Humanitarian Demining: Reality and the Challenge of Technology - The State of the Arts

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Abstract: *In the context of humanitarian demining it is essential to have a reliable and accurate sensor or an integration of heterogeneous/homogeneous sensors with efficient and reliable data fusion and processing techniques. In addition, it is necessary to overcome the constrain on the resources to speed up the demining process in terms of time, cost, and safety enhancement of personnel and operation. A portable handheld mine detection approach to sensor movement is slow and hazardous for individual deminers. Armored vehicles may not thoroughly protect the occupants and may be of only limited usefulness in off-road operations. Robotized solutions with effective sensing capabilities 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 and perform verifying processes when used in combination with handheld mine detection tools. Furthermore, the use of many robots working and coordinating their movement will improve the productivity of the overall mine detection process through the use of team cooperation and coordination. This paper evaluates the available mine clearance technologies and disscusses their development efforts and limitations to automate tasks related to demining process.In addition, it introduces technical features and design capabilities of a mobile platform needed to accelerate the demining process and achieve safety with cost effective measures.*

Keywords: *humanitarian demining, mine detection, demining robots, mechanical demining, service robots*

1. Introduction

Landmines are prominent weapon and they are so effective, yet so cheap, and easy to make and lay. A mine is detonated by the action of its target (a vehicle, a person, an animal, etc.), the passage of time, or controlled means. Anti-personnel (AP) mines can kill or incapacitate their victims. Additional major effect of mines is to deny access to land, and its resources. 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). The removal and destruction of all forms of dangerous battlefield debris, particularly landmines and other unexploded ordnance (UXO), are vital prerequisites for any region to recover from the aftermath of a war.
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 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 difficulties. The direct cost of medical treatment and rehabilitation exceeds US$750 million. This figure is very small compared to the projected cost of clearing the existing mines. The production costs of AP mines are roughly between 3 and 30 US$. But, 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 false alarms). 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). Currently, there are 2 to 5 millions of new mines continuing to be laid every year. The annual rate of clearance is far slower. There exists about 2000 types of mines around the world; among these, there are more than 650 types of AP mines. What happens when a landmine explodes is also variable. A number of sources, such as pressure, movement, sound, magnetism, and vibration can trigger a landmine. AP mines commonly use the pressure of a person's foot as a triggering means, but tripwires are also frequently employed. 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). 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 mechanisms and they stay active for long time. Modern landmines are fabricated from sophisticated non-metallic materials. New, smaller, lightweight, more lethal mines are now providing the capability for rapid emplacement of self-destructing antitank (AT) and AP minefields by a variety of delivery modes. These modes range from manual emplacement to launchers on vehicles and through both rotary and fixed-wing aircraft. Even more radical changes are coming in mines that are 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.

2. Humanitarian Demining and Requirements

Humanitarian demining scenarios differ from military ones in many respects. The objectives and philosophy are different. 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, and removes reliably and safely every single mine, and UXO from a targeted ground. 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), and a 100% to a certain 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 impact 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. Difficulties Facing Mine Detection and Clearance

Landmines are usually simple devices, readily manufactured anywhere, easy to lay and yet so difficult and dangerous to find and destroy. They 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), the 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 and soil composition, 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. 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. Activation methods can be classified into three categories, pressure, electronic, and command detonation (remote control). 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

Although demining has been given top priority, currently mine’s clearing operation is a labor-intensive, slow, very dangerous, expensive, and low technology operation. The current rate of humanitarian mine clearing is about 100 thousand per year. It is estimated that the current demining rate is about 10-20 times slower than the laying rate, i.e., for every mine cleared 10-20 mines are laid. Therefore, to stabilize the mine situation, it is necessary to increase the current capability of mine clearance by 10-20 times.

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. Demining Techniques and 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. Currently, almost all humanitarian mine clearance is still required to apply hand clearance method that uses ‘prodding’ or ‘probing’ within its loop to assure high reliability. Manual probing is slow, labor intensive and extremely dangerous and stressful process.

5.1 Mechanical Equipment and Tools for Mine Clearance

A good deal of research and development has gone into motorized mechanical mine clearance in which their design is 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 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 or thick bush, 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.

In general, 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. However, to achieve better clearance rate, these machines can be used in conjunction with dog teams and/or manual clearance team, which double check an area for remaining mines.

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, Armored wheel shovel, Mine clearing cultivator, Floating mine blade, Rollers, 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; Geneva Centre for Humanitarian Demining, 2006).

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. 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. Cost effective and efficient clearance techniques for clearing both landmines and vegetation have been identified as a significant need by the demining community.

5.2 Mine Detection and Sensing Technologies

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 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 tool with regard to the location, environment, 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, and at the real site. This should be followed by having 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. The work must be performed in close cooperation with end-users of the equipment and 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.

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. The effectiveness of metal detectors can be inhibited by mines with extremely low metal content or by soils with high ferrous content and hence other detection techniques have been and are being investigated. 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.

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, 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, 2001).

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.

5.3 Robotized solution for Mine detection and Clearance

A portable handheld mine detection approach to sensor movement is slow and hazardous for individual deminers. Armored vehicles may not thoroughly protect the occupants besides other practical and environmental limitations. Many efforts have been recognized to develop effective robots for the purpose to offer cheap and fast solutions. Research into individual, mine-seeking robots is still in the early stages. In their current status, they are not flexible and cost effective solution for mine clearance. But, if designed and applied at the right place for the right task, they can be attractive and effective solutions. Three main directions can be recognized in development: Teleoperated machines, Multifunctional teleoperated robot, and Demining service robots.

9. Robotics and Humanitarian Demining

The A 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. 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) It should be capable of withstanding 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 Aerieal 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. 1). 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; Geneva Centre for Humanitarian Demining, 2006). 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; Geneva Centre for Humanitarian Demining, 2006; 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.

Fig. 1. Different types of light flails in action.

10.1.2 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 2 shows Hobo, Hobot and Thrasher robots.

Fig. 2. Remotely operated vehicles from Kentree.

10.2 Multi Functional Teleoperated Robots

10.2.1 Demining mobile robot MR-2 (Engineering Service Incorporation (ESI))

MR-2 is an off-road, modular, teleoperated, multi-sensor mobile platform designed to detect landmines, including those with minimal metal content, and UXO. MR-2 is a modular system comprising a remotely operated vehicle (ROV), control unit, MR-1 robotic arm for scanning, laser range camera and metal detector (ESI, 2003). MR-2 uses only one metal detector (of-the-shelf unit that can be easily detached and used manually), and combines the latest laser/ultrasonic based terrain imaging technology that allows the metal detector to adaptively follows the terrain surface while avoiding obstacles. MR-2 can perform neutralization of landmines using MR-1 arm under the supervision of remotely located operator. MR-1 is a ragged modular dexterous robotic arm (See Fig. 3). The 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. MR-2 works at high-speed scanning (up to 5 km/hour) with wide detection path (about 3 m). The MR-2 is an autonomous mine detection system that operates at high speed with minimum logistic burden. The MR-2 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 MR2 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 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.

(a) The MR-Robot. (b) Laser/US imaging. (c) Metal detector. (d) MR-2 with MR-1.

Fig. 3. The MR-2 demining mobile robot.

10.2.2 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 4 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).

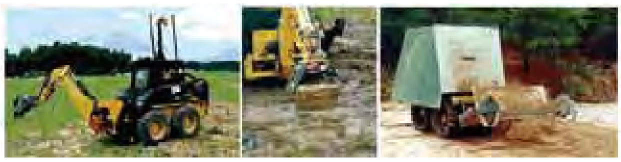

Fig. 4. The ETODS in action.

10.2.3 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.5).

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 (Geneva Centre for Humanitarian Demining, 2006). 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. 5. 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 patforms targetting range of applications. Among these are MARV, MATILDA and ACER Robotic Platform, The mobile base platform of ACER is armored with ballistic steelhas a size of 83"Wx62"Hx56"L and it weights 4500 LB. It is powered by 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 radius (see Fig. 6).
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. 7). The OCU is feactured 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 weight s 6 Lb. and powered by 12 VDC NiMH with 120 VAC adapter.

Fig. 6. The mobile base uni of ACER with some of possible attachements.

Fig. 7. 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.

10.3 Demining Service Robots

10.3.1 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 8 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. 8. The DERVISH robot

10.3.2 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. 9). 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.

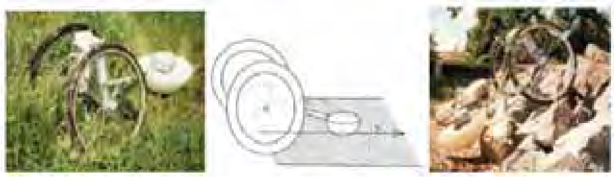

Fig. 9. PEMEX - BE (PErsonal Mine EXplorer)

10.3.3 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.

Fig.10. The Shrimp III Robot

In May 2001, the developer announced version 3 of the robot, Shrimp III (See Fig.10). 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 Aluminium and it is equipped with modular electronics.

10.3.4 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 Defence 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 armoured 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. 11). 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.11. The 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. 12, 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.

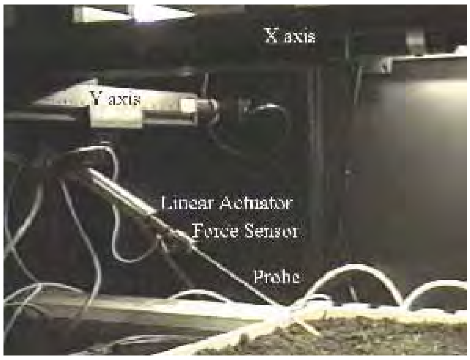

Fig.12. A laboratory prototype of a single mechanical means of manual prodding.

10.3.5 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 13 illustrates different versions of AMRU and Tridem robots.

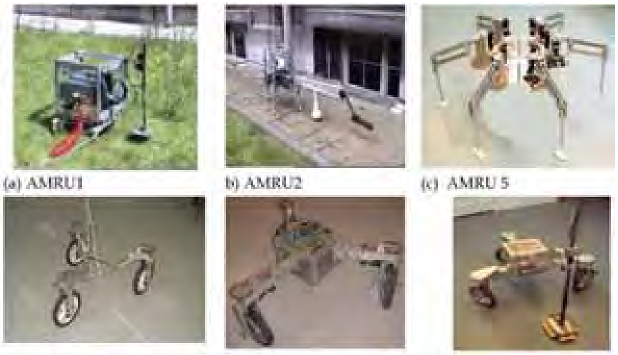

Fig.13 Different versions of AMRU and Tridem robots

10.3.6 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. 14). 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.

Fig. 14. The WEELEG Robot.

The robot mobility and maneuverability is limited, no demining sensors have been used, and no demining testing and evaluation has been reported.

10.3.7 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 manoeuvrable 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. 15).

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. 15. The STAR robot in different situations.

10.3.8 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 16 presents different versions of COMET. The presented technical solutions are heavy in weight, require logistical and maintenance care, high in cost, and have limited manoeuvrability.

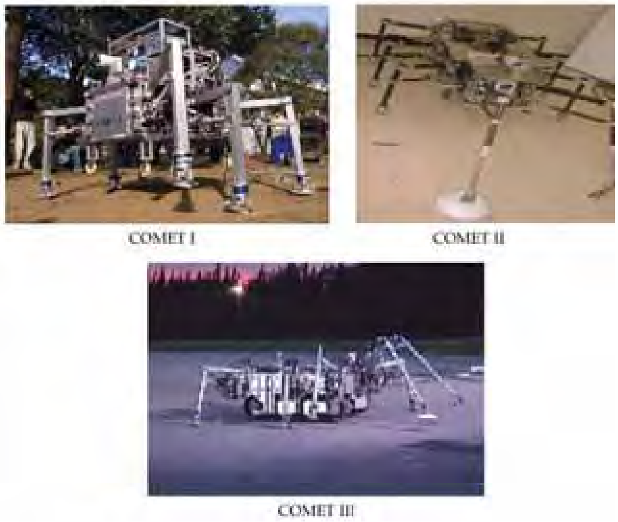

Fig. 16. Different versions of the six legged mobile robot COMET.

10.3.9 Buggy and Legged Robots (TIT in Japan)

The research at TIT has been manily focus to develop biologically inspired robots. Part research group targets are to adapt different robotics technology and mechanisms to support humanitartian 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 to have adaptable robot with respect to the terrian and able to handle several tasks by utilizing the legs as a manipulator with different module attachements (see the concept in Fig.17). 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.

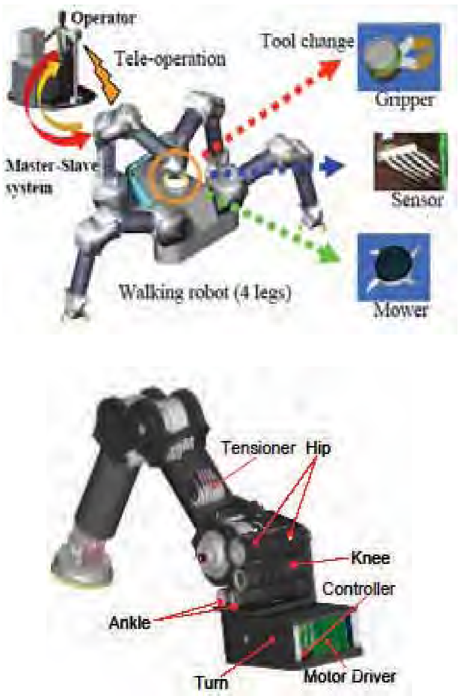

Fig. 17. The concept of TITAN-IX with implementation of the leg unit for the demining mission.

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 manipnlator, 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.

Fig. 18. Buggy system mounted ALIS and a picture of ALIS.

Fig. 19. The Minehand unit.

The buggy system and its arm was integrated with advanced landmine imaging system (ALIS) (see Fig. 18), developed by Tohoku University in Japan and consists of a metal detector and GPR for evaluation test flat terrianin in Afghanistan (Dec. 2004) and then in Canbodia (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 results on the testing evaluation in relation to the control of the robot system has bave been reported. Currently, the group is conducting the dynamic analysis of the robot syetem.

10.310 1. 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 interchangable 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. 20).
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 safey 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. 21(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. 21(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.

Fig. 20. The Mine Hunter Vehicle (MHV).

Fig. 21. Two interchangeable Radar sensor modules.

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 addiotion, critical points are directly associated with the required logistics, system and maintenance cost, and operational speed.

10.3.11 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 achive 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. 22(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 asa 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 odur sensor. No specific sensors preferences have been asigned 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. 22(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 spinalaxis (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, ad the 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. 22. Ares Robot.

11. 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.

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 impage analysis to help interpreting mine suspected scences for the purpose of area reduction. Multisensor data fusion technique facilitated by intelligent computational techniques has been developed and applied to enhance tasks interpretation.

12. Conclusions

The major technical challenge facing the detection of individual mine, is 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 a discrimination capability that includes the fusion of information coming from multi heterogeneous and 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 to clear landmines in all types of terrain. This should be associated with neutralization, in which there is a need to develop safe, reliable, and effective methods to eliminate the threat of individual mines without moving them.

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 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 with specifications that can fulfil 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 that can deal with different terrain. Modularized robotic 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, it is necessary to carefully study conditions and constraints of the demining operations. 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 are not an appropriate solution for mine clearance. 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. 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. 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 infrastrucrures 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.

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 demining equipment 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. 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 and because it does not turn a fast profit and as such there should be a recognized contributions for the developed countries and international organizations to support such efforts.

13. References

Acheroy, M. (2005). Spaceborne and Airborne Mined Area Reduction Tools. Workshop on Inventory and analysis of operationally validated results related to mine action space and airborne surveys, Zagreb, Croatia, Scientific Council of CROMAC.

Arikawa, K. & Hirose, S. (1996). Development of Quadruped Walking Robot TITAN-VIII," *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'96)*, 1996, pp.208-214.

Blagden, P. M. (1993). Summary of UN Demining. *Proceedings of the International Symposium on Anti-Personnel Mines*, Montreux, April 1993, CICR/ICRC, pp 117-123.

Bruschini, C.; Bruyn, K. De; Sahli, H. & Cornelis, J. (1999). EUDEM: The EU in Humanitarian DEMining. *EU report*, Brussels, 1999.

Burke, S. (2003). The U.S. Department of Defense Humanitarian Demining Research and Development Program. *Journal of Mine Action*, Vol. 7, No. 1, April 2003.

Cain, B. & Meidinger, T. (1996). The Improved Landmine Detection System. *EUREL*, 1996, pp. 188-192.

Cruz, H.; Lisboa, J.; Pedro Santana, P.; ARui Maltez, R.; Barata, J. & Luís Flores, L. (2005). Two Sustainable and Compliant Robots for Humanitarian Demining. In *Proceedings of the IARP International Workshop on Robotics and Mechanical Assistance in Humanitarian Demining (HUDEM2005)*, June 2005, Tokyo, Japan, pp. 64 – 69.

Danielson, G. & P. Blachford, P. (2003). DIANA 44T Test and Evaluation – August 2003. Ref.: 13 345:60629, *Swedish Armed Forces, Swedish EOD and Demining Centre*, 2003.

Danielsson, G. & G. Coley, G. (2004). Minecat 140 Test and Evaluation – Sept. 2003. Ref.: 13 345:60099, *Swedish Armed Forces, Swedish EOD and Demining Centre*, 2004.

Dawson-Howe, K. M. & Williams, T. G. (1997). Automating the probing process. *Proceedings of the International Workshop on Sustainable Humanitarian Demining* (SusDem'97), Zagreb, Croatia, Oct.1997, pp. 4.24-4.29.

Debenest, P.; Fukuhima, E. F. & Hiroso, S. (2003). Proporal far Automation of Humanitanan Demming with Buggy Robots. *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'03)*, 2003, pp. 329-334.

Department of Defense, Humanitarian Demining Research and Development (R&D) Program (2002). Other Completed Mine/Vegetation Clearance Equipment. *Development Technologies Catalog 2001-2002*.

Eisenhauer, D. J., Norman, C. O., Kochanski, F. K., and Foley, J. W. (1999). Enhanced Teleoperated Ordnance Disposal System (ETODS) for Humanitarian Demining. *Proceedings of the 8th International Meeting of the American Nuclear Society (ANS)*, Pittsburgh, PA, April 1999.

E. S. Inc. MR-2 Demining and Hazardous Materials Handling Robot. Available online at (2005-03-23): *http://www.esit.com/mobile-robots/mr2.html*

Espirit HPCN, (1997). Industrial R&D Requirements for Humanitarian Demining. (Available through <*http://www.cordis.lu/espirit/ src/report43.html/*).

Estier, T.; Piguet, R.; Eichhorn, R. & Siegwart, R. (2000a). Shrimp, a Rover Architecture for Long Range Martian Mission. *Proceedings of the Sixth ESA Workshop on Advanced Space Technologies for Robotics and Automation (ASTRA'2000)*, Netherlands, Dec. 5-7.

Estier, T.; Crausaz, Y.; Merminod, B.; Lauria, M.; Piguet, R. & Siegwart, R. (2000b). An Innovative Space Rover with Extended Climbing Abilities. *Proceedings of Space and Robotics 2000,* Albuquerque, USA, February 27-March 2, 2000, pp. 333-339.

Fyfe, K. R. (1996). A Mechanical Means of Land Mine Detection. *University of Alberta, Department of Mechanical Engineering*, 1996, Canada.

http://www.mece.ualberta.ca/staff/fyfe/landmine.html

Gage, D. W. (1995). Many-robot MCM Search Systems. *Proceedings of the Autonomous Vehicles in Mine Countermeasures Symposium*, Monterey, CA, April 1995, pp.9.56–9.64.

Geneva Centre for Humanitarian Demining, (2006). Mechanical Demining Equipment Catalogue. *Geneva Centre for Humanitarian Demining*, Geneva, Switzerland.

Goose, S. (2004). Overview of Antipersonnel Mine Stockpile Destruction. *ICBL Treaty Working Group*, June 2004.

Guccione, S. & Muscato, G. (2003). Control Strategies Computing Architectures and Experimental Results of the Hybrid Robot Wheeleg. *IEEE Robotics and Automation Magazine*, (IEEE Piscataway, U.S.A.), Vol.10, N.4, December 2003, pp. 33-43.

Habib, M. K. (1998). Multi Robotics System for Land Mine Clearance. *Proceedings of the International Conference on Robotics and Computer Vision (ICRACV'98)*, Singapore, Dec. 1998.

Habib, M K. (2001a). Mine Detection and Sensing Technologies: New Development Potentials in the Context of Humanitarian Demining. *Proceedings of the IEEE International Conference of Industrial Electronics, Control and Instrumentation (IECON'2001)*, USA, 2001, pp. 1612-1621.

Habib, M. K. (2001b). Machine Assisted Humanitarian Demining Mechanization and Robotization", *Proceedings of the International Field and Service Robots'2001*, Finland, pp. 153-160.

Habib, M. K. (2002a). Mechanical Mine Clearance Technologies and Humanitarian Demining: Applicability and Effectiveness. *Proceedings of the 5th International Symposium on Technology and Mine Problem*, California, USA, April 2002.

Habib, M. K. (2002b). Mine Clearance Techniques and Technologies for Effective Humanitarian Demining. *International Journal of Mine Action*, Vol.6, No.1, 2002.

Healy, A. & W., Webber, W. (1993). Sensors for the Detection of Land-based Munitions. *Naval*

Postgraduate School, Monterey, California, N PS-M E-95-003, September 1993.

Hewish, M. & Ness, L. (1995). Mine-detection Technologies. *International Defense Review*, October 1995, pp. 40-46.

Hirose, S; Takita, K.; Kato, K.; Torri, A., Ogata, M. & Sugamuna, S. (2005). Quadruped Walking Robot Centered Demining System - Development of TITAN-IX and its Operation. *Proceedings of the 2005 IEEE International Conference on Robotics and Automation (ICRA'2005),* Barcelona, Spain, April 2005, pp.1284-1290

Humanitarian Mine Action Equipment Catalogue (1999), German Federal Foreign Office.

Institute for Defense Analyses (2005). Proof of Performance Test Report on Mine Clearing/Survivable Vehicle. Alexandria-USA, March 2005.

International Committee of Red Cross (1993). Antipersonnel Mines: An Overview. Geneva, September 1996. (See also: http://www.icrc.org/).

International Committee of Red Cross (1996). Antipersonnel Mines- Friends or Foe? ICRC Publication, Ref. 0654, Geneva, 1996.

International Committee of Red Cross (1998). The Silence Menace: Landmines in Bosnia and Herzegovina. ICRC Publication, Ref. 2160, Geneva, 1998.

International Test and Evaluation Program for Humanitarian Demining (ITEP), (2006). *ITEP Work Plan 2000-2005*. Portfolio of the ITEP Participant's finalized test and evaluation activities, March 2006.

Kentree Ltd, Kilbrittain, Co Cork, Ireland

King, C. (1997). Mine Clearance in the Real World. *Proceedings of the International Workshop on Sustainable Humanitarian Demining,* Zagreb (SusDem'97), pp. S2.1-8.

Leach, C. (2004). Bozena 4 Mini Mine Clearance System Assessment Phase 1: QinetiQ/FST/LDS/CR044502/1.0. Farnborough, 2004.

Leach, C.; Blatchford, P.; Coley, G. &, J. Mah, J. (2005). TEMPEST V system with Ground Engaging Flail Cambodia Trials Report. *Farnborough: NETIQ/FST/LDS/TRD052379*, 2005. p. 3

McFee, J. E. (1996). Multisensor Mine Detector for Peacekeeping: Improved Landmine Detector Concept. SPIE Technical Conference 2765, March 1996.

Muscato, G. & Nunnari, G. (1999). Leg or Wheels? WHEELEG a Hybrid Solution. *Proceedings of the International conference on climbing and Walking Robots (CLAWAR'99)*, Portsmouth, U.K., 14-15 September 1999.

Nicoud, J.-D. & Habib, M. K. (1995). PEmex-B Autonomous Demining Robots: Perception and Navigation Strategies. *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'95)*, Pittsburgh, August 1995, pp. 419-424.

Nicoud, J.-D. (1996). A Demining Technology Project. *Proceedings of the International Conference on Detection of Abandoned Land Mines (MD'96)*, Edinburgh UK, October, 1996, pp.37-41..

Nicoud, J-D. &. Machler, Ph. (1996). Robots for Anti-Personnel Mine Search. *Control Engineering Practice*, Vol. 4, No. 4, pp. 493-498.

Nicoud, J.-D.; Guerne, F. & Brooks, J. (1998). Report on the DeTec-2 Testing in Cambodia Nov. 18-21, 1997. *The Journal of Humanitarian demining*, Vol.2, No.2, 1998.

Nonami, K. (1998). Robotics for Humanitarian Demining. *Proceedings of the 9th International Conference on Advanced Robotics* (ICAR'98), Tokyo, 1998, pp. 591-594.

Nonami, K.; Huang, Q.J.; Komizo, D.; Shimoi, N. & Uchida, H. (2000). Humanitarian Mine Detection Six-Legged Walking Robot. *Proceedings of the 3rd International Conference on Climbing and Walking Robots*, Madrid, Spain, 2000, pp. 861-868.

OAO-Robotics, OAO Robotics**.** Remote Operated Mine Detector website *http://www.manitgroup.com/oao.htm*

O'Malley, T. J. (1993). Seek and Destroy - Clearing Mined Land. *Armada International*, Vol. 17, No. 1, February-March 1993, pp 6-15.

Perez, M. L. (1996). A Low-Cost Multi-Terrain Autonomous Vehicle for Hostile Environments. *UCRLFJC-124S0, Technical Information Department, Lawrence Livermore National Laboratory,* University of California, Livermore, California 94551, December 1996.

Physicians for Human Rights (1993). Landmines, A Deadly Legacy. *Human Rights Watch*, New-York, 510p, ISBN 1-56432-1 134.

Republic of Croatia, Croatian Mine Action Centre (CROMAC) (2202). Testing of MV-4 Mine Clearing Machine, *Sisak*, May 2002.

Salter, S. H. & Gibson, CNG. (1999). Map-Driven Platforms for Moving Sensors in Mine Fields. *Mine Action Information centre Journal*, Vol.3, No.2, Summar 1999.

Santana, P. F. & Barata, J. (2005). Unmanned Helicopters Applied to Humanitarian Demining. In *Proceedings of the 10th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA 2005)*. pp.729 - 738 (vol. I), Catania, Italy, September 2005.

Santana, P.F.; Cândido, C. & Correia, L.(2006c). A Biologically Inspired motion controller for Four-Wheel Steering-Robots. *Technical Report*, IntRoSys, November, 2006

Shim H.; Koo T. J.; Hoffmann, F & Sastry, S. (1998). A Comprehensive Study of Control Design for an Autonomous Helicopter, *In Proceedings of IEEE Conference on Decision and Control*, Florida, December 1998.

Sieber, A. (1995). Localisation and Identification of Anti-personnel Mines. Joint Research Centre, *European Commission*, *EUR 16329N*, 1995.

SMART consortium (2004). SMART - final report.

Tojo, Y.; Debenest, P.; Fukushima, E. F. & Shigeo Hirose, S. (2004). Robotic System for Humanitarian Demining - Development of Weight-Compensated Pantograph Manipulator. *Proceedings of the IEEE International Conference on Robotics and Aumrnatlon (ICRA'2004)*. New Orleans, LA, 2004, pp. 2025-2030.

Treveylan, J. (1997). Robots and Landmines. *Industrial Robots*, Vol. 24, No. 2, pp. 114-125.

US Department of Defense, (1999). Humanitarian Demining Development Technologies. *Catelogue*, USA, 1998.

US Department of State (1994). Hidden Killers: The Global Landmine Crisis. *Report to Congress*, Washington D. C., Publication 10225, December 1994 (See also: http://www.state.gov/

Van Westen, C. J. (1993). Remote Sensing and Geographic Information Systems for Geological Hazard Mitigation. *ITC-Journal*, No. 4, 1993, pp. 393-399.