshadowed the smell of explosives in small quantities. Among other foods that did not have a strong smell such as cake, apple, banana, cheese, and milk, the mongoose demonstrated a great affinity to cheese.

2.7 Experimental Results of Training Mongooses to Detect Explosives

The mongooses were trained by bringing a small amount of C4 explosives wound to one end of a stick while observing the behavior of the animal. If the mongoose came closer to the stick, we gave a "beep" sound with a slice of cheese as the reward. The sound helped us to get the attention of the mongoose. As stated earlier we had two mongooses. One was small and the other one was larger in size. Both mongooses did not show much improvement during the first ten days. But the larger one made a sudden improvement during the next few days. It started to learn to detect explosives. When we moved the stick with explosives nearer, it tried to pull the stick and search for cheese. Gradually we decreased the amount of explosives attached. At the beginning we had to insert the stick into the cage for the mongoose to detect it. Gradually we kept it away as much as possible and at last we were able to make it detect keeping the stick at the outside edge of the cage. After some time, it became eager to look for explosives upon hearing the "beep" sound. Furthermore, as we moved the stick along the cage it followed the path. Following **figure 1** gives an idea of how the mongoose improved during our experiment. We did the test twenty times a day.

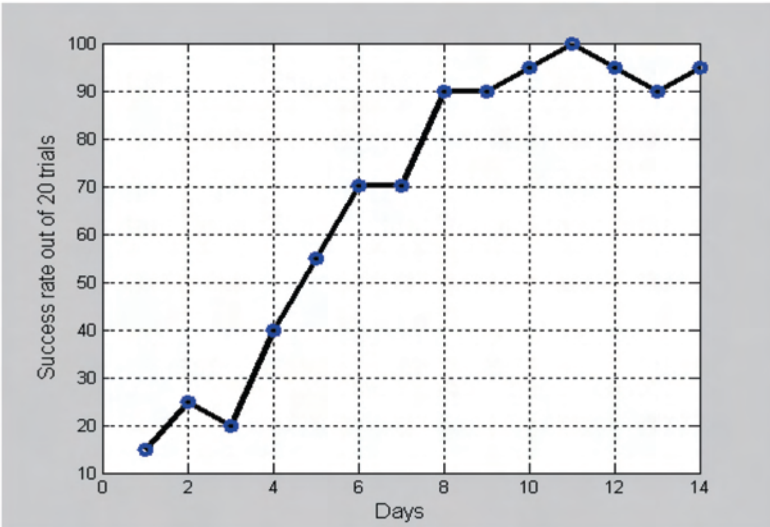

Fig. 1. The daily improvement of the mongoose's ability to associate explosives to an anticipated reward

Two weeks after this improvement, we extended our experiments in several alternative paths. We wanted to give the mongoose the idea that it will receive the reward if and only if it detected explosives. Therefore, we used several sticks. One was without explosives. Another had an edge covered by a cloth, but without explosives inside. We used another stick with a cloth attached and gave it the smell of a perfume. The fourth stick had explosives attached at the end. Different sticks were presented to the mongoose in blocks of 40 trials. Over time, the number of times the stick with explosives was presented was brought down to test the accuracy of the training. After two and half weeks time it was able to successfully distinguish between several similar types of sticks, and find the correct stick containing explosives.

Day	No. of times explosive stick was used out of 40 trials (X)	Successful Trials (out of x)	Percentage of Success (%)
1	26	4	15.38
2	28	3	10.71
3	26	6	23.08
4	21	8	38.10
5	18	7	38.89
6	17	8	47.06
7	17	9	52.94
8	15	7	46.67
9	15	8	53.33
10	16	10	62.50
11	13	9	69.23
12	14	11	78.57
13	10	9	90
14	9	9	100
15	10	8	80
16	8	7	87.50
17	9	9	100

Table 1: The improvement of the ability of mongoose to detect a stick with explosives among similar sticks without explosives

Having succeeded with the above training phase, we moved on to remove all visual cues available to the mongoose by covering the cage with a black screen. The sticks with or without explosives were brought closer to the cage from behind these screens. In order to attract the attention of the mongoose to sniff for explosives, we tapped on the cover before moving the sticks. Gradually it learnt to move towards the cover by sensing the smell. At present the mongoose has become able to distinguish among several smells.

3. Mongoose – Robot Coupled System

The primary role of the robot is to guide the mongoose along a desired path. After a number of experiments with different robotic platforms, we designed a robot that looks and walks like an Iguana frequently seen in tropical forests in Sri Lanka. **Figure 2** shows the laboratory made robot that weighs 4 kg. The trained mongoose is attached to the robot with an elastic cord. The cord is attached to the robot through an angle sensor that allows the robot to sense the direction of drag of the mongoose. The legged robot consists of two independent units, each resembling the shape of an Iguana. The two units are kept together using two rods hinged at the front and the rear end of each unit. Two units are driven by two geared DC motors that can be controlled independently. Therefore, turning involves one unit moving faster than the other or one unit reversing while the other unit moves forward.

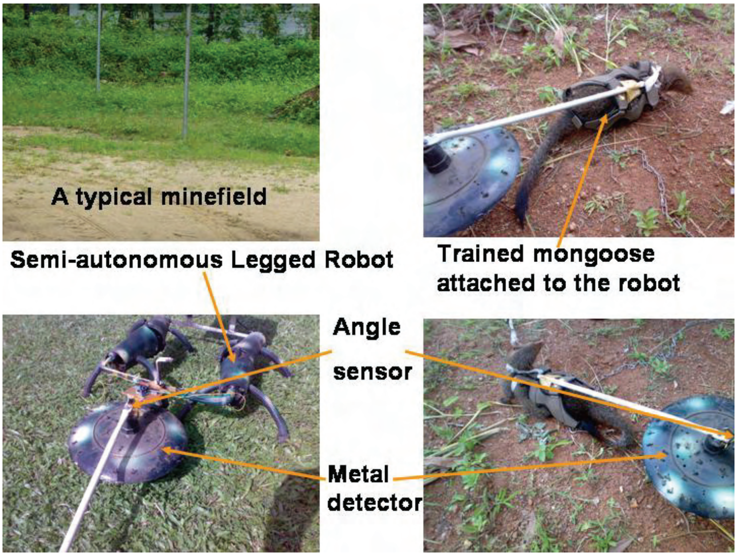

Fig. 2. How the mongoose is attached to the legged mobile robot called MURALI (**M**oratuwa **U**niversity **R**obot for **A**nti-**L**andmine **I**ntelligence)

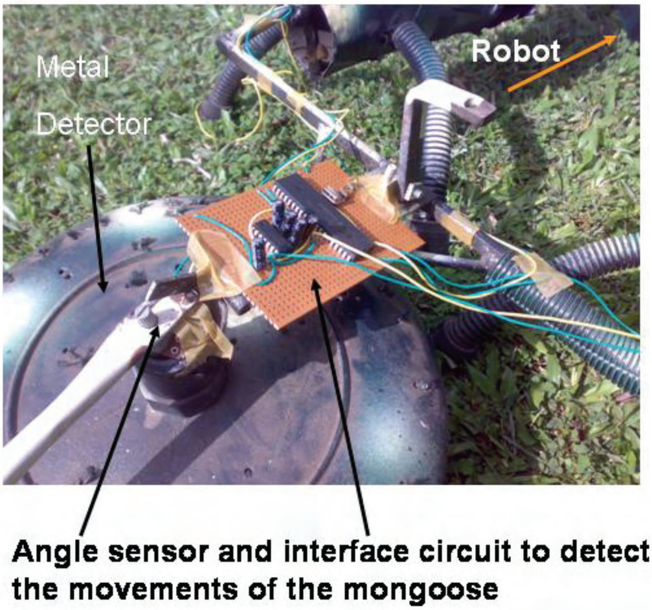

Fig. 3. How the angle sensor is interfaced to the slave PIC16f877 microcontroller

Figure 3 shows how the robot's end of the cord that connects the robot to the mongoose is attached to an angle sensor. The sensor information was filtered and given to the analog port of a PIC16f877 slave microcontroller. The slave microcontroller is interfaced to a mother microcontroller that controls other sensors and actuators of the robot as shown in the schematic diagram in figure 4.

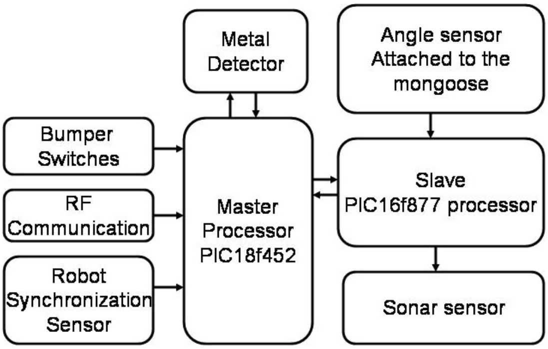

Fig. 4. The how different sensors and actuators are interfaced to the mother board of the robot

3.1 Experimental Results of Robot-mongoose Integrated System

Experiments were carried out by burying a small trace of explosives < 1g just beneath the ground in different directions (-45^0, -30^0, +30^0, and +45^0). The explosive trace was kept 3m beyond the initial position of the mongoose. The robot sensed the direction of drag of the mongoose while the mongoose was sniffing for the explosives. **Figure 5** shows that the mongoose takes less than 25 seconds to find the correct location after a brief phase of sniffing to trace the target.

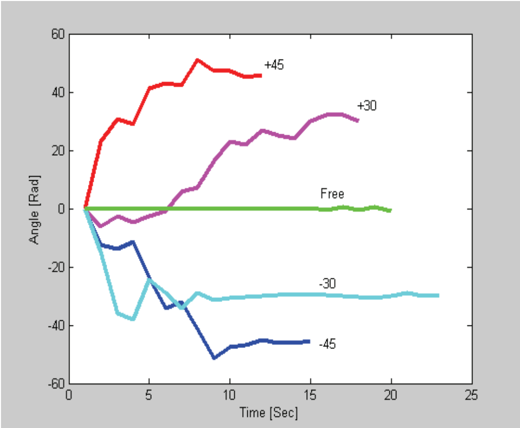

Fig. 5. The drag behavior of the mongoose for explosives buried in different target locations

3.2 Proposed Behavior Arbitration Mechanism in a System of a Rodent, Robot, and Human Systems that will Orchestrate Effective Navigation Behaviors

The proposed system consists of a semi-autonomous robot, a trained animal to sniff for a target chemical, and a human trying to control the robot and understand the behaviors of the animal from a remote location as shown in figure 6. Therefore, the final behavior of the system is an outcome of an interaction of three mutually dependant sub-systems with the surrounding environment.

Therefore, the effectiveness of the whole mission depends on how the behaviors recommended by each sub-system are arbitrated. Some of the published behavior arbitration mechanisms can be categorized into the following broad classes (Arkin R.C., 1998; Brooks R.A., 1986; Hoff J. & Bekey G., 1995; Cooper R. & Shallice T., 2000; Maes P, 1991).

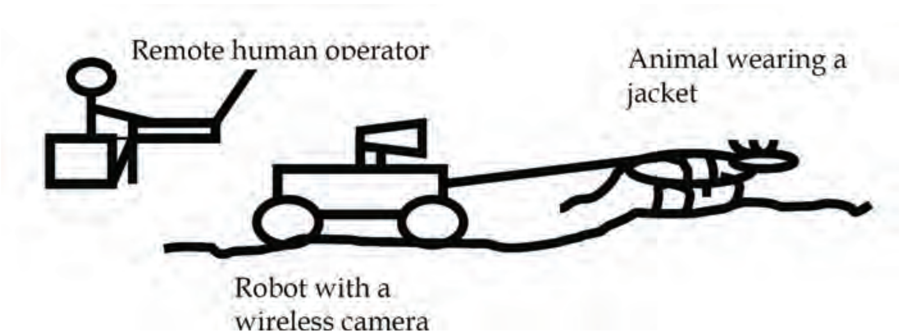

Fig. 6. The animal-robot-human system

3.3 Voting for actions

There is an arbitrator that votes for actions recommended by different behavior modules (Arkin R.C., 1998).

3.4 Subsumption Architecture

Behaviors are stacked in layers. The behaviors occupying higher layers can suppress those occupying lower layers given a situation [58].

3.5 Vector Addition

The actions recommended by each behavior are fused by taking the vector summation of the actions [59].

3.6 Analysis of Each Sub-system in the Proposed Method

In the proposed method, the human, robot, and the animal may influence the other sub-systems in the following ways:

The human operator will watch visual feedback taken from the wireless camera mounted on the robot and send control commands through a wireless link to the robot. Therefore, he/she may influence the system in the following ways:

1. Send control commands to keep the robot on track.
2. Command the robot to avoid obstacles.
3. Assist the animal to scrutinize an off track area by deviating the robot from the track.
4. Force the animal to avoid certain paths where the robot can not go, by controlling the robot to take an alternative path.
5. Control the speed of the robot relative to that of the animal to improve efficiency and to avoid intimidating the animal.

The semi-autonomous robot will execute its autonomous behaviors while accepting commands from the remote human controller. Therefore, it may influence the system in the following ways:

1. Keep the animal on a given track.
2. Use its autonomous behaviors to avoid obstacles.
3. Provide visual and haptic feedback to the human operator.
4. Reward the animal with a pleasing sound if it finds a target chemical.
5. The animal may influence the system in the following ways:
1. Drag the robot to different directions depending on the smell perception.
2. Force the robot to stop if it wants to scrutinize a location further.
3. Force the robot to accelerate and decelerate.
4. Elicit behaviors to alert the human.
5. Force the robot to avoid obstacles.

3.7 Azimuth Control of the Robot

At present the azimuth of controlled by the remote control commands sent by the human operator by watching the behaviors of the mongoose. The semi-autonomous behaviors of the robot contribute to intricate control actions in response to local conditions immediately in front of the robot. However, we propose an advanced behavior arbitration mechanism based on a weighted vector summation of actions recommended by each sub-system as given bellow.

Let, $\phi(k)$ is the azimuth of the robot, $\alpha(k)$ is the angle of drag of the animal, and $u(k)$ is the azimuth recommended by the human at time k. Therefore, the vectors $[\phi(k)\ \phi(k-1)\cdots\ \phi(k-N)]$, $[\alpha(k)\ \alpha(k-1)\cdots\ \alpha(k-M)]$, and $[u(k)\ u(k-1)\cdots\ u(k-L)]$ represent the pattern of behavior of each sub-system in the recent past. The length of the vectors are decided by the order parameters given by N, M , and L .

Then, the azimuth of the robot at time $k+1$ is given by an adaptive autoregressive model given by $\phi(k+1)=\psi^T x$, where, $\psi^T=[a_0\ a_1\ \cdots a_{N-1}\ b_0\ b_1\ \cdots b_{M-1}\ c_0\ c_1\ \cdots c_{L-1}]$ is a vector of parameters and $x^T=[\phi(k)\ \phi(k-1)\cdots\phi(k-N)\ \ \alpha(k)\ \alpha(k-1)\cdots\alpha(k-M)\ \ u(k)\ u(k-1)\cdots u(k-L)]$.

The dynamics of behavior arbitration depends on the parameter vector ψ , and the order parameter vector $[N\ M\ L]$. We envisage to study a method to adaptively change $[N\ M\ L]$ and ψ , so that the influence made by the behavior of each sub-system will adaptively change to orchestrate the best behavior.

3.8 Speed Control

We tend to believe that the Subsumption architecture is suitable for speed control as shown in **figure 6**. The robot and the animal negotiate a speed by vector addition. The human suppresses any decision taken by the system of the robot and the mongoose.

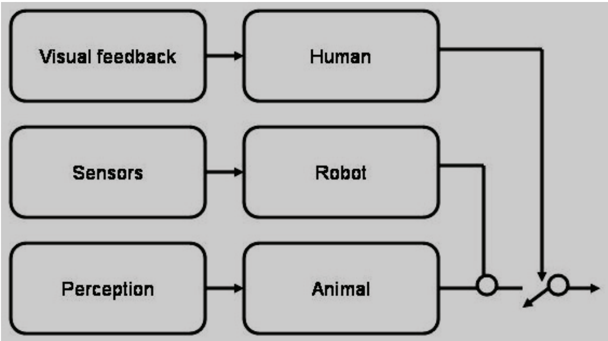

Fig. 6. The overall control algorithm of the robot

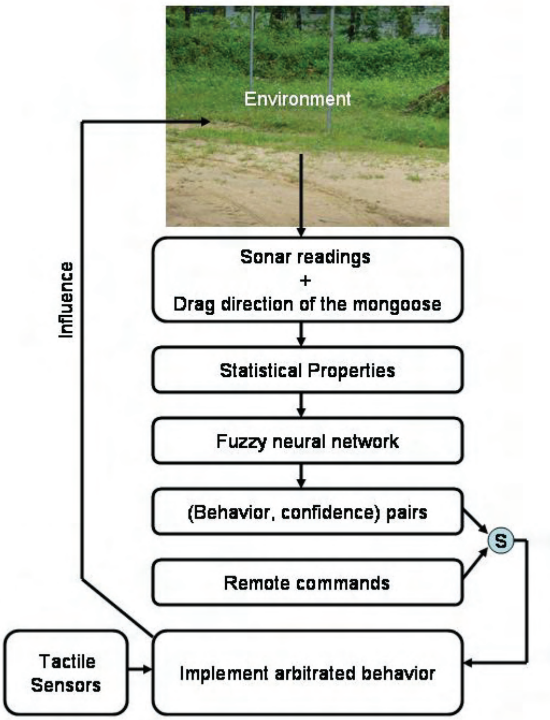

Figure 6 shows the proposed control algorithm of the human-robot-animal integrated system to detect landmines.

4. Discussion

To the best of the author's knowledge, this is the first time a human-robot-animal integrated system is tested for antipersonnel landmine detection. The proposed system tries to integrate distinct capabilities of three different systems to improve the effectiveness of landmine detection in a cluttered environment. The mongoose is found to be a rodent with extremely sensitive olfactory capabilities, dexterous navigation capabilities in a cluttered environment, and small enough to burrow through rubble. The lightweight legged robot (4kg) can move in a minefield without detonating landmines, carry a metal detector, and interact with the mongoose and the human. The remote human operator can analyze the behaviors of the animal-robot system and judge how best the system should move from a remote location. Therefore, the system achieves a fundamental objective of humanitarian landmine detection by improving the effectiveness and accelerating the detection process through removing the human operator from the minefield. The design gave much emphasis on reducing the need to have expensive sensors and sophisticated image processing systems in order to make it as cost effective and reliable as possible. Therefore, there were only a single sonar proximity sensor and two bumper switches attached to the front of the robot.

However, further improvements are needed in the arbitration mechanism that optimizes the synergy among the human, robot, and the animal by improving the learning algorithms. The robot can learn from both the animal and the human though the teaching signals can be noisy. The animal can learn from both the human and the robot to navigate with the robot attached to it. The human can learn from the animal and the robot by observing the limitations of the animal-robot system. We are conducting further research on learning algorithms that suits this scenario. Commensurate efforts have to be taken to simplify the learning algorithms to suit commercially available embedded processors and to improve the processor network to accommodate the extra processing load. Furthermore we hope to automate the training process of mongooses based on the wealth of knowledge we have gathered through manual training. This will allow the trainers to run the training sessions round the clock.

5. Acknowledgements

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16

Power Tillers for Demining in Sri Lanka: Participatory Design of Low-cost Technology

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1. Introduction

There is increasing consensus on the fact that landmines heavily affect the development of contaminated countries and that mine action activities need to be integrated into general development initiatives.
There is also general acknowledgment that machines have fallen short of expectations: only few are actually employed in the field and are often down for maintenance, waiting for spare parts or for experienced technicians to fix them coming from abroad.
These reasons are at the base of the idea of adapting commercially available power tillers to demining applications. Different modules attachable to the powertiller, modified to be the tractor unit, have been designed in a participatory way together with deminers. In fact, we believe that involving deminers in the whole design process would allow them to get familiar with the innovation process, which is a key component of the development process, and would help to create a machine closer to real needs, made of materials available locally and therefore with greater chance of success.
The project presented here therefore focuses on the participatory design and development of a new small machine for helping to remove landmines in the Vanni region in Sri Lanka, where landmines are of the small plastic type containing approximately 50g of TNT. The whole work encompasses the creation of four modules: tractor unit, ground processing tool, vegetation cutting tool, and the control unit to drive the machine from the safe distance of 20m.
The tractor unit is the power tiller modified to resist possible explosions of landmines underneath and adapted to the remote control, while the ground processing tool is the means by which landmines are lifted up on the soil surface to facilitate later hand removal by deminers. The ground processing tool is placed on the front of the machine, to allow landmines to be removed before the tractor unit passes over them. The vegetation cutting module can be attached on the front of the machine when vegetation is too thick for the machine to pass through. It is powered by the power tiller engine and is supported by the same supporting frame of the ground processing tool.
This chapter analyses the currently available cost-effective technologies on the demining market, before presenting the power tiller idea and the participatory methodology used for

designing it, followed by a detailed description of the four modules. It finally ends with further work, acknowledgments and conclusions.

2. Mine Action in Development: Possibilities for participatory Design of Low-cost Technology

The Geneva International Centre for Humanitarian Demining (GICHD) has recently launched a new research project, seeking to assist government officials, donors and mine action and development practitioners to better link mine action with development (LMAD). It is seen as essential that mine action and development initiatives are effectively coordinated at all levels in order to align mine action with national and local development priorities, incorporate mine action within national development plans and budgets, increase stability of mine action funding and provide more effective mine action and development interventions (Naidoo, 2007).

After conflicts, countries generally transit through three main phases: immediate post-conflict stabilisation, reconstruction and traditional development with assistance from international donors and financial institutions. Even if in some cases, as Sri Lanka, dormant conflicts resume, slowing the transition through the phases, the development stage is eventually achieved.

Mine action activities take place along the whole process, targeting different aims in different phases. During the development phase, mine action is more likely to concentrate on community priorities, as main roads and other infrastructure have already been cleared and re-opened. In many countries this phase lasts for a long time. "What is certain is that mine action programmes in heavily contaminated countries will almost certainly not be able to declare victory in the short-to-medium-term."(Filippino, 2005).

Therefore, mine affected countries would need to equip themselves adequately for the long haul and programmes have to assess their performance in terms of results that make a positive difference to people's lives. In fact, although we know that millions of people living in 79 countries are affected by landmines (ICBL, 2006), the size of the global landmine problem is not yet well defined, being missing indicators measuring indirect impacts of landmines on people's lives. The post-conflict impact of landmines on development goes far beyond the direct and cruellest effects on human lives and health; other important indirect effects are caused by the fact that landmines create obstacles to free movement within affected areas, posing restrictions on people's freedom and ability to access basic needs such as food, shelter, clean water, hygiene, transport, education and work, compromising their human development.

Moreover, the threat posed by landmines is only one among many others that people living in affected countries are facing everyday, such as the threats posed by HIV, malaria, road accidents, and so on. Therefore, approaching the landmine problem in relation to all the others, in the wider context of development, would lead to the possibility of being able to deal with it for longer and to do it in a more effective manner. In fact, donors' attention to demining is decreasing: donors are showing fatigue having spent money in demining activities for years without having seen the results promised. The goal of having the world free of mines by 2010, is no longer realistic due to the slow and often incomplete nature of demining operations.

Approaching the landmine problem in the wider context of development suggests a change in the methodology to design humanitarian demining technologies.
That science and technology play a pivotal role in the development process has been shown by the exponential rate of growth of living standards after the industrial revolution. After 1820, 1/6 of the world population achieved high-income status through consistent economic growth and technology has been the main driving force behind. “I believe that the single most important reason why prosperity spread, and why it continues to spread, is the transmission of technologies and the ideas behind them”(Sachs, 2005), says Jeffrey Sachs, special advisor to the former UN secretary-general Kofi Annan.
In fact, one of the main differences between rich and poor countries is in their tendency to innovate; in poor countries inventors often do not have the incentive to invent because they know they will not be able to recoup the large fixed costs of developing new products. Even if the diffusion of technologies developed else where can help development by bringing to poor countries new ideas and tools, often technologies are not designed taking poor countries’ ecological conditions into account and therefore are not suitable to tropical or arid or mountain environments found in these countries.
Indeed, rapid economic development would require that technical capacities suffuse the entire society, from the bottom up. In any developing countries, home-grown technologies would be needed to adapt the global process to local needs in areas ranging from energy production and use, construction, natural hazards mitigation, disease control and agricultural production as well as humanitarian demining.
Therefore, a new methodology to design technology in a participatory way together with local end-users is here presented and used to design a new mechanical system for helping humanitarian demining operations in Sri Lanka.
Specifically, we propose to develop low-cost technology using local resources adapting already available agricultural technology to demining tasks; leveraging mature technology would allow the exploiting of local knowledge already acquired through decades of use. Skills acquired in modifications of agricultural technologies to demining applications, could be used later on to increase agricultural production. Technological innovation in the field of agriculture is one of the major contributors to development.
This participatory approach would empower local communities by increasing their technical knowledge while making use of their own experience and skills.

3. Mechanical Demining Equipment: Field Experience of Machines Available on the Market and Analysis of Low-cost Locally Made Ones

A research we carried out in 2004, funded by the European support measure EUDEM2, showed that the current state of field use of off the shelf machines was limited, especially if compared with sensor technologies. The aim of the study was to ascertain the current demining technologies available in various contaminated countries and end-users feedback about them; the audience targeted was both the researchers approaching the problem of designing new demining technologies and NGO’s workers in affected countries. During the three months spent in the field, we visited nine organizations working in four different countries: Mozambique, Namibia, Sri Lanka and Cambodia (Cepolina et al., 2004).
While gathering various data, we asked nongovernmental organization logisticians about the maintenance costs of technologies in terms of the operating cost, salary of operators,

downtime due to mechanical failures, time between failures and cost to repair failed machines. Generally, we found a huge difference between the maintenance costs of a machine and that of a sensor. Taking as an example our data gathered in Mozambique, the maintenance costs per month of a machine in use at an organization were US$530 while the cost for maintaining a sensor was $194. These calculations do not even take into consideration the cost of training, which lasts for 25 days for a machine and less than one day for a sensor (Cepolina, 2006).

Thus, we believe high maintenance costs are one of the key factors behind the low adoption rate of machines by demining organizations. In our calculations, the high maintenance expenses were primarily due to the excessive cost to repair machines, multiplied by the high frequency of machine failures. We concluded that demining machines available on the market are complex systems that have not been conceived by the deminers who use them; nor have most machines been developed specifically for the environment in which they are being used. However, the organizations visited had few resources invested in personnel and workshops for mechanical technologies, each using between zero and two machines. An exception was represented by one organization visited, employing nine different mechanical technologies. All machines were adapted from mature technologies modified with locally available material in a specialized workshop. During the summer of 2006 we visited another demining programme in Georgia and there were many machines in use, covering all operations. In this case as well, the presence of a specialized team of mechanics helped daily with the maintenance of machines.

By using the following scheme, the cost-efficiency of such locally developed machines is much higher than the ones that were developed elsewhere.

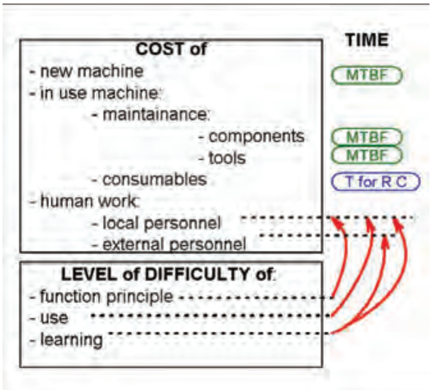

Fig. 1. Cost-efficiency paradigm

This is due to the fact that machines developed locally have initial lower cost, shorter down time and lower repairing cost. Among such mechanical technologies were machines built upon construction equipment, using off-the shelf attachments such as vegetation cutters or sifters armoured when necessary, off the shelf trim cutters, locally produced rollers designed to mechanically activated mines when towed on suspected areas as well as rakes and ground scrapers.

However, it is shown that investing in machines requires also investments in maintenance capabilities. In fact, a new philosophy has recently proven to be successful: some machines are currently delivered with a mobile workshop and the technicians in charge of taking care of the maintenance for the whole duration of work. While this approach can be very effective, it does not empower local communities as there is no knowledge transfer; therefore is more suitable for emergency responses than for development phase.
Among mechanical technologies available on the market and documented in the Mechanical Demining Equipment Catalogue 2006, published by the GICHD, the cheapest is Tempest Mk V. It costs 120,000 USD and is classified as multi-tool system presenting a range of attachments from vegetation cutter to ground engaging head. It is produced in Cambodia in the Development Technology Workshop using local materials and facilities. Although not adapted from any existing technology, it is designed to incorporate materials that are locally purchased within developing mine affected countries as Cambodia and to be easily repairable without factory support. Moreover, DTW offers an upgrade package which extend the normal working life of Tempest, as all machines can be completely stripped down and disassembled before being refurbished with any new factory modifications or equipment used. The upgrade package costs 20% of the original purchase price.
Generally, the cost of machines increases as the size increases, mini and medium flail systems weighing from 3000 to 14500 kg costing between 220.000 and 300.000 USD, other than Tempest multi-tools weighing from 4700 to 7500 kg costing between 200.000 and 425.000 USD and Tillers weighing approximately 50.000 kg costing around 1.500.000 USD.
Unfortunately, the price of many machines presented in the Catalogue is not reported, making it difficult to analyse the difference between mechanical demining technologies adapted from mature technologies such as tractors or construction equipment and other technologies. Nevertheless, among advantages of machines adapted from other technologies is often mentioned the availability of spare parts from local dealers of the manufacturing company producing the prime mover.

4. Power Tillers for Demining in Sri Lanka

Given that every mine problem is unique and strictly linked to the area where it occurs, the research focuses on one particular region of Sri Lanka: the northern area of Vanni. Designing a technology for operation in a specific region helps to concentrate efforts on a well-defined problem; moreover, it allows local deminers to be involved in a project from which they will benefit and to exploit the knowledge they have acquired over long years working in the field.
We have chosen Sri Lanka for several reasons: people are generally well educated (having typically attended 10 years of school), enthusiastic, and willing to work and learn new skills. Additionally, at the time the project started, the country was facing an immediate post-conflict situation in which people were strongly involved in rebuilding the country. Unfortunately after presidential elections of November 2005, the situation deteriorated rapidly: the fragile cease-fire agreement signed in 2002 collapsed in everything but name due to almost daily violence. Although the ongoing conflict creates more difficulties in logistics and communications, we believe that a participatory approach to the design of a new technology could assume an important role in support of the efforts to achieve peace.

New tools not involving face to face communication were thought and used for design phases prior to the effective prototypization in loci.
A one-month trip to the Vanni region in Sri Lanka was organized in January–February 2005. The trip was aimed at establishing contacts, deepening knowledge of the local environment and improving communication skills to make the participatory contribution more effective. We interviewed groups of deminers to start the research in the right direction, better understand local needs and establish a reciprocal trust between local people and expatriates coordinating humanitarian operations in Sri Lanka. Most notably, in the field information was gathered by working on the functional requirements for a system of small, light and cheap demining machines to be used for working close to the deminers. The need of such a system arose from the study conducted in 2004 in collaboration with EUDEM2. When deminers were asked about their preferences for new machine technology, they expressed a strong desire for new machines that were small, light and cheap. They wanted them to help in the most boring/difficult parts of their job, particularly cutting vegetation and processing the ground, specially the hardest one, currently scarified using a simple rake called heavy rake, to remove the soil hiding mines.
Based on these findings, we suggested adapting power tillers to demining applications. Power tillers are widely used and commercially available in Sri Lanka, and their second-hand market is largely spread. They are easy to transport as they are small and light, and they are available with different types of engines. The most powerful one (approximately 14 kW) is sturdy enough for our task, being Vanni region soil either sandy or soft because of alluvium type.
Power tillers, also known as walking tractors, two-wheel tractors or iron buffalos have a great importance in their nations' agriculture production and rural economies. They not only have rotovator attachments but also moldboard and disc-plow attachments. Seeders, planters, even the zero till/no-till variety can be attached. Reaper/grain harvesters and micro-combine harvesters are available for them. Also very important is their ability to pull trailers with two plus ton cargoes.
The population of power tillers in developing countries is surprising high. China has the highest numbers that are estimated to approach 10 M, Thailand has nearly 3 M, Bangladesh has over 300,000 Sri Lanka 120,000, India 100,000 Nepal 5,500. Parts of Africa have begun importing Chinese tractors and Nigeria may have close to 1,000 (Wikipedia, 2007). Numbers are likely to increase as the availability of draft animals is reducing.
By adapting power tillers to demining application we intend to increase the number of these machines available to rural villages. After operations they can be re-converted to original agricultural use and exploited for increasing agricultural production.
As suggested by the NABARD association (NABARD, 2007), to achieve the desired average farm power availability of 2kW/ha, necessary to assure timeliness and quality in field operations in India, agro services centers could be established. There, machinery could be provided on custom hire basis to the small and medium farmers who cannot afford purchasing their own machinery as and when it is needed. In the same manner, in parallel to agricultural machines, the agro service centers could provide also machines for demining applications, based on agricultural machines. They could develop locally modifications required to effectively address the demining problem, hire these machines and provide assistance.

5. The Snail System

The originality of the project lays in the fact that end-users are involved in the whole design and development process of the machine.
We believe that is really important to understand the context in which a technology will work and the consequences the technology can cause on the society that will use it.
Therefore, in parallel to the technical work on the machine, we are also researching into the relationship between landmines, humanitarian demining technologies and development and we are proposing a new methodology for designing mechanical technologies for humanitarian demining in a participatory way together with deminers having worked in the field for a long time.
A first concept of the system to design technology in a participatory way, termed *Snail System,* has been elaborated and used.

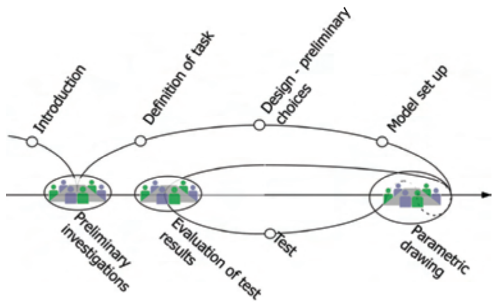

Fig. 2. Snail system

The Snail System is an iterative design methodology allowing a progressive involvement of end-users in the design process. Snails are lines connecting subsequent steps of the design process that develop along a straight line indicating work progress.
Meetings with end-users happen along the straight work progress line. Every decision is made with end-users; only studies prior to these decisions, such as the preparation of possible choices, simulations and calculations, are carried out by researchers and later presented to end-users.
The design evolves along all the traditional steps including the creation of models, as tools to support design decisions making.
Models can be either mathematical, digital mock-ups, when prepared in university laboratories or very simple models made with material ready available, also called crap-ups (Roth, B., 2006), when done in the field together with end-users. The idea is making prototypes quickly, even very rough ones, to get the ideas flowing and to find out which direction seems most fruitful. Test is done by discussing together with all people involved in the subject, at all different levels, from locals dealing with the problem everyday, to researchers living in western countries. Learning by mistake is very effective, especially at early stages of the design process.
Each Snail represents a work module necessary to carry out the main package of the total work for the project. The workflow of technology design is represented by Snail lines, as often it is iterative; the design process is repeated until a satisfactory result is reached.

Together with end-users, we have tried to involve many other possible contributors into the design process of the machine to make it more effective. People working for manufacturing companies of components we used, international demining experts, various representative of NGO's, people working in garages were agricultural machines are fixed and researchers of various universities gave their precious contribution to the project.
In order to involve local end-users into the design and development of the new machine, participatory techniques have been used, such as ranking and rating tools.
When not able to meet end-users or other researchers and experts contributing to the work face to face, the project website (http://www.dimec.unige.it/PMAR/demining/) was used as communication channel. There, power point presentations have been linked to the main pages describing the work and instructions on how to add comments or modifications to them using collaborative online tools provided by Zoho services (http://www.zoho.com/) were added. When modifications are made anonymously they are visible in real time in website pages, directly contributing to the work.

6. Participatory Agriculture Technology (PAT) for Humanitarian Demining Project

Therefore, the main goal of the project is to adapt agricultural machines to assist humanitarian demining operations in the Vanni region of Sri Lanka.
Deminers asked for their preferences during group interviews, expressed a strong desire for new cheap and light machines, small enough to be fitted in the back of a small truck. They want machines to help in the most boring/difficult parts of their job, particularly cutting vegetation and processing the ground, specially the hardest one, currently scarified using the heavy rake. In fact, no metal detectors are employed by Norwegian People's Aid (NPA), the NGO partner of the project with the University of Peradeniya in Sri Lanka, as soil is ferrous and mines have very low metal content; instead, ground is excavated at the depth of 100mm, specified by local authorities, to expose to eye sight buried landmines. Two simple rakes with handler extended to 2m are used: light rakes to remove loose soil and hard rakes to process more compact and deep soil. Vegetation is manually cut with simple gardening tools like saw, sickle and shears.
Therefore, the target of the project is to develop a modular system using as core module a power tiller and equipping it with modules specialised for ground processing and vegetation cutting, able to process the soil and make demining operations with the excavation tools currently used by local deminers faster. A special end-effector to process the soil and bring mines up to the soil surface is being designed. Each machine can be considered a semi-autonomous system, helping a single deminer in his work, and a certain number of machines can be controlled automatically to perform area-reduction operations, working as a multi-agent system. Deminers will always assist machines: once a mine is found and lifted up on the soil surface by the special end-effector, a deminer can remove the mine manually. Manual mine removal has been introduced in order to lower the complexity and cost of the machines, as well as to allow a quicker integration of machines in operational procedures.
Between small agricultural machines available in Sri Lanka we have chosen to employ power tillers, as they are very common and widely used, being one of the most important multi-purpose agriculture and transport vehicles in the country.

A modular top-down design approach was chosen. Starting from the task, defined by deminers, the mechanical modules able to accomplish the work were conceived. The project involves the mechanical design of three modules: tractor unit, ground processing tool and vegetation cutting tool.

The project foresees also the implementation of the control of the machine that needs to be operated remotely, when Unexploded Ordnance (UXO) and fragmentation Anti Personnel (AP) mines are known to be present.

The overall essential requirements the machine has to satisfy are:

- reliability: 100% clearance
- safety of operator: 100%
- depth of demining: 100 mm
- width of clearance: 1200 mm
- speed of clearance: higher than manual
- types of mines: small plastic blast-type AP mines
- cost: 20.000 €
- remote control distance: 20 m

Considered mines are small because they are between the less harmful existing ones, containing up to 50g of explosive only. UXO and fragmentation mines are also present, especially Claymore types, but only in certain known minefields. The machine is specifically designed to be proof against AP blast mines and to resist damages caused by fragmentation devices.

Cost is one of the main points of the project, being one of the major causes of poor adoption of machines into demining programmes. The price of €20.000 does not include the research and developing cost and is equally divided between the modules and the control.

A preliminary test was performed in order to get physical understanding of the effects of a mine explosion on the power tiller, when a mine is activated by one wheel.

Results (Salvi & Cepolina 2005) were encouraging as the power tiller chassis was not considerably damaged after four explosions, suggesting that only a thin steel plate, possibly presenting small holes in order to lower its weight, could be used to protect it. Steel open cage wheels deformed after the explosion and lost blades. We believe that damages to them were limited by their open structure allowing part of the blast wave to expand in air. Upon test results the implementation plan to carry out the project was developed.

The implementation plan foresees the development of a first prototype in the workshop of the University of Genova. After testing it in conditions similar to the ones found in Sri Lanka, the experience gained and lessons learnt will be used to develop a second prototype in a local workshop in the Vanni region of Sri Lanka.

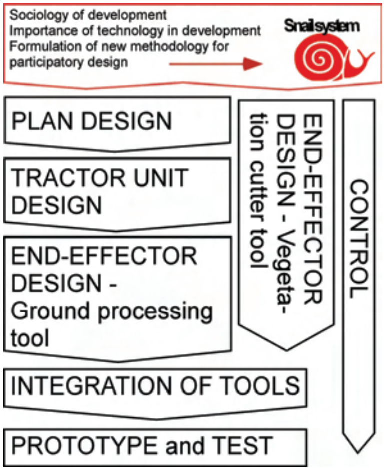

Fig. 3. Implementation plan.

7. Tractor Unit

Pursuing the idea of employing mature technologies already available in the country and particularly small agricultural technologies, as basic machine, the suitability of the power tiller as tractor unit was verified first.

Between the main reasons leading to the idea of using the power tiller, there were its small dimensions and its low weight. In order to process the ground in front of a deminer, the machine has to work in the demining lane, which in Sri Lanka is 1200 mm wide: 100 mm on each side are used for verification of working depth. In order to be transported easily to the minefield, the machine has to fit in the boot of the small ISUZU ELF trucks mostly used by NPA, carrying up to 2000 Kg in 1,8 x 5 m area. The weight and dimensions of one of the biggest powertiller available on the Sri Lankan market, produced in China by the Dongfeng Brand, the DF-12L model with 10kW engine are more than suitable.

The powertiller shown on the right hand side of fig. 4 is the one we have in the laboratory, on which we are working. It was produced in Italy in 1944 and presents similar characteristics to the one we would like to employ in Sri Lanka. We bought it second hand for 100€. After some work, it started running again.

Obviously, the speed of work of a power tiller is higher than the one of a manual deminer, calculated during time and motion studies held for the EUDEM2 survey equal to 0,0037 m/s. The working speed of a power tiller processing the ground with a milling tool can be considered equal to 0,2 m/s.

The cost of power tillers is low, especially in developing countries like Sri Lanka, where a 10kW one can be bought for €250, €70 if second-hand.

Fig. 4. Power tiller in use at the University of Genova Vs Power tiller available in Sri Lanka

The effective employment of a power tiller as tractor unit has to be evaluated considering functional requirements. Moreover, attention has to be paid at keeping the machine extremely simple, avoiding adding to a very simple basic unit such as the power tiller, complex modifications or tools.

Parameters have been identified that contribute to achieve extreme simplicity and effectiveness, referred at as *Simpleffectiveness*.

The features the tractor unit has to present in order to be *Simpleffective* are:

- forward/backward motion (traction)
- steering: 1m curve radius
- energy supply to end-effectors
- stability
- assessment of ground processing depth
- mine disposal
- safety of operator
- shock wave protection for machine (and operator, in manual use)

The machine has to be mine resistant: it has to be designed to be proof against anti-personnel (AP) blast mines, while resisting damages caused by the fragmentation associated with UXO and anti-personnel fragmentation mines.

A first indicative analysis of the mobility and energy requirements suggested that the power tiller is suitable to the aim, with only little adjustments. In fact, power tillers present several gears, the number depending on the model, including at least one for going backward; steering can be achieved thanks to the differential gear. Moreover, part of the energy coming from the engine can be used for actuating the end-effectors through the power take off.

Generally, power tillers available in Sri Lanka do not have a battery on board, therefore one should be added to supply energy to the control unit.

A rough estimation of the power required to push or pull an end-effector to process the ground at 100mm depth, 1200mm wide, in clay soil, at 0,1m/s working speed is 3 kW. The power absorbed by a vegetation cutter tool 120 cm wide, like cutting bar, is 4 kW.
While the vegetation cutting tool is certainly placed on the front of the power tiller to allow the machine to pass through thick vegetation, two different possible working configurations for the ground processing tool, designed to rake the ground and bring mines up on soil surface, have been identified: one with the ground processing tool at the back (G-P-B) and one with it on the front (G-P-F). The choice is subject to the evaluation of *Simpleffective* parameters values in the two cases.
A physical, a multi body and a 3DCAD model have been created to support design decisions, through simulations and tests.

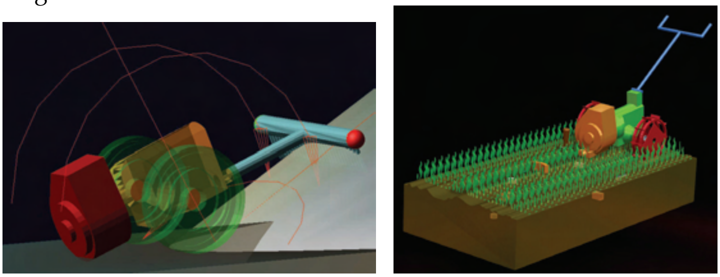

Fig. 5. Multi-body and 3DCAD models of power tillers

While the multi body model was aimed at assessing the stability of the two configurations under different load conditions, the physical model was aimed at supporting the test of the preliminary version of the tractor unit armouring to resist detonations of AP mines.
In fact, a way to protect the tractor unit from shock waves caused by the explosion of a landmine under a wheel was researched first.
Following the idea of modifying the power tiller as little as possible, it was chosen to protect the tractor unit by allowing the wheel to drop off when explosion occurred. The idea was that if physical connection was interrupted, the shock wave transmission to the axle and to the power tiller drive train should be significantly reduced. Moreover we believed that damages to the wheel should be reduced as well.
Therefore, breakable connections to be placed between the wheel and the flange were designed for withstanding normal working load conditions while breaking when an explosion occurred. The idea was to interrupt the transmission of the shock wave from the wheel touching the ground to the power tiller axle and subsequently to the gear train. To connect modern wheels to the axle of the old power tiller it was necessary to design a supporting flange. The breakable connection is therefore designed to be fastened to the flange connected to the axle on one side and to the wheel on the other side (see fig. 6). The breakable ring is made of cast iron ASTM 30 class.

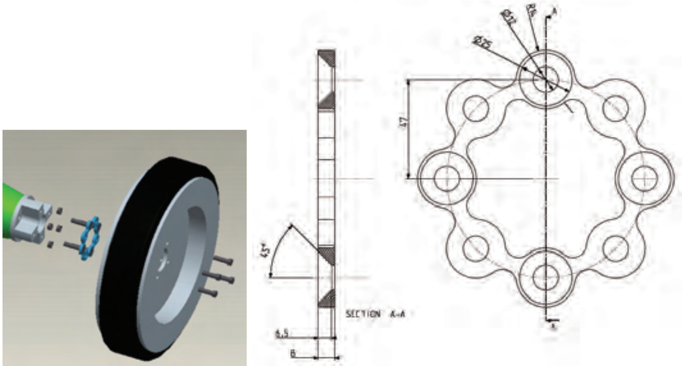

Fig. 6. Assembly of wheel, breakable ring and flange and technical drawing of breakable ring

In case of explosion and fracture of the ring, most likely to happen along the bridges, a new ring could be replaced simply by screwing it into the flange first and into the wheel later.

A blast test was organized in May 2006. It took place under the supervision of Danilo Coppe, one of the major explosive experts in Italy, in an open air cave near to Fornovo, Parma. The aim was to verify the suitability of the preliminary version of the tractor unit armouring, based on the concept of the breakable connection, to resist detonation of AP mines. Together with the breakable ring, two other breakable connections were tested, simply constituted by two sets of screws, fastening the wheel to the flange, presenting double and single cuts along their body.

Wheels tested were common agricultural pneumatic wheels, filled in with two different types of elastic gums: GoFill tyre filler and GoSeal tyre sealer, kindly provided by GoGomma, who has also agreed to provide a workshop in the field in Sri Lanka with second hand machines necessary to fill in every kind of wheel with those special elastic gums, in case of positive test result.

Five explosions took place, with landmines respectively underneath:

- wheel filled in with GoFill
- wheel connected to the axle with breakable ring
- wheel connected to the axle with screws with double cut
- wheel connected to the axle with screws with single cut
- wheel filled in with GoSeal.

Unfortunately, results from tests were not as expected and the preliminary armouring is not currently suitable to protect the power tiller from damages caused by the detonation of AP landmines under wheels.

In fact, the principle adopted into the design of the breakable connections proved not to work; although the wheel connected through the breakable connection dropped off during two of the three explosions, the physical detachment happened after the blast wave was already passed through the connection and entered the power tiller structure, as it can be seen from measures recorded by the accelerometer placed on the axle.

The blast wave travelling at supersonic speed passed through the medium before it had the time to deform and break. Nevertheless, the breakable connection worked at reducing the total energy transmitted by the blast wave to the power tiller, by filtering waves at high frequency. Therefore, the breakable connection designed acted more like a high frequency filter than a low frequency filter, as expected.

The wheel rims got damaged almost in the same manner after each explosion except for the second, when the mine was not placed directly underneath but slightly internally. Therefore, no advantages of using the breakable connection are visible on wheel deformations. The reason for this could be that they remain physically connected to the power tiller until the breakable connection breaks, absorbing the same low frequency waves of the blast wave that pass through the power tiller structure.

Even if not damaged too much by each explosion, the wheel filled in with GoFill could not keep on working normally after the fourth explosion. The wheel filled in with GoSeal could definitely not keep on working after the first explosion.

The energy released by the blast wave and passed through the power tiller during the fifth explosion was 5 times less than the energy passing through the structure during the first explosion and 3 times less than the energy passing through the structure when the breakable connection was in place, see fig. 7. (Cepolina, 2007).

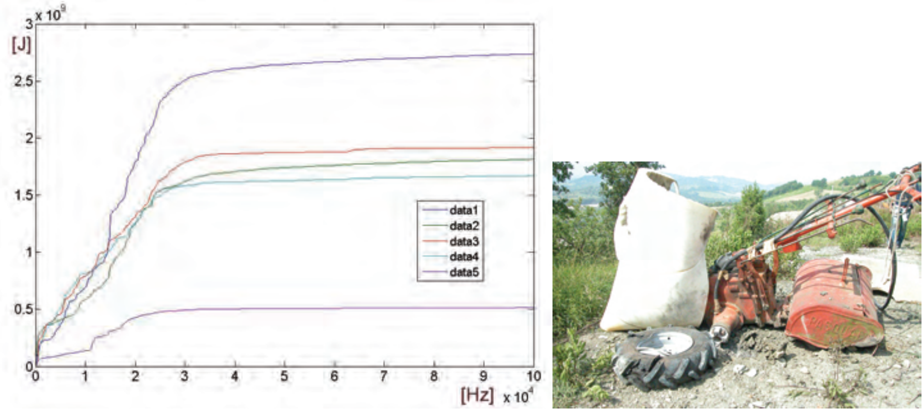

Fig. 7. Energy[J] versus frequency[Hz] passing through the power tiller in the five explosions (data1 refers to first explosion, data5 to the fifth); power tiller after fourth explosion

This suggests that pneumatic wheels filled in with air and liquid, in this case GoSealer, work at reducing the total energy transmitted to the structure better than solid wheels, filled in with GoFill. This result is in accordance with results obtained by Defence R&D Canada (Hlady, S. 2006) who conclude that detonations under water-filled tires transferred more kinetic energy upwards than either the standard or runflat tires.

8. Tractor Unit Re-design

Upon these test results, we have decided to place the ground processing tool on the front of the machine.

This lowers the possibility to have an explosion under the machine as landmines should have already been removed when the machine passes. In order to increase traction, rubber tracks have been added connecting driven wheels to additional wheels supporting the

ground processing tool on the front. Remote control of the tractor unit is then possible by actuating the two semi-axles through brakes, also added. Moreover, we believe that tracks could absorb part of the energy of an accidental explosion underneath by deforming flexibly.
Therefore, the system will work in the configuration shown in fig.8. having both the end-effectors on the front, the vegetation cutting tool supported by the same frame supporting the ground-processing tool.

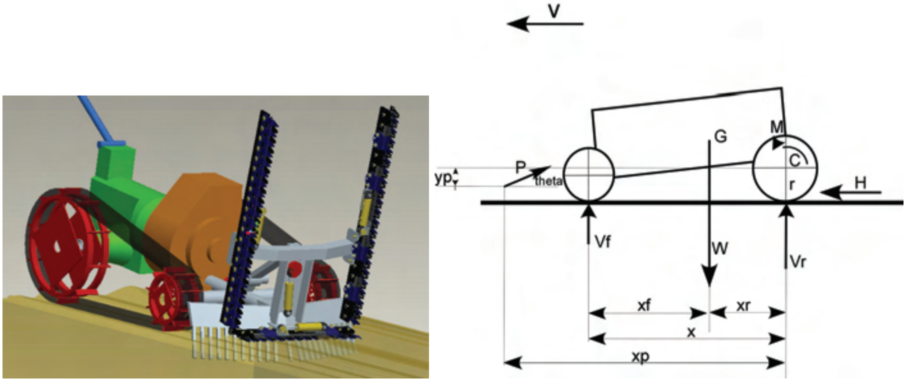

Fig. 8. Working configuration of the machine; first analytical model

The redesign of the tractor unit includes the design of the frame supporting the tools and the front wheels, the design of a tensioning system for the tracks, the choice of rubber tracks and the design of open cage wheels working as sprockets for the tracks. Moreover, it also includes the design of the front attachment for the tools.
The detailed design of these components has been done taking the power tiller Pasquali PL CV10 (7.5kW) available at the University of Genova in mind. Although this is similar to the power tiller that will be used in Sri Lanka, modifications to the current design will be necessary and will be implemented in the field together with deminers before developing the second prototype in a local workshop, making use of the experience gained in Italy.
Modifying the power tiller by adding two additional front wheels and ground engaging tools at the front will affect weight transfer and the whole performance of the system.
First, a rough estimation of the implement draught force was made using two different approaches. From Agricultural Machinery Management Data, ASAE D497.5 FEB2006, published by the American Society of Agricultural and Biological Engineers (ASABE), the draft force, defined as the force required in the horizontal direction of travel for tools operated at shallow depths is given by eq. (1).

$$D = F_i \cdot [A + B(S) + C(S)^2] \cdot W \cdot T \tag{1}$$

Where, D is the implement draft, F id a dimensionless soil texture adjustment parameter whose value is given in ASABE tables, A, B and C are machine specific parameters, given in ASABE tables, S is field speed, W is machine width, T is tillage depth. The value for the draft force necessary to push a tool, considered as a sweep plow in primary tillage, 1200mm wide, at 100mm depth, at 1.1km/h, in fine textured soil, is approximately 2.5kN.

A second estimation of the draft force of approximately 2kN was obtained extrapolating data regarding a 19 tine scarifier fitted with 150mm wide dart points (Kruger&Palmer, 1982).
To analyse the performance of the new system, a simple analytical model (fig. 8) was created, in first approximation simply modelling the power tiller as a four wheel tractor. To take into the consideration the actual presence of tracks, the drawbar pull resulting from equilibrium equation was increased by a factor of four, obtained by analysing performances of the same tractor with wheels and with tracks (Macmillan, 2002).
Considering the hypothesis of constant velocity, soil reaction forces under the front and the rear wheels can be calculated from equilibrium equations (fig. 8):

$$V_f = W\frac{x_r}{x} - P\cos\theta\frac{r-y_p}{x} - P\sin\theta\frac{x_p}{x} \tag{2}$$

$$V_r = W(1-\frac{x_r}{x}) + P\sin\theta(\frac{x_p}{x}-1) + P\cos\theta\frac{r-y_p}{x} \tag{3}$$

Where, the drawbar pull P is generally given by the difference between tractive force H and rolling resistance R:

$$P = H - R \tag{4}$$

While the tractive force H is generally associated with shear stress on soil, the rolling resistance R is associated with energy losses due to deformations of the wheel (elastic) and soil (plastic).
These forces can be theoretically calculated through complex expressions function of many parameters typical of the soil that are difficult to measure when not in the field and anyway differ from site to site. Nevertheless, from these formulas, a general understanding of the influence of design variable values on the force value can be obtained. Generally we have that the tractive force increases as the contact area between the machine and soil increases and as the total weight increases; rolling resistance increases as the dynamic weight on the wheel increases and as the wheel diameter decreases.
Using an empirical approach, instead, we are able to calculate the drawbar pull P as function of only one soil parameter, the cone index CI, measuring the resistance opposed by the soil to the penetration at the constant speed of 30mm/s of a circular cone of base area of 322 mm^2 and cone angle of 30°. Another expression of P, analogous to (4) is given in (5):

$$P = V_r \cdot \psi - V_f \cdot \rho \tag{5}$$

Where, Vr is dynamic weight on rear wheels, Vf is dynamic weight on front wheels, ψ is the tractive coefficient for rear driving wheels, defined as ratio between the drawbar pull and the dynamic weight on driving wheels, and ρ is the rolling coefficient for front wheels, defined as ratio between the rolling resistance and the dynamic weight on front wheels.
Empirical expressions for ψ and ρ (7) and (8) have been found by Gee-Clough in 1978 for wheels on agricultural soil in function of a dimensionless number called the tyre mobility

number M (6), function of the cone index CI, weight on tyre W, tyre width b, tyre diameter d, tyre section height h and tyre deflection under weight δ.

$$M = \frac{CI \cdot b \cdot D}{W_w}\sqrt{\frac{\delta}{h}}\frac{D}{D + 0.5 \cdot b} \tag{6}$$

$$\psi = \psi_{\max}(1 - e^{-k \cdot i}) \tag{7}$$

$$\psi_{\max} = 0.796 - \frac{0.92}{M}$$

$$k = 4.838 + 0.061 \cdot M$$

$$\rho = 0.049 + \frac{0.287}{M} \tag{8}$$

By substituting eq.s (2) (3) in (5) we obtain an expression of the drawbar pull P in function of tractor unit design variables indicated in fig. 8.

$$P = \frac{W\left[\psi(1 - \frac{x_r}{x}) - \rho\frac{x_r}{x}\right]}{1 - \psi[\sin\theta(\frac{x_p}{x} - 1) + \cos\theta\frac{r - y_p}{x}] - \rho[\cos\theta\frac{r - y_p}{x} + \sin\theta\frac{x_p}{x}]} \tag{9}$$

Therefore the drawbar pull of the tractor unit can be approximately estimated once the values of the following design variables are known:
xr, distance of centre of gravity from rear wheel
x, distance between axles (in tracks assembly, length of tracks)
r, radius of rear wheel
yp, vertical distance of point of application of P wrt C
xp, horizontal distance of point of application of P wrt C
θ, angle by which P is inclined wrt the ground
and W, total weight of power tiller plus implement.

The analytical model was used to choose the tracks and rear and front wheel diameters. Commercially available rubber tracks 200x72x47, 200mm width and having an overall length of 3384mm were chosen. Unfortunately these were not readily available in the shop and a pair of tracks equal but 230mm wide were kindly delivered for free by the Italian company Minitop.
Wheels 504 mm in diameter were chosen for both rear and front wheels. By plotting the drawbar pull resulting from eq. (9) versus diameter ratio Df/Dr, for the same 3DCAD model, for different soil types, i.e. different values of Cone Index CI, we obtained a general increase in drawbar pull as diameter ratio increased, more sharp for lower values of cone index, i.e. looser soils.

The same diameter for front and rear wheels seemed a good compromise between drawbar pull and simplicity: having only one type of wheel makes maintenance easier as wheels can be interchanged and stock simpler.
The value of 504mm diameter was chosen after the design of wheels was completed. In fact, wheels need to engage the track working as sprockets. We have chosen to have 11 engaging lugs simply shaped as trapezium based cylinders.

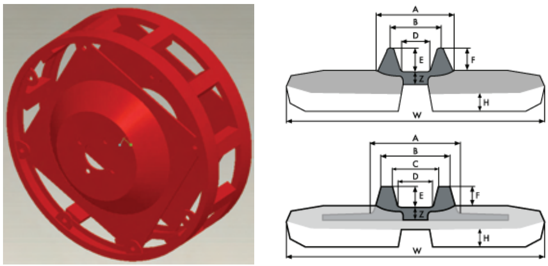

Fig.9. Sprocket wheel and track shape.

A refined analytical model was developed in second approximation, taking into account the presence of tracks instead of wheels.
In the first model the tractor unit has been treated as four wheel machine, and the effect of tracks has been considered generally as increasing the overall drawbar pull four times. In fact, the assumption of having only driven wheels at rear is not true anymore having both rear and front wheels contributing to traction as well as to rolling resistance.
Therefore eq. (10) can be used instead of eq. (4) to estimate the maximum drawbar pull the system is able to exert:

$$P_{\max} = H_{\max} - (\rho_f \cdot V_f + \rho_r \cdot V_r) \tag{10}$$

$$H_{\max} = 2A \cdot c + W \cdot \tan\phi \tag{11}$$

Where, $H_{\max}$ is the maximum tractive force the system can exert when tracks are locked and is given by eq. (11). W is the total weight of the system, A is the area of contact with the ground of one track, c is soil cohesion and ϕ is the angle of soil internal friction. ρ_f and ρ_r can be obtained from tables (Macmillan, 2002) reporting coefficients of rolling resistance versus tyre diameter, considering the front wheels approaching an harder ground and the rear wheels a more loose soil. Vr and Vf are known once the soil tool interaction force is known in modulus (already known) and direction (depends on the shape of the ground processing tool), from equilibrium equations applied to the system constituted by the entire machine plus tool.
Modifying the power tiller by adding the new components will cause an increase in its weight. In general, adding extra weight and enlarging the ground contact area to a tractor is desirable, especially if no idlers are to be used to keep the track in contact with the ground (to keep the frame as simple as possible) and ballast may have to be used to improve weight distribution between the front and the rear of the track. Nevertheless, adding weight could

cause to have the machine not slipping any more in lower gears before the engine gets stall. This is a form of protection as it limits the load on the transmission components: in most tractors the weight and tyres are such that in the lower gears the wheels will slip before the engine stalls, while in higher gears the opposite happens. Therefore, the maximum tractive force exerted by the machine when tracks are locked, and therefore 100% slippage occurs, was calculated and compared with the maximum force the engine can generate horizontally at wheel-soil contact. Equation (11) was used to determine the maximum tractive force for the power tiller weighing 480kg, employing the tracks chosen 230x72x47 on soil having an angle of internal friction of 30° as equal to 2716N. This doesn't take into account the contribution given by soil cohesion expressed by the first term of eq. (11) as it is negligible. The value obtained was compared to the force the power tiller can generate at wheel-ground contact, horizontally. This was calculated for the power tiller Pasquali purchased in Italy, having 7.5kW power, 50 gear ratio in the first gear, 250mm wheel radius, 1.1 km/h speed in first gear as equal to 25000N. Therefore, in low gear, the engine should not stall.

The frame has to satisfy the requirements of supporting front wheels and tracks, supporting the ground processing tool and vegetation cutter tool and allowing remote control. The chassis of the power tiller Pasquali presents two mounting areas that can be exploited for supporting the frame, one at the back and one at the front of the chassis. The power tiller has no brakes, but presents a differential gear.

Two disk brakes, second-hand from old motorbikes, were employed to break the two driven wheels and allow remote steering by actuating them separately. This solution was chosen for its simplicity: disk brakes are available everywhere second hand, are cheap and only little adjustments had to be made to the existing structure to fix them to it. Fixtures allowing the mounting of the disc brakes on to the power tiller chassis were designed, realized and tested together with the control. They are made of aluminium.

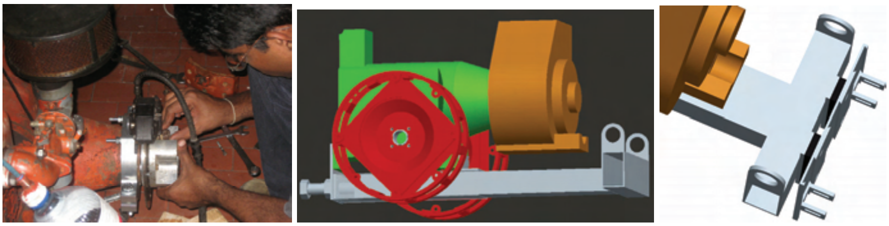

Fig. 10. Disc brake assembly; frame; frame-tools interface

Therefore, the idea of having a single frame supporting front wheels, tools and tensioning the track was pursued as the simplest.

The frame designed is represented in fig.10. and is characterized by being all made of steel standard profile, easy to build and to maintain as only welding of profiles available on the market is needed. It is constituted by a main fore – and aft frame member in the form of a rectangular hollow section fixed to the two mounting areas on the body of the tiller and extended forwards to the front axle member. On the same profile rearwards can be fit a ballast weight if necessary to improve the weight distribution. This main frame member has a second rectangular hollow section member sliding within it that carries the front axle. The rear end of this is located by a large screw at the rear of the tractor which is used to tension

the tracks. The front stub axles each running in two bearings is carried on the front axle member attached to the second member mentioned above.
Although the conventional method of tightening crawler tracks is to individually spring load them with compression spring located within the track, this arrangement allowing for any difference in length of the tracks and also for vertical deformation of the tracks between the wheels when the track passes over a stone or local hump, it was considered not to be convenient to use in the present work. Instead we decided to tension the tracks by pushing on the front axle member, on which the front wheels are mounted through the screw at the rear of the machine. This design is simpler and provides a near rigid arrangement by treating both tracks in the same way.
Depending on the difference in length of the tracks and the evenness of the ground, this arrangement will probably be satisfactory for some time and allow a decision to be made as to whether the mechanically more complex arrangement proposed above is required for long term operation.
As the machine presents modular structure, the interface between the frame and the tools as to be very versatile. The interface designed, where either ground processing tool or vegetation cutter tool can be mounted is characterized by presenting sliding frames, where different mounting hinges can be inserted and fixed at the required height. It is connected to the main frame through three dumpers, aimed at reducing the impact of shock waves, due to the accidental explosion of a landmine by the front ground processing tool, to the power tiller structure.

9. Ground Processing Tool

The task of the machine is to process the ground in order to make demining activities with excavation tools easier for deminers. The ground processing tool has to smooth the soil up to the required depth of 100mm never pushing mines deeper but possibly lifting them up. The requirements the ground processing tool has to satisfy therefore are to remove landmines from the lane where the machine is working and processing the soil at constant depth.
There are two possibilities for landmines disposal: collecting them or push them beside the machine. The first choice allows the work to be done all at once as no more verification or mine disposal is required after the machine has passed, but foresees also some complications: a sensor is needed to understand when a landmine has been found. Collecting more landmines in the same place can be dangerous as a big explosion could occur if an abrupt movement is done. The second choice of pushing mines beside is limited by the vegetation factor as if there is too much vegetation mines will be pushed in uncleared lanes and will not be visible. Nevertheless, we decided to implement it first as it is very simple and still practical when vegetation is not heavy.
The question of the form of the tool was a major aspect of the overall work and occupied a considerable portion of our time. There are few published precedents this aspect of the work although it has similarities to some tillage tools. There were three important implications in deciding the shape of the tool.
Weight transfer: most soil engaging tools involve a horizontal (draft) and vertical force. When the tool is mounted on the front of the tractor both of these forces, together with the weight of the tool, have the effect of transferring weight from the rear to the front of the

tractor. These effects are generally undesirable (on a rear wheel drive tractor) and hence it is important that they do not become excessive.

Depth control: the requirement for good depth control is to avoid the tool working too shallow and missing mines or digging too deep and causing the tractor engine to stall or the tracks to slip. Mounting the tool on the tractor alone is likely to cause a variation in depth as the tractor pitches in the vertical longitudinal plane. Therefore we decided to fit a depth wheel running in the undisturbed soil ahead of the tool. This reduces the weight transfer effect of the tool and assists in depth control. It is in the form of a cage wheel on the assumption that this will suffer minimum damage if a mine were to explode under it.

Soil cutting and sieving: soil processing involves two aspects cutting the soil at the required depth and allowing it to pass through a sieve separating any object and mine bigger than a defined volume. The smallest dimension of the smallest mine present in the Vanni region (the Type72 AP landmine) is 40mm; therefore space between tines must be smaller than this. Various forms of tool were envisaged and a single blade to cut the soil with an attached sieve was chosen.

It is desirable, in the interests of simplicity, that the tool is formed from plane shapes. The simplest form of such a tool is therefore defined by two angles: a rake angle between the tool and the horizontal (ground) in the longitudinal vertical plane; a small rake angle allows the soil to flow up the tool in a thin sheet and so encourages sieving, and a side angle between the tool and the vertical longitudinal plane in the horizontal plane; a small side angle tends to cause the soil to be moved to the side and pass outside the passage of the tool width.

Therefore, to achieve mine disposal sideways, the original design used for developing a small cardboard and straws model (fig. 11) having rake angle equal to 20° and side angle equal to 30° was changed into a new design presenting a bigger side angle equal to 50° and rake angle equal to 30°. The rake angle had to be increased to keep the distance of the tool tip from the frame relatively small.

The success of the tool in sieving soil and retaining or shedding mines depends on the form of the tool described above but also on the form of the sieve. Simplicity suggests that the form of the sieve members should either be in the plane of the sides of the tool, either parallel to the spine of the tool (effectively at the rake angle) or alternatively at the side angle (effectively horizontal). It would seem useful, in evaluative terms, to make one side of the sieve in one form and one in the other (fig.11). This would provide an immediate and obvious comparison of the two forms and guide future developments.

It is understood that some form of active movement of the tool would assist in breaking clods and clumps and so improve the sieving process. This however may not be necessary in sandy soil for which the initial form of tool is being developed. However it is likely to be needed for other heavier soils and for those which have been ripped with a plough.

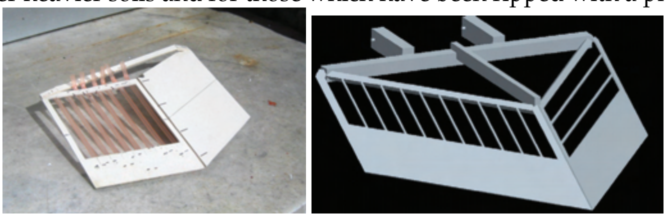

Fig. 11. First and second version of ground processing tool

Various methods might be envisaged to provide active motion of the tool, the simplest being using a 'bumpy' wheel. A depth wheel which was non-round would induce a near vertical motion to the tip of the tool.
An arrangement providing a means of lifting the tool when it is needed and at the end of the lane would also be necessary to overcome the problem of turning the machine with the tool in the ground. Work on the ground processing tool has to be completed.

10. Vegetation Cutter Tool

The task of the vegetation cutting module is to cut the vegetation obstructing the passage of the machine. When vegetation is present and the module needs to be employed, deminers, following the machine to locate and pick up mines lifted up on soil surface by the ground processing tool, will firstly proceed to remove the vegetation cut by the machine with the light rake.
Vegetation of the Vanni region can be classified into three types: light, if only grass is present, medium if there is also bush and heavy, if there are palm trees. We would need to use the vegetation cutting module only in case of medium and high level vegetation. When palm trees are present, the task of the module is only to cut leafs, as palm tree is protected by Sri Lankan law.
The power tiller we are employing as tractor unit has 7.5kW engine; due its limited capacity, energy consumed by the vegetation cutting module should be as low as possible. The other requirements the module has to meet are the general ones valid for the whole machine: it should be low-cost, easy to use and maintain, robust, made of few simple parts, easy to find on the local market, able to work in dusty and dirty environment at high temperatures.
Moreover, as it is supported by a frame on the front of the machine it should also be as light as possible. Generally, large machines using flails, tiller units or brush cutters (Koppetch, 2006) are employed for cutting vegetation in minefields. According to the general philosophy of the project and due to the small size of the power tiller, instead of analysing dedicated systems we looked into existing technologies for cutting vegetation available on the agricultural market. Those are of four types: string trimmers, lawnmowers, hammer knife mowers and cutter bars. Because of their ability to cut small bushes as well as grass, they large cutting width, low cost and low power absorbed, we have decided to employ cutter bars as cutting system. Moreover cutter bars present a high level of modularity. In fact, they are constituted by two identical knife bar sections mounted on two frames, one fixed and one moving. In the version available on the market, rotary movement of the power take off (pto) is transformed into linear sinusoidal movement of the upper moving bar thanks to an eccentric and a sliding joint.

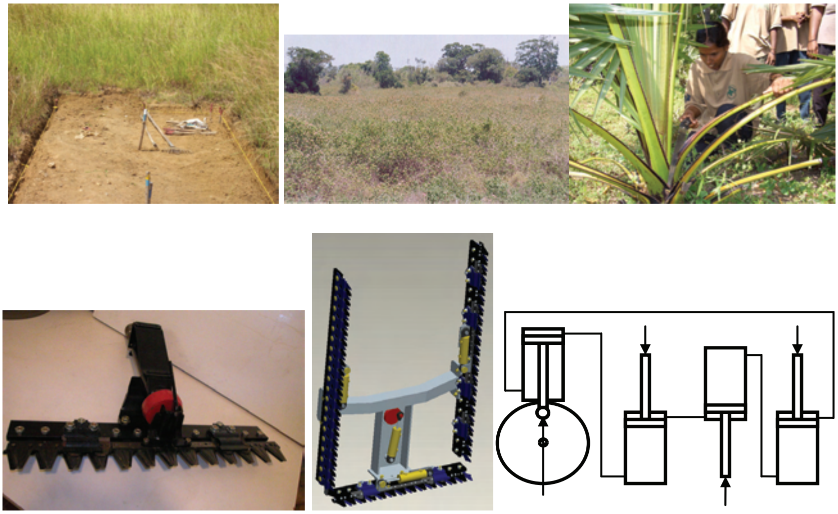

Fig. 12. Vanni region vegetation types: light, medium and heavy; cutter bar, vegetation cutting module architecture and layout of actuating cylinders

In order to create the space necessary for the machine to proceed when vegetation is thick, we have decided to employ three bars at the same time: one horizontal and two vertical. Vertical ones allow the machine to proceed in the bush and near to palm trees; they also cut tripwires if present. Different cutter bars with different lengths are available: they only differ for the number of teeth, the length of frames supporting the two knife bar sections and the number of components fixing bar sections to frames.

The overall number of components types is therefore limited, allowing simple maintenance even in the field. To repair the cutter few items per type of components are necessary to the operator, who can assembly and disassembly the whole system using only one wrench 17mm size for nuts and a small hammer for pins fixing the mobile bar to its frame. Commercially available 650 mm and 1050mm long bars are suitable to be mounted horizontally and vertically respectively.

Between possible actuating systems, a pneumatic one was preferred. In fact, it can produce high forces while occupying a reasonable compact space; it allows for flexible placement of components, is cheap, robust and easy to repair and maintain. To actuate the three cutter bars, double acting cylinders were chosen, providing both forward and backward stroke with the same force. To generate power it was chosen to employ another double acting cylinder actuated by an eccentric connected to the pto. This solution presents the advantage of being simpler, more robust and cheaper; moreover, it allows avoiding the use any type of control as the eccentric determines the correct motion law of the cylinder connected to it. Motion is transferred to cutting bars with no other components needed. After choosing the actuation type, the architecture of the actuation system was chosen. A simple and compact solution was chosen. All cylinders are identical: only one type needs to be bought and stockpiled for maintenance. Repair in the field is also easier because operators need only few components. Moreover it is modular, if two cylinders are disconnected the volume of the two remaining facing chambers is equal. This is particularly useful when palm trees are not present in the minefield and only grass is present. Detaching the two vertical cutter bars allows saving power and fuel. The frame chosen is made of steel and is shown in fig.12.

11. Control Unit

The control system has to allow the tractor unit to be operated remotely in forward motion with steering acting on the semi-axles. Generally power tillers are controlled manually by an operator walking behind them.
After having started the machine manually, while keeping clutch pressed, the gear is shifted and forward/backward motion selected. Then, the clutch can be released causing wheel to decouple and motion starts. The operator follows the machine adjusting the acceleration according to working needs. When direction needs to be changed, firstly the differential is actuated to allow non-synchronized movement of the wheels. Direction is manually changed acting on handles. When the power tiller is moving in proper direction the differential can be switched off to preserve the direction.
After having analysed manual operations, the features to be actuated by the control system were selected. All existing levers can be automated but changing direction, which is usually performed by the operator, rises up a problem. As a solution, external braking system constituted by the disc brakes was considered. Turning is therefore achieved in this way. When direction is not relevant the differential firstly is actuated. Then, when wheels can be moved in not coordinated way, one of the brakes can be applied decreasing the speed of the wheel. This causes the direction to change proportionally to the difference in wheels speed. After reaching the proper direction, the brake is released and differential switched off forcing synchronous motion. According to previous considerations, the features selected for actuation are shown in table 1. Motion type analysis indicates that linear motion is needed mainly. In some cases actuation is needed in both movement directions in others one direction is passive. Deadlocks possibility should be regarded as source of further possible actuation problems. For actuation, pneumatic system was chosen having the following significant advantages in this application: natural linear motion, resistance to deadlocks, resistance to vibrations and contamination, big variety of actuators available.
The pneumatic system needs an air-compressor that will be mounted on board of the power tiller. Control system was designed accordingly to digital control system design Moore approach (Kostrzewski et al., 2007). Logic equations were implemented using Siemens Logo controller which is cheap and robust, allows for software based programming, conventional switches are not needed and extended communication features can be used.

Feature	Motion type	Actuator type
Differential	Angular and linear; linear easier to apply; deadlocks during switching the differential on	Single-acting cylinder, return stroke by spring
Clutch	Linear motion, big force, no deadlocks, one-side force needed	Single-acting cylinder, return stroke by spring
Acceleration	Linear motion, low force, position holding	Double-acting cylinder
L / R brake	Linear motion, one-side force, no deadlocks	Single-acting cylinder, return stroke by spring

Table 1. Power tiller controlled features

Fig. 13. Pictures of the valve bay and the control system assembled on the power tiller

12. Conclusions and Further Work

Considering the increasing consensus on the fact that mine action should be regarded as a development activity, there should be rapid change of the current approach. The paper summarises few topics in the domain and introduces a new integrated approach to the design of simpleffective demining technologies. The methodology is applied to the design of a simple modular machine for assisting mine removal through ground processing and vegetation cutting. The tractor unit is chosen in the agricultural machines domain (power tillers), so that to assure the full consistency with the local expertise and habits. Cost and sophistication minimisation is primary objective of the present project. The machine is equipped with a pneumatic remote control, versatile enough to be fit on almost every kind of power tiller.

The work on the machine is not completed yet, the complete design having to be finalised through FEM analyses, developed and assembled. The overall work on the first prototype currently at the University of Genova will end in October 2007. After proper tests, results, experience and lessons learnt will be used to re-design and develop a second prototype in Sri Lanka, based upon a slighter more powerful Chinese power tiller available on the local market. During November and December the author will work in the field together with deminers to finalize the project. If the civil conflict will impede it, the final prototype will be built in another country with similar characteristics to the Vanni region of Sri Lanka, like Jordan. All information regarding the project as test reports are freely available at the project website: http://www.dimec.unige.it/PMAR/demining/index.html

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