TECHNISCHE UNIVERSITÄT WIEN

VIENNA UNIVERSITY OF TECHNOLOGY

DIPLOMARBEIT

A Contribution to the Use of Robots for Humanitarian Demining

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines Diplom-Ingenieurs unter der Leitung von

o.Univ.Prof. Dipl.-Ing. Dr. Dr.h.c.mult. Peter Kopacek
E318
Institut für Handhabungsgeräte und Robotertechnik

eingereicht an der Technischen Universität Wien
Fakultät Maschinenbau
von

Robert Bunzl
9625548
A - 2130 Mistelbach, Am Pulverturm 21

Wien, im Dezember 2002

Unterschrift

Contents

1 Introduction

The indiscriminate use of landmines has become a tragic legacy of civil strife around the world. Landmines impede international efforts to help war-torn countries regain their economic and social infrastructures. Clearing landmines and the debris of war diverts billions of euros that could otherwise be spent on desperately needed development projects.

1.1 The Problem

Although the exact number of landmines is unknown, it was previously estimated that as many as 80-110 million landmines are scattered within at least 70 countries around the world. There is a growing consensus in the international community that the number may be lower, in the range of 60-70 million. The difference in these estimates stems from the difficulty in getting an accurate count in the confusion of warfare, especially in developing countries. However, the key issue is not the total number of landmine-affected countries, nor the number of landmines in the ground. Far more significant as indicators of the problem and as potential measures of success are the number of landmine victims and the amount of land affected by landmines.

Landmine Monitor states that 90 countries which are affected with mines and unexploded ordnance (UXO). In addition, Landmine Monitor lists eleven other areas that are not internationally recognized countries, but which Landmine Monitor researches and reports on because of their particular mine-affected status. Antipersonnel mines are often found in combination with antivehicle mines and UXO in many of these countries. A handful of these countries suffer solely from the legacy of the explosive remnants of wars dating back to conflicts in the first half of the last century. The enduring threat of landmines and UXO in these countries still puts the civilian population at risk.

Landmine Monitor has identified at least 7,987 new landmine/UXO casualties in calendar year 2001. About 70% of reported casualties are civilians. However, it is important to remember that this figure represents the reported casualties and does not include the thousands of casualties that are believed to go unreported. Innocent civilians are killed or injured in remote areas which are physically far away from any form of assistance or means of communication. By acknowledging these facts it is quite obvious that it is impossible to state an exact figure of casualties, it is likely that the number of new landmine casualties is between 15,000 and 20,000 per year.

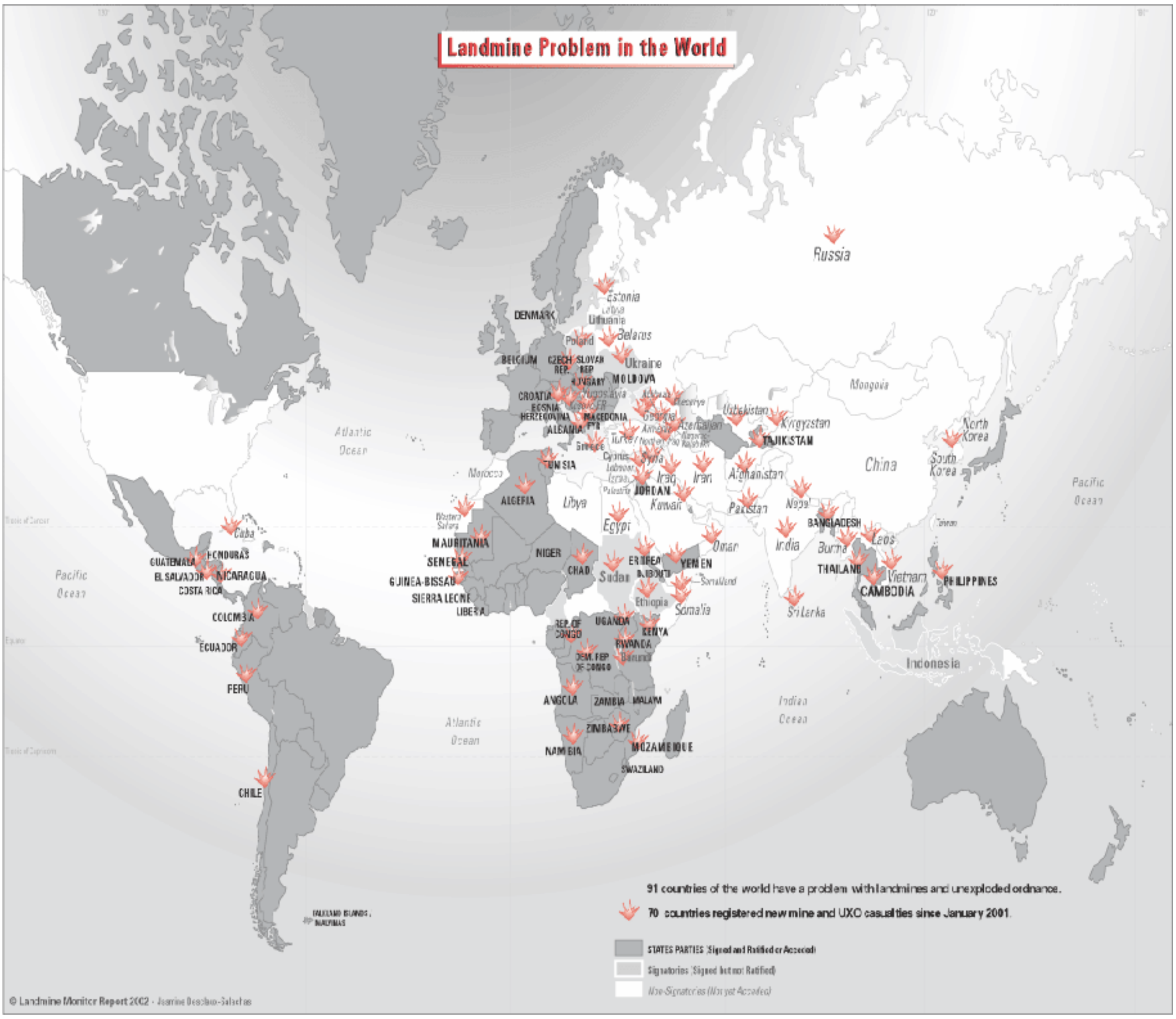


Figure 1: Landmine problem in the world [Land02]

1.1.1 Long-Term Effects of Landmines and UXO

The effects of the landmine scourge extend beyond the costs of landmine removal and immediate medical treatment of the victims. The cost to remove one landmine is, on average, from $300 to $1,000 and the cost for surgical care and fitting of an artificial limb is $3,000 or more per amputee in some countries [USDo98]. But the further problem is the long-term effect on people and their environment. Landmines play an extreme negative role in the process of restoring war-torn societies to normal life. They consume billions of dollars of assistance that could be used to bring prosperity and reconciliation, and they continue to take their toll long after the guns have fallen silent. In effect, landmines have an impact on virtually every aspect of life in the mine-affected countries and strongly influence the international community as it seeks effective ways to help those countries recover.

Unless removed and destroyed, landmines:

- pose huge ancillary social costs
- create vast numbers of internally displaced persons (IDPs)
- impede economic recovery, prolonging the need for international assistance
- prevent the delivery of government services
- serve as physical obstacles to unity and reconstruction
- create conditions for the spread of disease, as well as inflicting injuries, ending lives
- encourage continued militarization of post-conflict societies

1.1.2 Landmines

Mines are prominent weapons because they are simple devices, so effective, yet so inexpensive, readily manufactured anywhere, easy to spread and yet so difficult and dangerous to detect and destroy. The production costs of anti personnel mine are between 3 and 30 $ [Habi02].

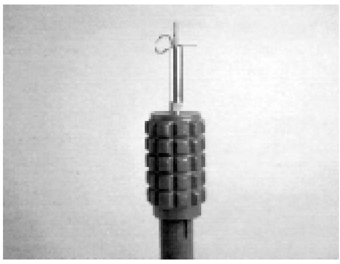
Mines are usually defined as victim-initiated devices, but an exact definition is difficult because command detonated mines are initiated by an observer and not the victim.

Antipersonnel (AP) Landmines: These devices are designed to explode when a person walks on, or, in some case, near them. They are often laid to protect military installations from enemy approach. In some countries, antipersonnel mines are used to prevent enemy soldiers from removing antitank mines from strategically placed minefields. In addition to maiming enemy soldiers, AP mines may delay enemy forces as soldiers are required to remove a severely injured comrade from the field of battle. Typically the worst scenario occurs when armies utilize antipersonnel landmines indiscriminately to demoralize the civilian population by mining access routes to drinking water and firewood sources, grazing and agriculture lands, as well as travelling paths.

There are many, many types of antipersonnel landmines, but they can be put into five main groups.

Blast mines:
These are the most common kind of mine. They explode when someone steps on them. Pressure activated they rip off the lower half of the leg and projects shoe, dirt and bone higher up into the leg, causing secondary infection and higher amputation.

Figure 2: PMN blast mine [Walk02]



Fragmentation mines:
They are packed with fragments, which are projected by the explosion killing anyone within 25 metres and causing extensive damage to the legs, stomach and chest. They are often mounted on stakes above the ground to increase the shrapnel effect.

Figure 3: PMR-2A stake mine [Walk02]

Bounding fragmentation mines:
These mines jump up into the air to about the height of a person's chest before they explode into fragments. They kill the person who sets them off and they can wound people over a wide area.

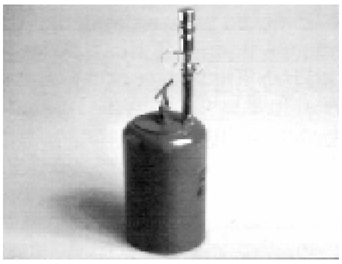
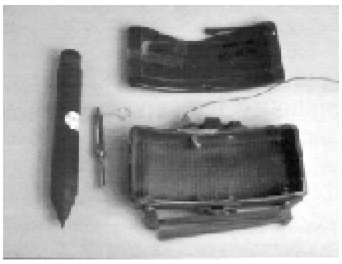


Figure 4: OZM-4 metallic bounding fragmentation mine [Walk02]



Directional fragmentation mines:
These mines shoot out steel balls in one direction at high speed. They are set off by tripwires or by remote control. Some kinds can kill people from as far away as 200 metres.

Figure 5: MON-50 directional fragmentation mine [Walk02]

Scatterable mines:

Scatterable mines do not need to be laid by hand; they can be scattered from aircraft or by artillery. They land on the ground without exploding. Some can even set up their own tripwires.

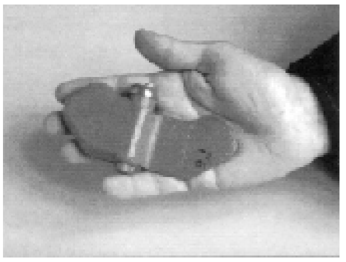


Figure 6: PFM-1pressure-sensitive scatterable blast mine [Walk02]

Antitank (AT) mines: These are larger devices that explode when vehicles drive on them. They are commonly used to limit and deter the movement of enemy troops.

Improvised Explosive Devices: Also referred to as Booby-Traps, these are designed to explode when a person opens a door or picks up or handles a particular object, such as a toy.

UXO (Unexploded Ordnance): Missiles, rockets, grenades and other explosives that fail to explode upon impact are referred to as Unexploded Ordnance, or UXOs. Most of these devices may still be ‘alive’ or active years, or even decades, after being deployed.

1.2 State of the Art in Humanitarian Demining

The accepted standard for humanitarian demining denotes: The concerted clearance of all mines and any other explosive devices from and the physical proving of the ground in a mined area followed by the issue of a certificate that declares that it is clear to a certainty of 99.6%.

Today there are essentially two strategies which can be pursued to clear land contaminated with explosive debris. The first is to attempt to carefully locate each explosive item and then either blow it up or burn it, or render it safe and remove it for dismantling or disposal elsewhere. The second strategy is to mechanically treat all the land to a suitable depth by grinding, milling or flailing in order to detonate or render inserviceable any explosive items.

1.2.1 Manual Demining

Manual clearance operations are painstakingly slow. A set of detailed instructions or Standing Operating Procedures (SOPs) must be followed at all times to ensure safe working; all deminers in an area must work in exactly the same way when clearing and when marking cleared areas.

Deminers generally work in a work group consisting of two or three deminers, often known as "breaching party" which refers to the established military name. One or two deminers are active while the others are resting or observing. A team or platoon frequently consists of 10 or 12 breaching parties.

Lanes are marked entering the mined area from the cleared perimeter lane. To reduce the risk of an explosion accidentally caused by another deminer a typical spacing between active lanes is 10 to 25 metres. Lanes are usually one metre wide and are marked as they are cleared with plastic tape on wooden stakes, painted rocks or similar markings.

Figure 7: Marked lane [MgMi02]

The exact clearance method used depends on the circumstances and the demining organisation, but it is common for the deminer to have a light wooden stick placed on the ground across the lane at the limit of the cleared area. This is the baseline and the deminer is always behind it while clearing the area in front of it. The first action is to probe carefully for tripwires by feeling carefully from ground level (or as close to the ground as permitted by the vegetation) to overhead with a bamboo or wire wand.

Vegetation is then cut back for as far as the deminer can safely reach forwards over the baseline, about half a metre. This is a painstaking operation that in some countries takes up to two-thirds of the total time of demining. Because of the risk of hidden tripwires, careful cutting with hand tools is required and all cut items are gathered as they are cut so that they do not fall on top of a trip-wire or hidden mine. Once the lane has been cleared of vegetation as far as the deminer can reach, the newly cleared area, typically one metre wide and about half a metre forwards from the baseline, is usually checked again for tripwires from ground level to overhead with a bamboo or wire wand.

Figure 8: Metal detector in use [MgMi02]

A metal detector is then used to identify any buried or surface metal items, and their location marked with a lightweight non-metal marker. Before each use the metal detector is checked by passing it over a known test-piece (a small metal target embedded in a plastic holder) to ensure that it is working correctly.

Starting at a safe distance, often about 200 mm back from the marker, the deminer prods and excavates towards the target indicated on the metal detector. The prodder is kept at a shallow angle, less than 30 degrees from horizontal, in order to contact the inert side of the mine first and not the pressure plate on top. Mines that have moved or were deliberately planted on their sides present a special danger.

Figure 9: Prodding [MgMi02]

The deminer works forward and down, clearing the ground until a target is identified. If a mine is found the deminer calls for a supervisor and withdraws. The supervisor will excavate just enough to be able to place a block of explosive to destroy the mine; detonation is usually done at the end of the day’s work.

More usually the deminer will find a small piece of metal. If nothing is found the area is re-checked with the metal detector and excavation continued until there is no longer metal indicated. Small rusty steel items can be very difficult to find and there may be no more than a few flakes of rust causing the false alarm. In many areas a thousand false alarms are found for every mine detected and so in some areas an individual deminer can expect to find an explosive item only every three or four months; this can lead to boredom and carelessness.

In areas without vegetation the SOPs may be substantially different. For example, in Afghanistan dogs are widely used for survey work. Two dogs are used separately to cover each piece of ground in a systematic manner, they walk forwards in a straight line on an 8 metre long leash and then return to their handler, sniffing the ground in both directions. The handler then moves sideways about two meters along the baseline and repeats the search. The dogs are trained to sit if they smell explosive vapour; the success of dogs depends very much on the close relationship between the dog and the dog-handler. All areas where a mine dog indicates the presence of explosive vapour are searched with a metal detector and all metal finds excavated carefully.

Most SOPs insist that the deminer should work prone while excavating suspicious objects, but many deminers prefer to work squatting or kneeling. There is a trend towards permitting this position, and some demining organisations are testing blast aprons which protect the legs and genitals while squatting or kneeling.

Figure 10:Protective clothing [MgMi02]

1.2.2 Mechanical Demining

Mechanical approaches rely on the use of motorized mine-clearers whose design is influenced by military demining requirements. The majority of machines deployed worldwide on mechanical mine clearance tasks are not specifically designed for the job. A number of mechanical mine clearing machines have been constructed or adapted from military vehicles or armoured vehicles of the same or similar type and with the same or reduced size. Also, commercial and agricultural machines/vehicles have been modified and adapted to suit mine clearance or bush cutting purposes. The mechanical approach is fast but it cannot yet achieve the humanitarian demining accuracy and safety standards at least in the near term and it is environmentally not friendly. Mechanical methods have emerged with their own strengths and weaknesses. With this technique, machines often do not destroy all mines in a contaminated area. Antipersonnel mines may be pushed on one side or buried deeper or partly damaged making them more dangerous.

Mechanical mine clearance systems are divided into two basic categories: (1) remotely controlled and (2) manned systems. A remotely controlled system is controlled from a safe distance using a hand-held radio-frequency module. A manned system is controlled from a protected position within the demining vehicle.

Vegetation Cutters and Removals

Heavy vegetation is a common phenomenon in a minefield. In many countries vegetation is a large problem facing demining and its removal can take up a substantial fraction of the time. Especially where lush vegetation spreads over uncultivated areas very quickly, vegetation impedes the work of manual deminers. It can be very risky and time-consuming to cut the undergrowth by hand. 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.

Figure 11: Tempest [Habi02]

The Tempest is a radio-controlled ground based system designed to clear vegetation and neutralizes some tripwire initiated 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-controlled subsystem, and a 1.2 meter wide horizontal chain flail with vegetation cutting tips.

Vegetation cutting heads and trimmers are produced by a large number of manufacturers worldwide. Cutters are usually sold with a hydraulic arm and can be fitted to many tractor types as long as the linkages are compatible. Agricultural tractor units can be equipped with armoured cabs to protect the driver.

Figure 12: Vegetation cutting head [Habi02]

Flails

Figure 12 & 13: Flails [Habi02]

Flails have been used primarily by the military to clear lanes through minefields, and several versions are deployed in humanitarian demining operations. They consist of large number of chains with clearing elements similar to hammers, attached to them and connected to a rapidly rotating drum that beat and mill the ground. The flails hit the ground and either detonate or destroy all types of landmines. They are resistant to anti-personnel mines. Each piece of ground is struck at least twice. The slower the forward speed of such machines is, the greater the clearance depth. The detonation of Anti-Tank (AT) mines typically causes one or two chains to be lost. These machines are large, expensive, and difficult to maintain, and can damage the terrain by removing the topsoil.

Earth Tillers and Rollers

Large and bulky clearance machines employing one or more rotating horizontal drums with special metal teeth similar to a rock crusher mounted on its circumference, capable of tilling the soil to a variable depth. Some tillers are able to reach landmines as deep as 50 centimetres. It uses speed, impact and mass to destroy mines as they move on the field. It can be mounted on a prime mover such as a mine-hardened vehicle, however, these machines are large and some weigh as much as 45 tons. This limits their effectiveness in some types of terrain, and maintenance costs (e.g., to replace the teeth) are high and thus may prove to be prohibitive.

Figure 14: Earth tiller [Habi02]

Rollers are usually pushed or pulled over terrain by another vehicle with the hope that the pressure exerted by their weight will either crush or detonate landmines. Rollers are particularly effective for proofing roads that are suspected of mine contamination. Rollers can be most effective in the early stages of humanitarian operations to allow the establishment of supply routes. Smaller rollers can easily be manufactured to achieve low costs and easy repairs. Numerous roller systems exist, but they tend to be heavy and require a powerful prime mover. They are fairly effective except on undulating or stony ground, or heavily vegetated areas. Terrain and the environment can limit their effectiveness.

Figure 15: Roller [TNMA01]

Ploughs

Figure 16: Plough [DeTe02]

Ploughs are pushed by a tank or an armoured bulldozer. The plough relies on a set of parallel tines, pushed through the ground. Mines are scooped up by the tines and brought to the surface, being pushed off with a lot of earth to either side of the vehicle track by the angled plough blades. Several mines explode. Many are buried into the pushed off earth, and very difficult to remove later.

1.2.3 Mine Dogs

Dogs have been used since antiquity by armies both passively and actively. Mine detection dogs and their uses have benefited from the knowledge of the earlier use of dogs in the military.

Dogs are not a replacement for deminers and metal detectors. Rather, they can be an additional mine clearing asset to a demining program. They can work more quickly than normal clearance teams, such as road and track sections containing widely spaced mines. They are also a valuable asset in battlefield areas with high metal content because they can speed up the detection process since they recognize explosive scent rather than metal.

Others are of the opinion that dogs should not be used to verify individual mines, but to verify the boundaries of a minefield.

In general, dogs are more effective in environmental conditions that include a degree of soil moisture, which increases the transportation of scents from the ground to air. Dogs usually work better in the morning when there is still dew on the ground. As the air heats up, the hot air rises along with the target scent making it more difficult to detect. It stands to reason that dogs are less effective in extreme weather conditions - be it snow, heavy rains and high winds. These conditions all displace scent. While a dog with good scenting capabilities is needed, dogs must also possess a good hunting instinct.

It is today generally accepted that dogs will not find 100% of all mines. It is not possible to give exact figures but most experts believe that dogs will be able to detect approximately 80-90% of all mines as an average after one pass if the dog and the handler are well trained [McLe02].

Figure 17: Mine dog [McLe02]

Today, about 400 dogs are used globally to search for mines.

1.3 Robots for Humanitarian Demining

Robots have always been used for applications which have been dangerous or unhealthy for humans, like painting car-bodies. Humanitarian demining is a dangerous challenge. Although special strategies, tools and protection devices are used today, for humans working in a minefield an element of risk will always remain. The only way to eliminate the risk completely is to avoid minefields. And a robotic solution allows humans to be physically removed from the hazardous area. In addition robots can perform tedious and monotonous tasks. And demining is indeed a very tedious and monotonous job for humans, which is one of the highest risk factors. The loss of concentration can end in a fatal accident.

The idea to employ robots in minefields is not new and many attempts have been made to design solutions for this task. The possible ways of design, the concepts of how to employ robots in demining, are multifarious. The attempts differ in the extent of employment. Some are designed to perform only a distinct part of the whole demining process while others are designed to complete the task from the beginning to the end. There are different opinions about the amount of employed robots. Some decided to use a single robot for all different sub-tasks while others use robot swarms made-up of identical robots or even swarms made-up of different kind of robots. Another important aspect is whether to use tele-operated or completely autonomous robots. These basic design considerations surely decide about the level of the robot system's complexity. One main reason why not a single mature robot, which has been proven in real minefields, does exist currently, are the unavailable technical means in the past for such a complicated and demanding process like demining. But today it seems possible to work with fully autonomous robot swarms capable of clearing a minefield with a minimum of human assistance and maintenance soon.

1.3.1 The Concept

The following considerations in this work are mainly based on the assumption that robot swarms are used for demining actions. There is the possibility to use mobile intelligent robots of one kind, each one equipped with devices for mine detection, mine removing, and for transportation. But most of the attention is focused on the use of three swarms of robots equipped either with detection devices or removing devices or transportation devices.

The theory is to employ the three swarms simultaneous in the minefield. The detection robots scan the field for possible mines. If a landmine is detected a nearby removal robot takes over and after the removal a transportation robot with free capabilities transports the mine out of the minefield to a collection area. The whole process is fully autonomous. Operators are only needed for monitoring and of course for maintenance. To achieve this goal the robots must have a high level of intelligence and must be able to communicate among themselves. Since the power supply of mobile robots is finite there is also need for docking stations. The host computer in figure 18 is needed to solve the path planning problem in a dynamic environment. Each robot represents for all other robots a dynamic obstacle which has to be avoided. The host computer controls centralized the moving of all robots by means of wireless communication. But such a host computer will be obsolete soon. Software packages in the onboard computer of each robot will take over this task.

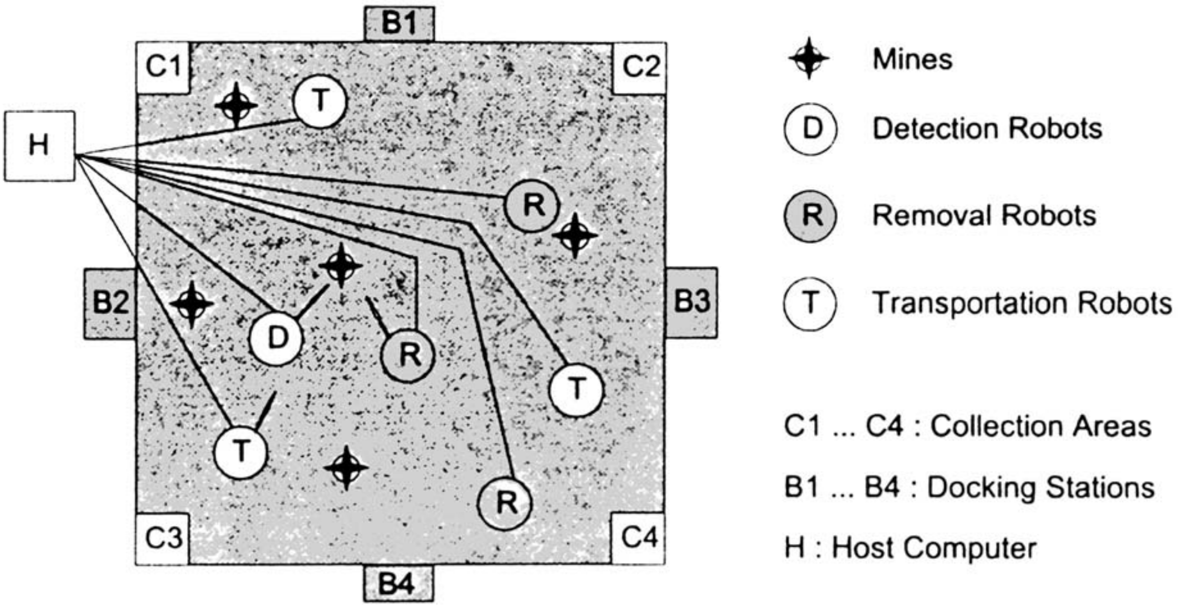


Figure 18: Humanitarian Demining Robot Swarms [Kopa02]

Modularisation of mobile robots especially of service robots is said to be the future. Developing single purpose robots for one distinct task is the reason for the comparatively low number of service robots today. A low cost solution by modularisation of the hard- and software will increase the number of robots dramatically.

These future perspectives are also available for demining robots. Modularisation does not only promise lower production costs of demining robots. There are advantages in maintenance procedures, flexibility of the whole system and reduced costs through accidental explosions. The fact that many modules in the three different types of robots are the same provides another reason for the use of a modular system.

The modular system presented in this work consists of a so-called 'Tool Kit'. The basis of the system is a commercially available mobile robot platform (MRP). This platform is equipped with the basic features required for mobile robots. The platform can then be upgraded with different peripheral devices according to the task to solve. For example a mine detection sensor will be indispensable for a detection robot and is a terrific example for such a peripheral device.

To make the robots capable of performing the requested task, they need to be equipped with a control system. The control system is responsible for the robots reaction to sensor inputs and for the execution of predefined sequences. One main task is the navigation which has some technicalities in regard to demining applications. An important technology of great use not only for navigational tasks is the global positioning system.

However, technical feasibility is not the only aim of the development of such a tool kit, but it is also necessary to reach economic efficiency. Therefore optimisation of the work process of the robots is necessary. As robots are usually relatively slow it is useful to develop navigation strategies for the robot swarms to save time.

Beside the modularisation of the hardware it is also necessary to use modular software architecture. Without appropriate software the advantages of a modular system can not be used.

1.3.2 Requirements for Demining Equipment

Standard equipment requirements for the humanitarian demining do not exist, but the following requirements for systems, that should improve the work of demining, can be summarized [Kopa02]:

- The system (robot, vehicle or equipment) should be of low-cost because it should be affordable to countries who simply can not afford the expensive systems available on the market.
- If possible, all parts and components used should be commercially available in order to reduce maintenance costs and availability problems.
- The system's size has to guarantee (grant)easy transportation and user-friendly handling
- The system should be of a robust design and capable to work in rugged environments.
- Operation time should be simple and failsafe (user-friendly operation) for all skill-levels to reduce training problems

- Operation time should be at least 2 hours before re-fueling or re-charging and that work should not take more than 30 minutes.
- Ability to distinguish mines from false alarms like soil clumps, rocks, bottles and tree roots. This process is called false rate. A high false rate is wasting time.
- Operation in a variety of soil types, moisture contents and compaction states.
- Ability to detect both types or in fact a variety of different mine types and sizes.
- Operation in vegetated ground cover.
- Operation on bumpy and/or tilted ground surfaces.

This list is a huge challenge for robot designers and some experts are doubtful that the requirements can be fulfilled in the short run. But considering especially the first two points a tool kit could offer notable advantages to accomplish these requirements.

2 Modularisation of Mobile Robots

The beginning of robotics was characterized by the effort to design robots, which can be used for many different tasks and applications. The idea was that these universal robots would be produced in such large numbers that the price would drop rapidly. But soon designers came up with highly specialised robots for concrete applications, because their prices were much lower than the prices of the universal ones. This is one of the main reasons why the number of service robots in use today is comparatively low.

Modularisation of mobile robots and especially service robots is promising to increase their number dramatically. The general philosophy of modularization of mobile robots is that a manufacturer produces a number of modules by which user can assemble such configurations of robots which are the most appropriate for a specific task.

2.1 Typical Configuration of a Modular Mobile Robot

“Modular Mobile Robot is intelligent (low, medium or high degree of intelligence) semi or fully autonomous vehicle (wheel, legged, chain, crawling, climbing or special locomotion) with all its systems (locomotion, driving, control, navigation and communication) build on a modular principle, able to carry peripheral systems (robot arms etc.) or tools (conventional or special) for transporting of loads (e.g. pallet) or executing different industrial (assembly, disassembly, etc.) or service (cleaning, inspection etc.) operations in the world coordinates.” [Shiv01]

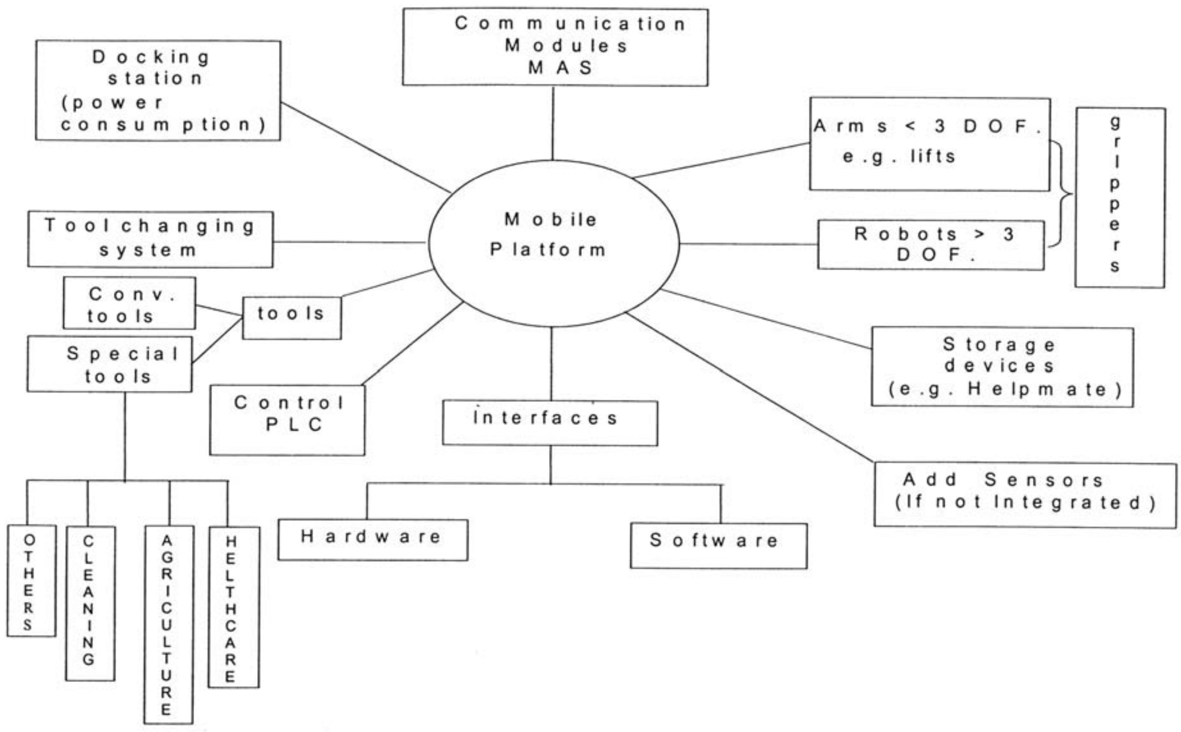


Figure 19: Modular Robot System [Shiv01]

2.1.1 Mobile Robot Platform

The basis of a modular concept for demining robots is the Mobile Robot Platform which can be described as a multi-use mobile robot that is developed in its basic configuration including all the most important and vital features for its mobile functions systems.

These platforms can be divided in some basic systems:

- Locomotion system
- Driving system
- Main control system
- Communication system

Locomotion System

The locomotion system can be realized on different principles, like wheel-, chain-, walking- or special-locomotion. All these principles have different characteristics in regard to costs, weight and efficiency in varying terrains.

Driving System

The driving system consists of: power sources, actuators and transmissions, which enable the platform to perform the necessary movements.

Main Control System

The main control system is usually microprocessor-based and responsible for the actions executed by the robot. It should be powerful enough to meet the requirements of all current tasks and possible future tasks.

Navigation System

The navigation system normally consists of an array of, possibly different, sensors for the perception of the robots environment and of course of some kind of software which designates the rules for the robot-movement.

Communication System

The communication system connects all the systems in the platform and the platform with the environment.

2.1.2 Arms and Peripherals with Less than 3 DOF

The mobile robot platform has to be equipped with a mechanical or other system which is able to manipulate tools or grippers and operate with them. Simple arms, lifts, fork mechanisms etc. are needed to perform some simple tasks. Though these tasks could be performed by a dexterous powerful arm as well, it would be simply too expensive.

2.1.3 Arms with More than 3 DOF

Some operations performed by mobile robots require functions of flexible robotic arms with higher number of degrees of freedom. Some of these arms are controlled by the main control system of the mobile robot platform, others are controlled by a special microcontroller or by a **P**rogram **L**ogic **C**ontroller.

Some of these sophisticated systems installed onboard of mobile robot platforms are independent robots having all-typical subsystems. Of course there is always some communication and interaction with the platform, but theoretically such onboard robots can perform task autonomously.

2.1.4 Grippers

Grippers are designed to imitate the human hand and operations which are fulfilled by it. It is highly complicated to imitate the complex motion sequences of a human hand. Therefore most of the grippers are only a simplified copy with less DOF.

There are different categories of grippers used in robotics. Mechanical grippers apply certain forces by using fingers to keep the object safely grasped. They can be actuated by all common principles and are often equipped with sensors to avoid damaging the handled object.

Vacuum grippers are mostly applied for sensitive and fragile materials. The surface characteristics of the handled object limit the applicableness of vacuum grippers.

Electromagnetic grippers are used for manipulating magnetic sensitive materials. Of course the possibility to use special grippers designed for specific tasks is always an alternative.

2.1.5 Tools

The mobile robot platform can be upgraded and modified by adding a number of peripheral systems and tools for the performance of different tasks or functions. There is a large variety of tools, which can be used.

Basically these tools can be divided into two major categories:

- Conventional tools
- Special tools

Conventional Tools

Conventional tools are similar in regard to their function to conventional hand-held tools for manual operations. The difference is found in their design, since they have to be fixed on the mobile robot platform, and actuation.
Different actuating systems for the tools are applied:

- Electromechanical
- Electromagnetic
- Pneumatic
- Hydraulic

Examples for conventional tools:

- Screw drivers
- Drilling tools
- Polishing tools

Most conventional tools are attached to an onboard robotic arm and controlled via a special microprocessor system and a number of sensors which enable the performance of a variety of operations automatically.

Special Tools

A special tool installed onboard of a mobile robot platform changes the same to a specialized mobile robot system. If special tools are lightweight constructed, the manipulation system will be able to be more flexible and with wider reach. Heavy tools cannot be very flexible. They need more rigid and strong manipulation systems. So only one degree of freedom is applied frequently, and the other DOFs are realized by the mobility of the platform.

The variety of tasks realized by service robots and especially personal robots is much broader than of those in the production sector. This is why they require a much larger number of variations of the robot peripherals. An example for a mobile robot platform equipped with a specialised tool could be for instance a grass cutting robot.

2.1.6 Tool Changing System

Installing a tool changing system enables the robot to achieve a wide variety of performable operations. Tool changing systems are normally placed at the end of a robot arm. They have to be light, simple and very reliable.

They again use electrical, electromagnetic, pneumatic and hydraulic actuators. As they work with tools of different actuation principles they use the same type of actuation as the tools themselves.

There have to be also onboard magazines which host the tools. These magazines have to ensure easy access and must be able to free the used tool and output another easily and safely.

2.1.7 Additional Sensors

The basic configuration of each mobile robot platform has its integrated sensors. The navigation system makes excessive use of sensoring to determine position and avoid collision. But there are numerous possibilities to upgrade the system with additional sensors for some special applications or to extend its abilities.

2.1.8 Storage Devices

In many mobile robot applications transportation is an important part of the overall task. To transport different items mobile robot platforms have to be upgraded with another type of peripheral devices: special storage systems or devices.

Storage devices have to be designed with regard to the required space, loading and unloading conditions and possible special environmental conditions for the transportation of sensible items.

2.1.9 Interfaces

The crucial point to make a modular system work is an appropriate connection between the mobile robot platform and the modules and among different modules themselves. The hardware interface should ensure a proper mechanical connection and concurrently ensure power and information supply. Software interfaces are at least as important as hardware interfaces. Without a good cooperation in the software layer new added modules can not complete their tasks and are therefore of no use.

2.1.10 Communication Modules MAS

Although mobile robot platforms are normally equipped with a communication system it could be necessary to use some special communication systems. Especially in multi agent systems (MAS) where a team of robots acts together is communication between the team members of importance.

2.1.11 Docking Stations

There are two types of docking stations

- Battery recharging (or fuel, compressed air filling) docking stations
- Loading unloading stations

Batteries are today the most used energy sources for mobile robots. Combustion engines are used for heavy mobile robots working open-air. There are worldwide efforts to develop new or more efficient energy sources.

An automatic recharging system for mobile robots would be desirable because it would ensure to operate continuously. This would include sensors to notice the necessity of recharging the system. Then the mobile robot has to move to the docking station and refuel. Good designed systems should assure an appropriate connection of the robot to the docking station, an optimal recharging process and a proper fulfilment in regard to the accurate amount.

2.2 A ‘Tool Kit’ for Demining Robots

The former chapter dealt with a general modular concept for mobile robots. The following chapter investigates the feasibility to use such a modular robot system in form of a tool kit for demining actions. A tool kit can be imagined as a package of modules like that one discussed before. It may consist of two or three different mobile platforms and an indefinable number of peripheral devices to assemble different configurations according to the expected tasks.

Firstly, the question why such a tool kit should be used is answered. To point out the advantages of a modular system for demining the standard procedure of demining has to be considered. Assuming a mine infected area has been made out the subsequently clearance process can be divided into following steps.
At first the exact positions of each single mine should be known. Therefore the mine has to be detected by some sort of detection system and the position of the mine should be stored someway.
Second, the mine has to be removed which could mean in the case of a buried mine that it has to be excavated. It might be that the mine gets defused before removing it completely. But there are landmines in use which can not be deactivated. Another possibility would be to detonate the mine by using an explosive charge. Since mines include a lot of chemicals which get into the ground in case of a detonation it is better not to detonate them. Mine cleared areas are often used for farming; hence a chemical pollution of the soil is undesirable.
If the mine didn’t detonate, it would have to be transported out of the area and collected at some place.
Considering these actions, it is obvious that one single robot designed to accomplish all these tasks has to be a pretty sophisticated device. On the other hand it can be seen that there could be employed at least two different types of robots.
One type is responsible for detecting and one for removing the mines. It is likely to use a third robot-type for transporting the removed mines out of the area.

Even at the first blush it is obvious that these three types of robots, specialized for distinct tasks, have a lot of things in common. Because all three types have to work in the same environment, many modules used in the different robots are the same. These components represent common help to reduce the overall amount of modules and make an implementation of a modular robot concept a lot easier. Not only the acquisition costs are decreasing, the efforts for maintenance and training of the operation personnel would decrease as well.

Another advantage is the flexibility. It could happen, for example, that the terrain of the minefield changes dramatically and another type of locomotion system would be now the system of choice. Using a modular robot system, it would be easy to change the locomotion module or the platform and continue the work. Different types of soil or different types of landmines may demand different removal tools. This is not a challenge for a modular system.

Especially for demining actions it is always useful to have spare parts available. Of course, working with a design which forwards the repair procedure in regard to save time and effort has to be a key-issue. These needs are perfectly covered by modular systems.
Under these conditions an accidental explosion which damages a robot is not the worst. The repair is comparatively cheap and the work is not interrupted too long.

Therefore the task of humanitarian demining is truly a good example for showing the full potential of a modular concept.

A question to be answered before even starting with the development of a modular system for the purpose of demining is whether the whole system is only used for demining applications or whether the system should perform some other service applications as well.
If the system should be a ‘specialized’ one, it would have the advantage to be able to design some of the modules for only this special purpose. This should clearly enhance the performance of the system. On the other hand one of the original motives for using a modular concept was the desire to lower the costs and a broader field of application raises the number of employed robots which obviously lowers the cost.
The intention is to have a standard modular system for mobile robots which can execute every possible task on the model of personal computers for example which can be used for so many different purposes with only changing some hardware components and upgrading the software. But since it was not possible to create a specialized robot for the task of demining up to now, it could be overconfident to try to develop a highly modularized system which is among other things capable to accomplish that work.

Of course this should be the goal in the long run. In the short run it should be satisfying to begin with a merely demining system. In addition, considering the number of landmines buried today, it seems that the market should be big enough for such a system.

For the following considerations it was presumed that there will be three different robots in duty which are built together from a tool kit for demining robots. These three robots are one for detection, one for removal and one for transportation of landmines.

2.2.1 Mobile Robot Platform

Like mentioned in the introduction the mobile platform should be commercially available to keep the costs low. But it is absolutely imaginable that the available platforms do not suit for demining actions. Most of the commercially available platforms are rather simple and only designed for indoor applications even to keep the costs low. At the worst there is no other way than to design a suitable platform. But before, there is the chance to upgrade existing platforms, in a cheap and easy way if possible, according to the demands.

It is likely that such a tool kit consists of more than one platform. To begin with the use of different locomotion systems for different terrains could be a reason for. Especially if the use of completely different systems like wheeled and walking locomotion is considered it may easier to use different platforms than to change the locomotion system like other modules in the tool kit. Changing between wheeled and chain locomotion is possibly simply enough to design a platform transformable between the two systems. Secondly the tasks of the three different types of assembled mobile robots out of the tool kit require different levels of force and stiffness. Detection robots are likely to need much smaller platforms, depending on the type of sensing technology used, than removal robots which require high forces for excavation actions. Therefore the tool kit should contain different platforms to enhance the flexibility of the whole system.

2.2.1.1 Body

Under laboratory conditions the body of a mobile robot may not be indispensable, but during outdoor applications sensible system of a robot need protection. It is quite possible that a mobile robot works well in the laboratory but completely fails to perform the same tasks outdoors.
Typical problems are temperature changes, moisture, dust, dirt and a lot more. The purpose of the body is to shield all parts which do not have to interact directly with the environment from the same.
If the working area should have an extreme climate it could be necessary to use some sort of air-conditioner to cool or heat the sensible components.

Beside these general problems which concern all robots working outdoors demining robots have the need of additional protection. The best protection would be of course to assure that no robot detonates a mine. But that is not likely, so at least the expensive components should get some special protection. A shield for explosive protection may consist of two different layers. A hard outer layer with good ballistic properties and an energy-absorbing inner layer made of polyethylene for example. Beside this protection against blast and fragmentation there is also need for additional considerations. Especially sensible electronic components need shock protection. These components should not have direct contact to the body. They should rather be cushioned to withstand an average mine explosion. Another important point is the immense amount of dust made through an explosion. It has to be kept separated from all components which need clean working conditions. Components which are not inside the body of the platform should be at least isolated.

The most popular shape of the body today is a cylindrical form. Beside the convenience to be able to place rings of sensors around the cylindrical shape another advantage is that the body can be build of standardized cylindrical rings, one on the top of the other, where each one contents another component. The platform can be upgraded easily with new components simply by raising the platform with a new ring.

2.2.1.2 Locomotion system

Since mines are likely to be placed in many different terrains it should be especially attached value to the locomotion system.

The most spread type today is the wheel locomotion system. Typically the number of wheels amounts to three, four or six.
The extensively use of wheeled locomotion systems has many practical reasons. The underlying mechanic is simple and easy to assemble. And the ratio of admissible total weight for payload to own weight is quite acceptable.
The problem is that wheeled systems are in rugged terrain not as efficient as in plain. As a basic principle it can be supposed that wheeled vehicles have problems to overcome obstacles higher than the radius of their wheels.
The advantage of using only three wheels is high manoeuvrability at the expense of balance. Four-wheeled systems are well developed in the car industry and all-wheel drive would be obviously desirable for off-road applications. But the best solution seems to be the six-wheeled one since this configuration is the most suitable for off-road territory. Moreover minefields are mostly not plain and additional scattered with small obstacles like stones and branches. A six-wheeled robot nearly achieves the same performance in off-road terrain than a robot with a chain locomotion system.

Figure 20: Wheel Locomotion [BeAn02]

Chain locomotion systems are successful for rough, muddy and sandy terrains. The comparative big tread allows robots with such a system to pass relatively big obstacles.

Not the heavier hardware compared to wheeled robots describe the main disadvantage, but the low efficiency of chains. Energy is dissipated by friction in the chain and by relative movement between the chain and the ground. Hence the robot needs a more efficient driving system which however increases the total weight. But especially in the case of demining a robot has to fall below a weight limit to avoid triggering the mines. On the other hand the use of a chain locomotion system enables the designer to decrease the pressure force of the robot onto the ground by simply increasing the length of the chains instead of reducing the weight of the robot.

Figure 21: Chain locomotion [PeKw02]

Walking locomotion systems are in general the better solution for rugged terrain compared to wheel and chain locomotion systems. But the development of these complex devices is only at the beginning. Nevertheless many mobile robots demining projects are using this concept. Legged vehicles can be omni-directional and can turn in place. A unique characteristic of walking vehicles is the ability to move with discrete foot placements, thus allowing the robot to avoid stepping on landmines or other delicate objects. Also, the legs of a walking robot cause much less damage to the terrain than a standard tracked vehicle. In addition, due to the freedom of leg placement, a legged robot can stop walking and then choose suitable stable footing to work on a mine, even on very uneven ground. Furthermore, its body posture can be changed while keeping the feet on the ground, thus essentially adding another degree of freedom for performing the task. An unexpected explosion damages a legged robot in a much lesser degree than a tracked robot if the posture is such that the legs are stretched out of the centre of the robot’s body like the legs of a spider. If the robot does mistakenly detonate a mine, the damage will be reduced to the end of the leg. In this way the body can be protected, although this approach does require lightweight, inexpensive, replaceable legs.

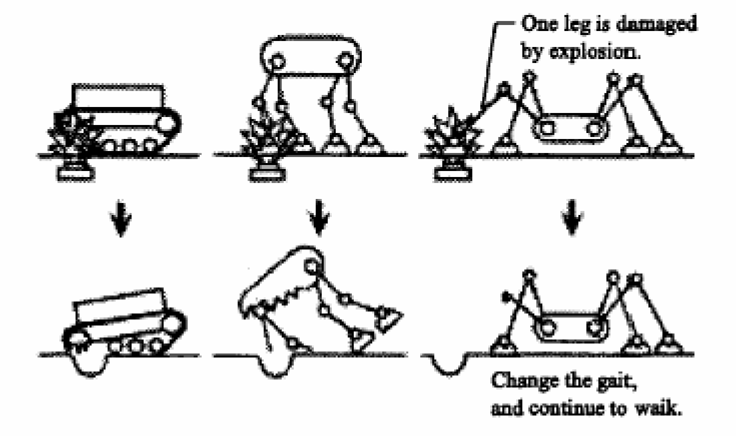


Figure 22: Main body protection feature in case of an explosion [HiKa02]

Another advantage for the use of legged robots in demining actions is that the legs may also be used as manipulators. In principal such legs are robot arms used for locomotion purposes. They only have to be equipped with a tool and can be used for other purposes. Disadvantages of legged robots are the relatively low movement speed and of course the complexity of the system compared to tracked vehicles in regard to the used mechanical parts and the control of the movement. Therefore it could take a long time until legged robot platforms suitable for real outdoor applications are competitive to standard tracked robots.

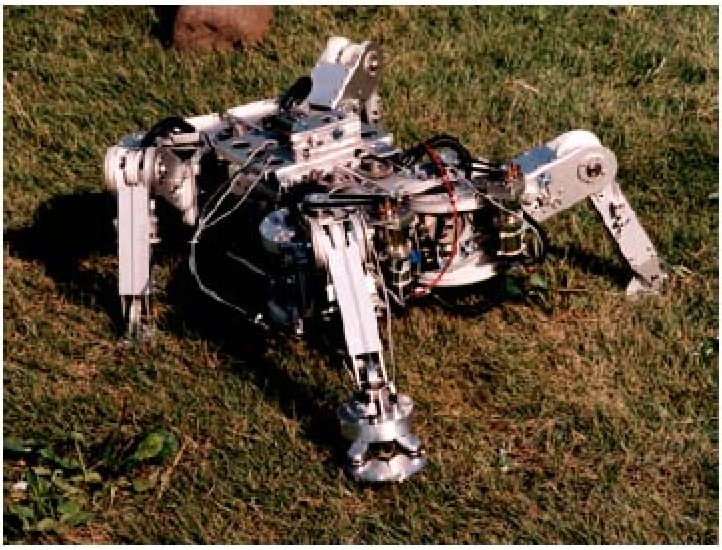


Figure 23: Walking Robot [Hiro00]

An interesting approach could be a locomotion system imitating the movement of a snake. This would have the advantage that the robot could move in dense vegetation. But these special locomotion systems are not sufficient developed and up to now they are not likely to fit into a low cost concept.

Figure 24: Snake robot [HiFu02]

2.2.1.3 Communication System

Radio modems provide wireless communication link between mobile robots. The range of available radio modems is various. The Khepera II robot base for example can be upgraded with a radio turret module [Khep02].

Figure 25: Radio Turret [Khep02]

Features

- Radio communication with up to 32 robots
- Direct robot addressing
- Error detection and correction
- Can communicate with a host computer

Specifications

Speed	up to 9600bps
Frequency	418 MHz or 433,920 MHz
Range	10m

Another possibility for inter-robot communication is the use of infrared light. The great disadvantage of IR is that it is line-of-sight transmission and therefore sensitive to fog, and other obstacles. An IR communication system [HuKe98] is described in the following. To transmit information a ring of twelve LEDs is used, each with a half power angle of 60 degrees. They are arranged 30 degrees apart to ensure 360-degree coverage. Figure 26 shows their theoretical light intensity changes with respect to the viewing angle. Four photodiodes have been used in each mobile robot to receive information. They are arranged 90 degrees apart (each with a half power angle of 120 degree), as shown in figure 27. This combination of LEDs and photodiodes allows communication regardless of the relative orientation of the robots.

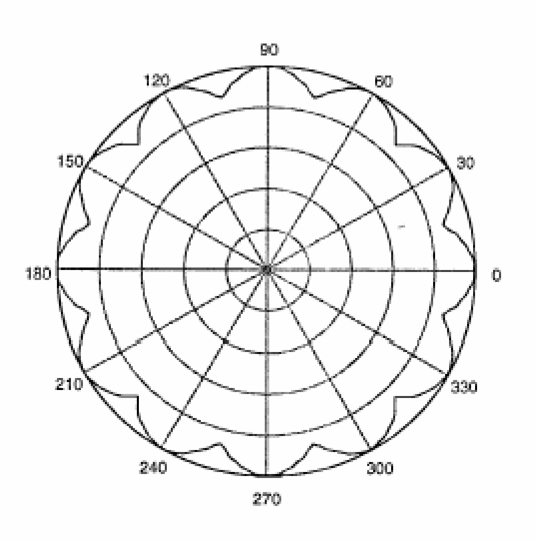


Figure 26: Theoretical light intensity change of LEDs with respect to the viewing angle [HuKe98]

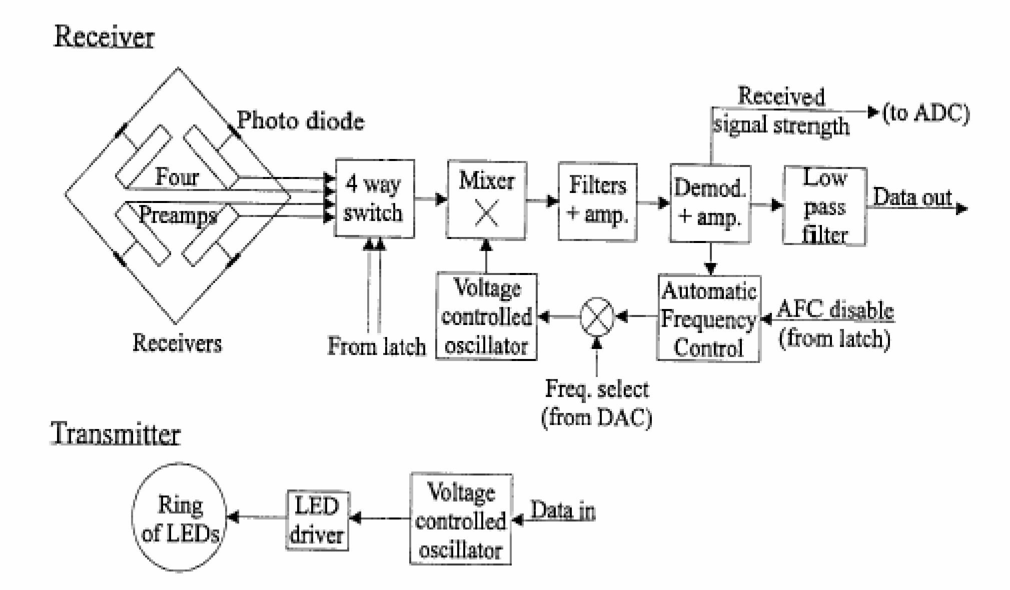


Figure 27: Block diagram of the communication system [HuKe98]

Figure 27 shows a block diagram of the communication system. Information is transmitted by frequency modulating the IR carriers, with the decoding being carried out using an off-the-shelf radio frequency (RF) integrated circuit. The information is present in the frequency changes around the nominal frequency. The transmissions from other robots are received by one of four photodiodes and are then mixed with selected tuning frequency (heterodyning). A filter is used to obtain the information with the correct carrier frequency. The received information is demodulated and passes through a low pass filter to give digital data. Data is received at 1200-baud using differential phase shift keying (DPSK), thus permitting automatic frequency control. The range of this communication system is over seven meters in the worst case.

Another possibility for communication is the use of wireless short range communication protocols like IEEE 802.11b or Bluetooth.

A wireless LAN IEEE 802.11b is a data transmission system that uses radio waves rather than a cable infrastructure, and provides location-independent wireless network access between computing devices. IEEE 802.11b wireless Ethernet is rapidly becoming the standard for in-building and short range wireless communication. Recent advances in wireless networking have made it inexpensive and fast. Many mobile devices such as mobile robots, laptops and PDAs already use this protocol for wireless communication.

The 802.11b standard defines two modes: an infrastructure mode and ad-hoc mode. In the infrastructure mode (illustrated in figure 28), the wireless network consist of at least one access point connected to the wired network infrastructure and a set of wireless end stations.

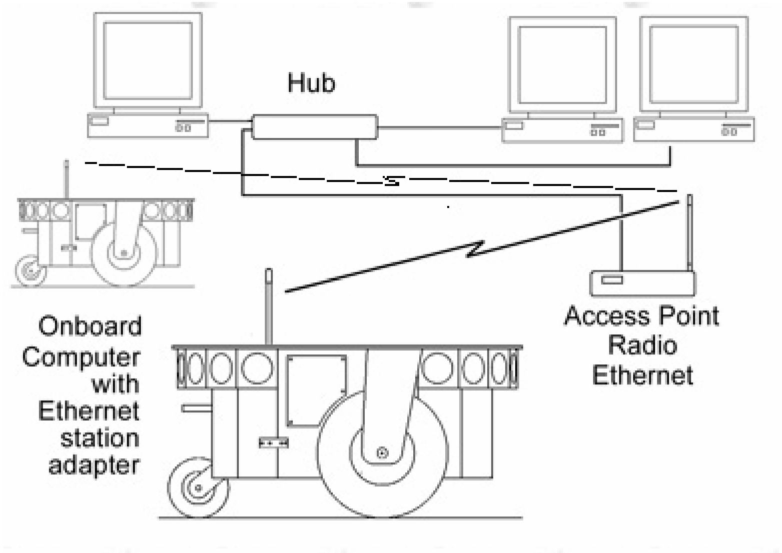


Figure 28: WLAN infrastructure mode [Acti02]

The ad-hoc mode (figure 29) is simply a set of 802.11b wireless stations that communicate directly with one another without using an access point or any connection to a wired network. This mode, featuring architecture similar to that used by Bluetooth, is useful for efficient set up of a wireless network anywhere that a wireless infrastructure does not exist.

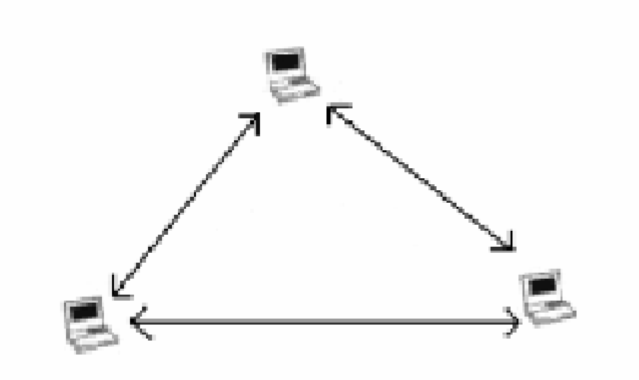


Figure 29: Ad-hoc networking [Dinc01]

Bluetooth wireless technology is a newer standard for short-range radio communication. It is designed by the Bluetooth Special Interest Group (SIG) as a low-cost and short-range wireless interface between mobile devices that provides low power consumption on the 2.4GHz ISM frequency band.

BT technology is independent of the operating system. Leading companies such as Nokia, Ericsson, IBM, Microsoft, Intel and Toshiba formed the SIG and today, more than 2000 organizations have joined it. Most of them are currently developing BT-enabled products under a specification developed by the group. In the real world, BT can be used for a variety of purposes, and will potentially replace multiple cable connections via a single radio link. BT-enabled products will automatically seek each other out and configure themselves into networks. Though small, such networks can be quite useful.

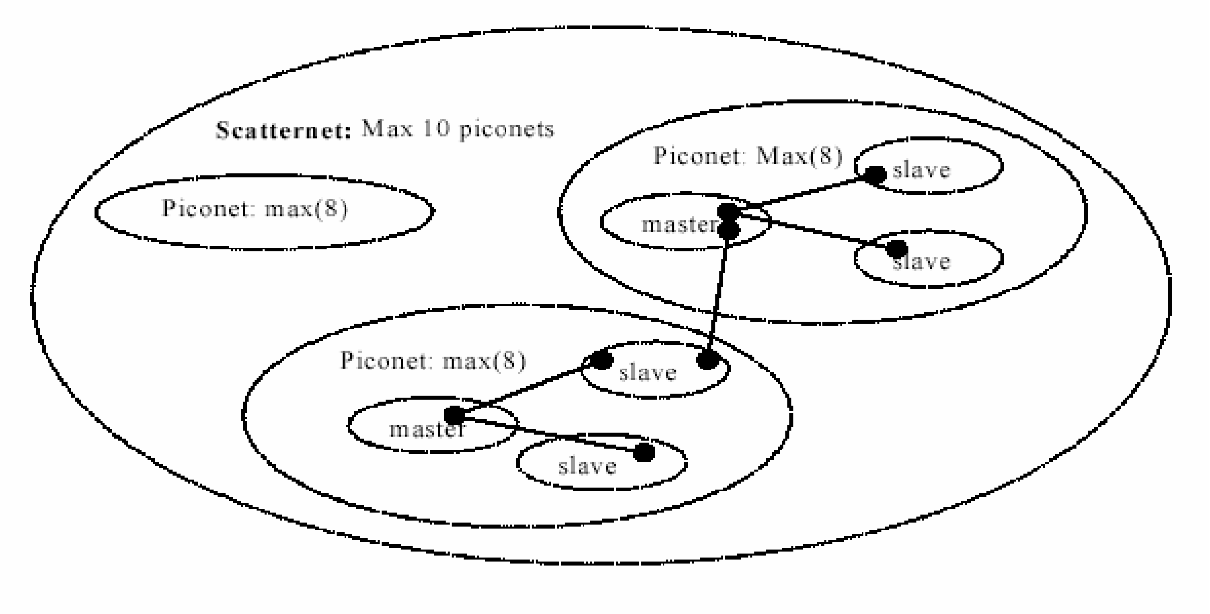


Figure 30: Bluetooth wireless ad-hoc network [YuVl01]

Bluetooth wireless technology is a new ad-hoc standard. Figure 30 shows the basic concept of the BT wireless ad-hoc network. It includes two sorts of networks, piconet and scatternet. The piconet contains only one node (BT-based-device) as the master and up to seven others as slaves. Any BT-based-device must be able to connect to any other device. Therefore any BT-based-device can be in the role of the master – the master function is not coupled to any special specifications. Groups of piconets, up to ten, form the scatternet.

2.2.2 Detection Robots

The robots for the detection of landmines are probably the most simple of the three types. The basic composition of modules common for all three types has to be upgraded only with additional sensor - the detection system. An overview over the most common actual and most promising detection technologies in future provides the following chapter.

Buried mines are unnatural objects. They are entities that differ from all other objects in their environment. As such, they have signatures that may be used to detect them, they cause changes in the soil around them, and the act of burying mines leaves evidence of their existence.

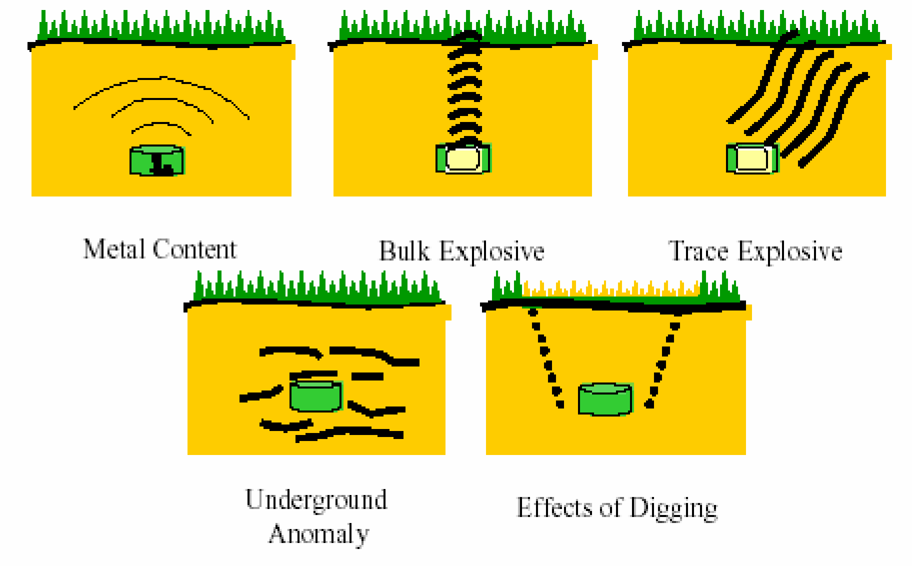


Figure 31: Mine signatures caused by buried mines [MoLe00]

The targets of mine detection and sensing technology are to achieve a high probability of detection rate while maintaining low probability of false alarm. But, the probability of false alarm rate is directly proportional to the time and cost of demining by a large factor.

Several promising (new) technologies for the detection of landmines are in development, each with its strengths and weaknesses. Careful study of the limitations of any detection and sensing capabilities with regard to the location, weather, environment and soil composition is critical along with the required technical operation and maintenance skills. Not all high-tech solutions may be workable in different soil and environmental conditions.

Beside the tremendous diversity of environmental conditions in which mines are laid, the wide variety of landmines makes the development of unique sensing technology so difficult. Landmines differ in size and composition, burial depth and grazing angle.

There are almost as many mine detection methods as there are types of mines. The following section lists the most important and promising sensor technologies.
Figure 32 displays the structure of the sensor technologies in regard to their manner of detection which are later on described in this chapter.

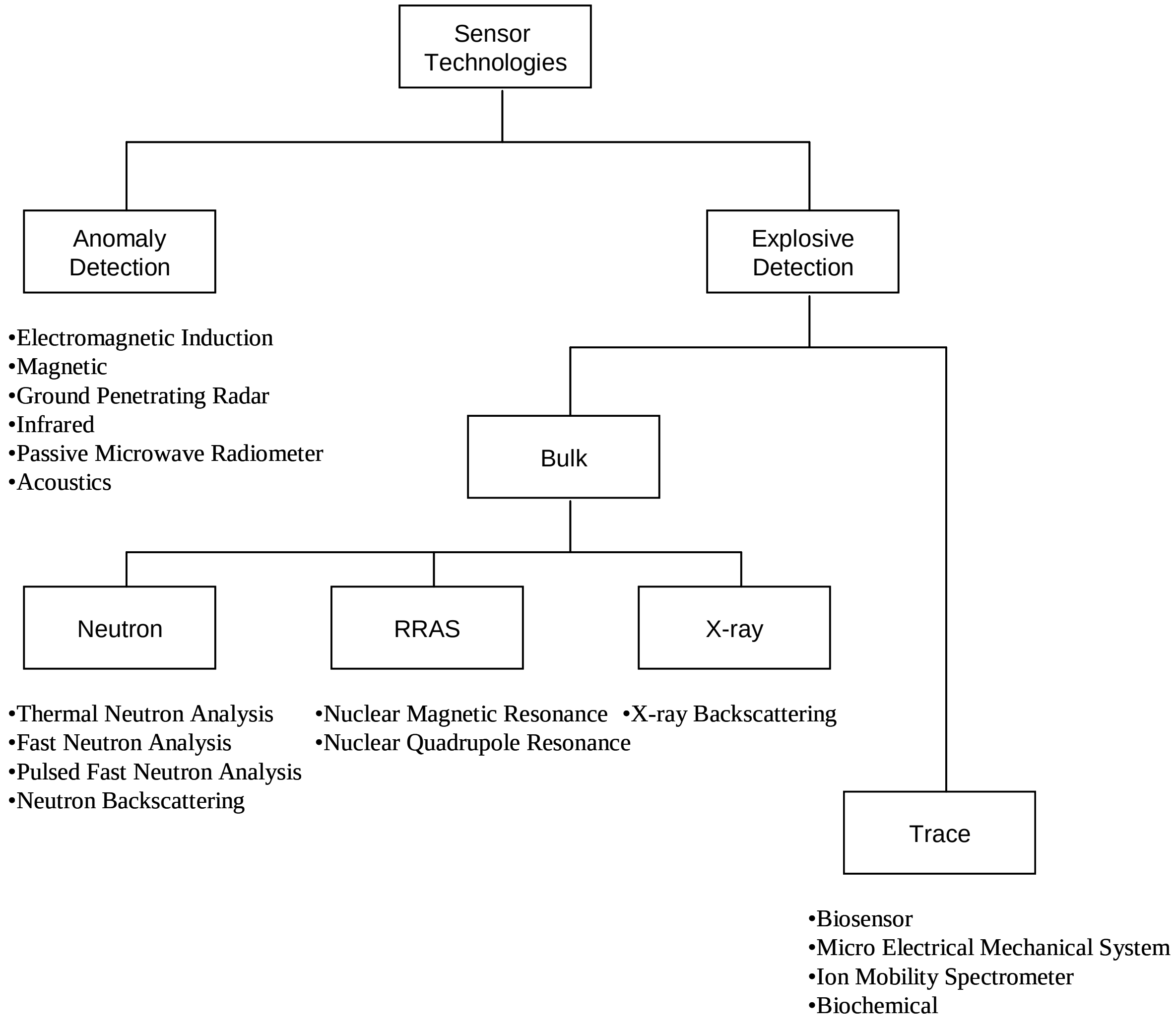


Figure 32: Organization of sensor technologies

2.2.2.1 Electromagnetic Induction

Electromagnetic induction devices, better known as metal detectors, are active devices capable to detect tiny amounts of metal at shallow depths. They are still the only detectors really being used in field.

Metal Detectors are composed of a search head containing one or more coils which carry a time-varying electric current and generate a time-varying magnetic field. That primary field reacts with the electric and/or magnetic properties of the target which could be the soil or any metallic object. The respond of the target is to generate a secondary magnetic field and that induces an electrical voltage in the receiver coil(s) in the search head which could be converted for example into an audio signal.

The secondary field is due to eddy currents, which are induced by the primary field in conductive materials. For that reason the detectors response is magnified for ferromagnetic objects and on the other hand some low conductivity metals, like some alloys or stainless steel, are more difficult to detect.

The secondary field depends, both spatially and temporally, on a large number of parameters such as distance, material type, orientation, shape and size of the buried object, but target characterisation is very difficult in general case.

Unfortunately metal detectors can not differentiate between a mine and metallic debris. In most battlefields, and not only there, the soil is contaminated with a variety of metallic objects like cartridge cases, shrapnel, metal scraps, etc. These objects lead to a false alarm rate of 100 to 1000 false alarms [Brus99] for each real mine. This is not only a waste of time, but it also induces a loss of concentration in case of manual demining which could be fatal.

This problem is aggravated by the efforts of mine producer to reduce the magnitude of metallic components in mines to counteract demining efforts. Therefore metal detectors are designed more and more sensitive with the result to increase the false alarm rate.

Metal detectors can be subdivided into Frequency Domain (Continuous Wave) and Time Domain (Pulse) systems.

Frequency Domain Metal Detectors

Continuous Wave systems make use of a discrete number of sinusoidal signals, often just one. They can employ separate transmit/receive circuits, measuring the small change in mutual inductance between transmit and receive coil(s) caused by nearby metallic or magnetic objects. Information on the target's nature is contained in the amplitude and phase of the received signal, as the detector approaches the target. Measurements carried out in background conditions can be used to reject part of the background signal itself, especially in areas such as sea beaches or strongly mineralised regions.

Time Domain Metal Detectors

Pulse systems work by passing pulses of current through a coil. The repetition rate is typical of the order of 1 kHz, taking care to minimise the current switch-off transient time (a few µs). Eddy currents are thus induced in nearby conductive objects and their exponential decay with time is observed. A Time Domain system measures how quickly the momentarily generated magnetic field is breaking down, which happens to be slower in presence of metal.
The eddy current decay time constant itself, some hundred µs, depends mainly on the targets conductivity, permeability and size. Low conductivity background and nuisance items, such as seawater for example, have a very short decay time. Therefore it is relatively easy to make the system insensitive to such materials by choosing an appropriate delay (some tens of µs) between the time of switch-off and the sample acquisition. A similar argument applies to purely magnetic but non-conductive materials, which are magnetised by the transmit pulse but demagnetises just as promptly after switch-off.

For that reason a pulse detector must be the system of choice when it comes to working in seawater or strongly mineralised regions. On the other hand Frequency Domain metal detectors have a higher overall sensitivity, and they are more suitable to detect low conductivity metallic objects such as those made of stainless steel.

Metal detectors have indeed become more and more refined and sensitive over the years, and it has often been said that they have reached their limits. But there are still opportunities for improvements.

As mentioned above the internal signal of metal detectors depends on the nature of the object under study, its size and depth. There are efforts to draw out at least part of this information. Another approach is to generate an image, for example by scanning a single sensor over a surface, and then try to deconvolve the detector's intrinsic response from the acquired data. Furthermore it has been suggested to study other sensors then the ordinary coils currently used in metal detectors.

Metal Detectors for Humanitarian Demining [Brus99]

- **Weight**: less than 2 kg. **Price**: in the 2000-4000 EURO range.
- **Size**: round, oval or rectangular head. In the former case the diameter is between 20 and 30 cm, to achieve sufficient depth and a reasonable scanning surface and speed.
- **Operating depth**: shallow, i.e. from flush (even with the surface) down to about 10-15 cm for minimum-metal mines, 20-30 cm for mines with an appreciable metallic content, and about 50-70 cm for large metallic objects such as UXO or metallic mines.
- **Electrical/Mechanical**: capable of working with standard cell batteries for a long time (tens of hours), and usually simple to use. Many demining teams pay more attention to the ergonomics rather than to the pure performances of the detector itself.
- **Output**: normally an audio signal, usually already the result of extensive internal data processing**,** from which an experienced operator can make some qualitative statement on the target and its position. When using manual methods as the *primary procedure*, **each** alarm is carefully checked until it has been fully understood and/or its source removed.

Beside the disability to detect non-metal mines and the probably high false alarm rate, the secondary magnetic field induced in metallic objects diminishes rapidly with distance.
But electromagnetic induction is a mature, proven technology.

2.2.2.2 Magnetic

Magnetic devices are sensible to nearby ferromagnetic objects, either via induced or residual magnetisation. They are called magnetometers, or gradiometers when used in differential arrangements. Gradiometers employ a pair of magnetometers separated by a set distance to measure differences in magnetic moments between the two sensors.

These sensors do not radiate any energy, but only measures the disturbance of the earth's natural magnetic field caused by buried and surface objects containing ferrous metal.
This is the main disadvantage and limits the applicability to a small percentage of mines. Like metal detectors they cannot discriminate landmines from metallic clutter and the ability to sense objects decreases rapidly with the distance between the sensor and the object.
On the other hand magnetometers are well developed, cost-effective and reasonably easy to use.

2.2.2.3 Ground Penetrating Radar

Ground Penetrating Radar has been in use for at least two decades for the detection of buried objects and soil studies in civil engineering, geology and archaeology. The ability of GPR to detect plastic mines is of particular interest for demining activities.

GPR works by using an antenna to emit electromagnetic waves into the ground. The frequency normally ranges in the microwave region from several hundred MHz to several GHz. Buried objects cause reflections of the emitted energy which are recorded by a receiver antenna. The critical parameter for detection is the difference of electromagnetic properties of the target and those of the ground. This means in particular the dielectric constant. As well the size and shape of the scanned object is obviously liable for the amount of reflected energy. This is one of the crucial points for the detection of AP-mines, which are rather small. Spatial resolution depends on the frequency used. Increasing the frequency provides a higher resolution but on the other hand implies a loss in penetration depth.

Ground penetrating radars can be subdivided in a number of classes, based on their signal characteristics.

Time Domain Radars

Impulse GPR

> This type emits a signal at a certain base frequency, which is modulated in the time domain so that pulses with regular intervals are sent to the antenna.

Chirp Radar

It transmits a pulse-train waveform where the carrier frequency of each pulse is rapidly changed across the pulse width.

Frequency Domain Radars

Frequency Modulated Continuous Wave GPR

Here the emitted signal is a continuous wave, which is modulated in frequency. The frequency is swept across a certain bandwidth in either a sawtooth or triangular fashion.

Stepped Frequency Continuous Wave GPR

Here the emitted signal has a steady carrier frequency, which is incremented with a fixed step at regular time intervals.

As AP landmines are small objects, high frequencies are needed for a better depth resolution and detailed echo. Unfortunately, if mines are buried too deep and the frequency is too high, it is possible that nothing will be detected because of the dramatically increased attenuation of the soil with frequency.

A solution to this dilemma is the use of large bandwidth in order to benefit form the advantage of both low and high frequencies. Such a large bandwidth can be obtained by a time-domain UWB GPR or a Stepped Frequency Continuous Wave GPR.

The terminology Ultra Wide Band (UWB) GPR is used for a system having a fractional bandwidth, which is larger than 25% [Frit01].

Returning signals may be obscured by extrinsic noise due to reflection from the ground surface and from underground sources. Intrinsic noise from the equipment itself will also detract from the signal. The signal to noise ratio is improved by using surface-removing algorithms and subtraction of both background and equipment noise.

GPR is a mature technology and can create images of surface or buried objects. Furthermore GPR systems can be used on airborne platforms.

Unfortunately GPR is slow to use, an adequate degree of automated data processing is desirable to enhance speed. Radar penetration depth is highly dependent on the type of scanned soil. The worst results are obtained with clay-content soil. Moisture also changes the dielectric constant of different materials through which the radar may pass, thereby affecting its effectiveness and accuracy.

2.2.2.4 Infrared

Infrared cameras are passive devices sensitive to radiation in the infrared part of the spectrum. All bodies emit infrared radiation. The infrared spectrum lies between 0.76 µm and 100 µm wavelengths.

In order to resolve objects with this technique a difference in the emitted infrared radiation is required. This can be caused by either a temperature difference between the body and the surrounding or an emittance difference of bodies at the same temperature.
The thermal properties of mines are different from their surrounding. Therefore, as the temperature changes with time, a mine will usually be either warmer or cooler than the ground in which it has been emplaced. The bigger the difference in temperature between a mine and its surroundings, the stronger the signal received by an IR sensor.
But this technique is also capable of detecting buried mines. What happens is that buried mines change the conditions in the ground. A buried object alters the migration of water, which changes thermal conductivity and heat capacity. The sensor measures the thermal contrast between the soil over a buried mine and the soil close to it.

The environment influences the detection of buried objects by infrared sensors quite heavily. Thermal radiation is absorbed, reflected and emitted by vegetation, rocks and soil. It is attenuated by atmospheric conditions that vary throughout the day. Rain, wind and even shadows influence the results.

Infrared sensor can be subdivided into two groups.

Passive Sensors

These sensors detect the energy emitted and reflected by the disturbed soil, which must differ from that of its surroundings. This is likely to happen around sunset when there is little reflected energy due to the sun, but the thermal energy that was absorbed by the mine, is being re-emitted. Current passive sensors operate in the 3 µm to 5 µm and 8 µm to 10 µm bandwidths [MoLe00]. The 5 µm to 8 µm range is not included since it is subject to high atmospheric attenuation.

Active Sensors

These sensors detect in the same fashion as passive detectors but they use an artificial source to illuminate the target. The disadvantage is that the heat source and its power supply increases weight and size of the system, and the detection process is slowed down since it takes a long time to heat a target or a disturbed soil before a temperature gradient will appear.

Infrared detectors work in a wide array of soil types and they are effective at detecting non-metallic objects. They can also be used to detect minefields from airborne platforms.
But infrared sensors have difficulty detecting objects buried deeply. The IR signature of landmines buried more than 15 cm may be too difficult to detect.

2.2.2.5 Passive Microwave Radiometer

Passive radiometers working in the microwave range of the electromagnetic spectrum are considered in particular for the detection of surface laid mines or shallowly buried mines.

A radiometer is an instrument that measures the power incident on an antenna. The antenna beam of a microwave radiometer is normally scanned over the scene of interest. In order to detect a target, a sufficient difference in microwave temperature between the target and its background must exist. In the case of a surface laid mine the vegetation and soil acts as the background.
The microwave temperature of the soil varies with the annual and diurnal cycle, and amongst other things, depends on the level of incoming solar radiation (insolation), soil composition, soil water content and microwave frequency. The soil surface temperature in the 10 GHz to 20 GHz region for typical conditions varies from 255 K to 310 K [Dani99].
Metallic targets have a low emissivity and strong reflectivity in the microwave band, whereas soil has a high emissivity and low reflectivity. Soil radiation depends therefore almost entirely on its physical temperature, whereas metal radiation depends mostly on the reflection of the

cold sky which illuminates it. Over the microwave range of 1 GHz to 10 GHz the microwave temperature of the sky is in the order of 6 K [Dani99].
The detection of plastic targets is also possible but more difficult, given that they produce a much smaller temperature difference than the metal objects.
A passive microwave radiometer measures the difference between the warm ground and a cold mine.

Passive microwave radiometers are reasonably simple devices and can be used to generate 2D images of objects placed on the surface or shallowly buried, with best results in dry soils, and for metallic targets.
Compared to IR sensors they are not very attenuated by clouds or rain, but the microwave emissions are much weaker than IR emission. As a result microwave emission takes longer to collect and require larger-aperture collection devices, which directly affects spatial resolution.

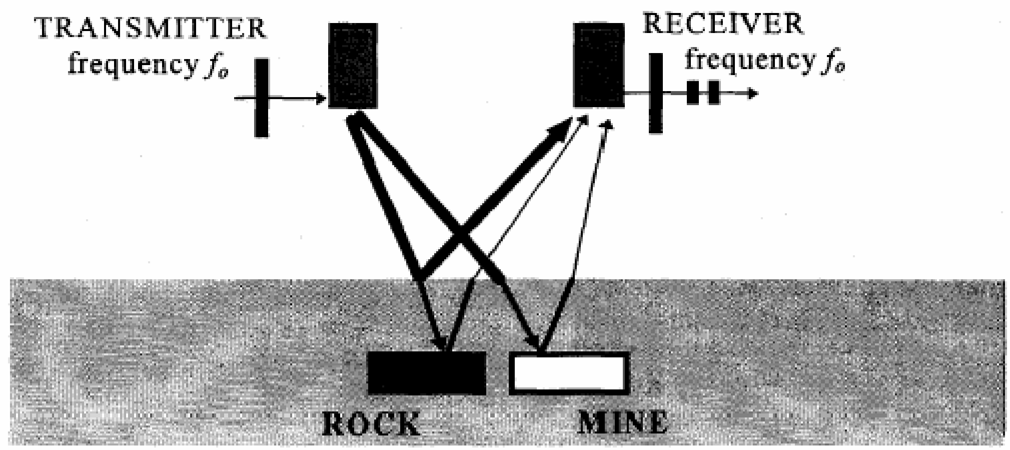
2.2.2.6 Acoustics

There are a number of acoustic methods of detecting buried objects such as mines. One way to employ acoustics is the identification of buried objects by viewing the images of the acoustic energy reflected from the soil. Other methods are based on the comparison of a reflected acoustic signal with a reference signal in order to provide detection of the object. The difference between these two signals indicates the presence of an object.

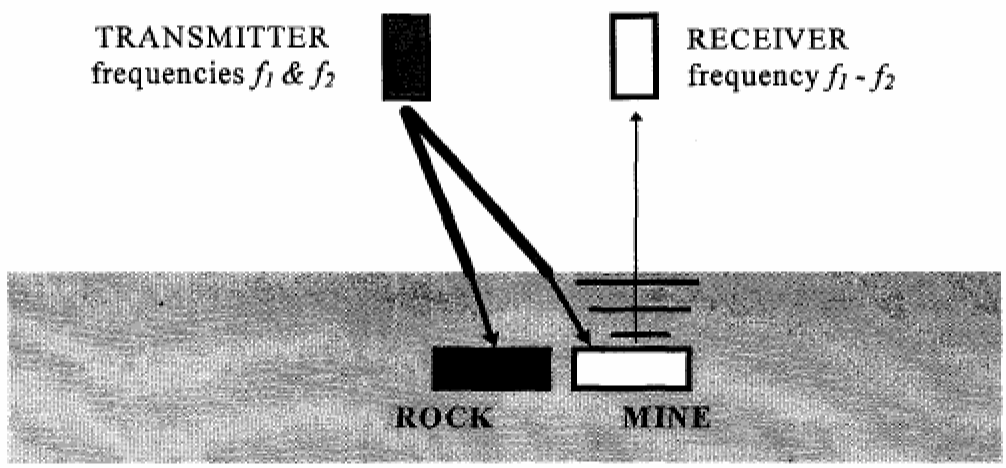
The problem of all these methods is, that variations in the physical properties of the ground (density, porosity, moisture content, etc.) as well as the presence of non-target objects (rocks, tree, debris, etc.) can lead to a high false alarm rate. Acoustic energy is highly absorbed by sand but should be capable of good penetration through very wet and heavy ground such as clay. Also, there are strong disturbances at the air-to-ground interface.

Another interesting approach of the problem is the Nonlinear Seismo-Acoustic Technique. This technique does not depend upon the material of which the object is fabricated. It depends upon the fact that a mine is a shell whose purpose is to contain explosives and associated detonation apparatus. The shell is an acoustically compliant article, which compliance is notably different from the compliance of the surrounding soil.

This mechanical compliance allows a shell to vibrate at the frequency of the sound which strikes it. The sound is radiated against the soil above the mine from a transmitter. The vibrating object, being buried in soil, bounces against the surrounding soil. The bouncing (nonlinear interaction at the mine-soil interface) causes sounds at frequencies different from the vibrations being imposed by the incident radiation.



a



b

Figure 33: Detection schemes; a) conventional location, b) proposed nonlinear technique [Dons98]

This overcomes a major problem of many active detection schemes which transmit some sort of radiation towards the surface of the ground. The radiation undergoes a series of reflections and is received by a sensor. The problem is not only that almost anything buried will cause reflections, but the problem goes even further because any sensor which is sensitive to the reflected radiation is also sensitive to the incident radiation, which is reflected from the surface of the ground.

The Nonlinear Seismo-Acoustic Technique allows the use of a sensor which is insensitive to the incident radiation and can focus entirely on the presence of the difference frequency that mines radiate. Other solid objects, such as rocks, tree roots, etc., have a mechanical compliance much, much smaller than that of mines and do not radiate this new frequency. Therefore this technique is capable of detecting metallic and non-metallic mines with low false alarm rate. Other advantages are real time response, simplicity, non-hazardous and low cost.

Acoustic systems are in danger of triggering the mine which is currently investigated. Since a mine is a highly sensitive device the acoustic radiation emitted by the system may contains enough energy to detonate the mine.

2.2.2.7 Bulk Explosive Detection

These techniques detect the explosive itself. They should not be confused with techniques that detect explosive vapours or other substances leaking from the mine or its surface, or trace particles deposit in and on the soil around a mine

There are several neutron-based techniques for detecting explosives in bulk form. They have all in common a neutron source to produce neutrons which are directed into the ground and a detector to characterize the radiation, usually gamma rays, emerged by the interaction of the neutrons with the soil and substances contained by the soil, like explosives.

Due to their zero charge neutrons can penetrate thick layers of material and interact directly with atomic nuclei. The interaction depends strongly on the kinetic energy of the neutron. Fast neutron scattering (bouncing) off a nucleus and slow neutron absorption into a nucleus can both increase the energy of the nucleus, which leads to the emission of a gamma ray. The probability of an interaction is very high at certain neutron energies, which are unique for each element. By measuring the energies and intensities of the gamma rays, the elemental composition of the inspected object can be determined, as characteristic gamma ray spectra for most elements are well known.

2.2.2.8 Thermal Neutron Analysis

TNA relies on the elevated nitrogen concentration of most commonly used explosive, which is much higher than in most common materials and in soil. The capture of a thermal (i.e. slow) neutron by a nitrogen nucleus results in the emission of a gamma ray with the energy of 10.8 MeV [Brus01]. As this is the highest energy gamma ray emitted by a naturally occurring isotope, it gives a very clear indication on the presence of nitrogen.
TNA is probably the easiest among the neutron based-techniques apart from neutron backscatter.
On the other hand it is relatively slow. Typical response times range from minutes to tens of minutes, depending on the material being investigated. In practice there are several obstacles to be overcome to apply TNA successfully for the detection of explosives. The pure nitrogen signal, which is at 10.8 MeV, is very characteristic but orders of magnitude weaker in intensity than the background signals. Possible interferences from other elements and an increase of neutron attenuation through some rare earth elements are also an issue.

2.2.2.9 Fast Neutron Analysis

FNA is based on the interaction of fast neutrons, mostly inelastic neutron scattering, with the nuclei of interest. During this process the high energy neutrons put elements in an excited, short lived state, in particular oxygen, carbon and nitrogen of explosives and soils, by hitting their nuclei. The nuclei return into their initial state by emitting gamma rays. By characterising the outgoing gamma rays, relative to their energy distribution, it is possible to calculate the elemental proportions.
FNA has the potential of delivering better results than TNA but is usually far more complex and expensive.

2.2.2.10 Pulsed Fast Neutron Analysis

Pulsed operations allow the use of timing information and can be very useful for background reduction. Given that the neutron pulses are short enough compared to the flight time across the object to be analyzed, Time-Of-Flight techniques can be used to determine the location of the detected material. When combined for example with the vertical scanning of the neutron source and the horizontal movement of the source/detector relative to the object, pulsing provides a three-dimensional spatial resolution capability.
The nature of the material is again provided by gamma spectroscopy. Up to now this technique has required rather large installations.

2.2.2.11 Neutron Backscattering

A ^{252}Cf source is placed above the soil together with a thermal neutron detector. The amount of detected thermal neutrons that are moderated in the soil and then scattered back into the direction of the detector mainly depends on the hydrogen content of the soil.
In almost all cases, the hydrogen concentration in landmines is, because of the explosive inside, higher than that of the surrounding soil. Therefore, if the detector is moved above a landmine, an increase in the detected thermal neutron flux can be observed.
Small variations in the distance between the detector and the soil, the standoff distance, significantly influence the count rate. That is why two identical detectors with a certain distance between them and a source positioned exactly in the middle are used. In this way, there is always a reference value available if one detector is above a mine and the other is not.
One of the main problems of this technique is the inability to detect metal mines. Therefore it should only be used in combination with another detection technique. In addition to that the signal-to-background ratio decreases rapidly if the water content of the soil increases.

Finally there should be considered that all these neutron methods emit radiation. An optimal source strength needs to be selected following the “as low as reasonable achievable” principle, but needs to be strong enough to get good results. A maximum yearly dose for any kind of personnel working with these technologies should not be exceeded.

2.2.2.12 X-ray Backscattering

High energy radiation is usually called X-rays or gamma rays according to how it has been generated. X-rays are produced when electrons from outer orbits fall into a vacant inner orbit. Gamma rays are electromagnetic radiation of nuclear rather than atomic origin, and are produced as a consequence of nuclear reactions or radioactive decay.
Backscatter systems produce an image from X-rays that are scattered back from the screened object towards the source. Because low-Z materials are more efficient at scattering X-rays, explosive-like materials are more contrasted in the backscatter image. “Z is, for a substance made up of more than one element, the apparent atomic number that results if the substance is treated as if it were composed only of a single element.” [Brus01]
The technique is intended for real time detection of AT mines. Potential problems come from shallow penetration, system complexity, sensitivity to soil topography, sensor height variation, and safety aspects due to the use of ionising radiation.

2.2.2.13 Radio Frequency Resonance Absorption Spectroscopy

RRAS is “the selective absorption of energy from an electromagnetic field due to resonance formed by interactions between the electric and magnetic moments of nuclei or electrons of atoms and external or internal fields.” [MoLe00] The two main RRAS methods used for mine detection are Nuclear Magnetic Resonance and Nuclear Quadrupole Resonance.

2.2.2.14 Nuclear Magnetic Resonance

Many nuclei spin and all nuclei are electrically charged. In a magnetic field, spinning nuclei have lower energy when aligned with the field than when opposed to it, because they behave like magnets. This energy difference corresponds to radio frequency, hence the nuclei are able to absorb and emit radio waves.
NMR works best when the target is inside the detecting coil. This is not possible with buried mines. Configuring NMR to detect buried mines from outside the coils results in poor detection. Therefore, NMR requires a superconducting coil and an appropriate cooling system to make use of the signals. The required high power source makes the whole system bulky.

2.2.2.15 Nuclear Quadrupole Resonance

NQR is a bulk inspection technology for detecting crystalline explosive solids containing nitrogen-14 (^{14}N) nuclei such as RDX, TNT and nitrates. Unlike NMR an external (static) magnetic field is not needed.

NQR technology is now emerging as likely mine detection candidate. It was first proposed for demining applications in the 1970s, but it could not be exploited until recent developments in high-speed electronics and computing power led to the ability to rapidly detect the weak signals emitted by the nitrogen nuclei. Today, the main explosive used in mines, RDX, TNT, tetryl, may be detected within seconds.

Nitrogen nuclei spin on their axes at precession frequency. Stimulation of the nitrogen nuclei by an RF pulse at their precession frequency causes all like-nuclei to spin in phase. After the pulse the nuclei return to their natural state during which time they emit a weak RF signal. If there is a sufficient mass of nitrogen responding in phase to the RF pulses, the weak signal can be detected.

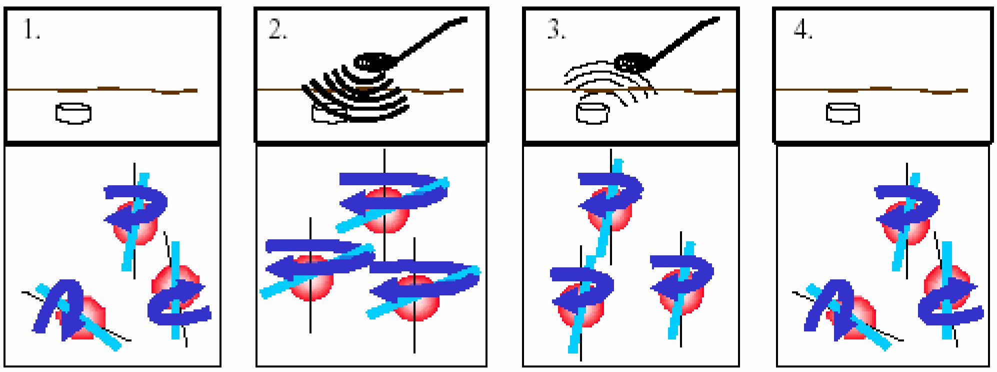


Figure 34: 1) nuclei spinning naturally out of phase, 2) hyperstimulated nuclei spinning in phase, 3) stimulated nuclei emitting a RF signal, 4) return to natural state [MoLe00]

NQR has the unique ability not only to detect explosives but also to identify them. Each material has a unique fingerprint of RF signals, depending on relative position and amount of nitrogen atoms in the molecule. Therefore an NQR detector must be specially tuned to detect each type of explosives that can be found in mines. Unfortunately it is not possible to construct a detector that searches all explosives. This is due, in part, to the complexity and weight of electronic components that would be required.

It should be noted that NQR responses can only be detected in solid crystalline structures. Liquid explosives, such as found in some mines, cannot be found using a NQR detector.

Both techniques, NMR and NQR, are not able to detect metallic mines, because the RF signals are not able to penetrate metal. They would have to be used in conjunction with a metal detector.
The size of the required data processing electronics as well as its power requirements for NQR systems are still to extensive. As miniaturization research continues in the electronics field and batteries become smaller and more efficient, NQR should progress very well as an explosive detection means.
Unlike the other bulk explosive detection techniques RRAS does not emit any kind of hazardous radiation.

2.2.2.16 Trace Explosive Detection

Trace Explosive Detection is the detection of explosive molecules that have emanated or leached from a mine into its surrounding environment. Samples are collected from the soil itself or from the air and then analysed for explosives

When a landmine is emplaced in the ground, vapours emanating form the explosive charge within the landmine can escape from the mine casing and into the soil. The vapour pressure is a very important indicator of how easily a substance tends to evaporate, and therefore shows how likely detection as vapour is going to succeed. Vapour pressures are often expressed as relative concentrations in saturated air, rather than in true pressure units, and are usually expressed in units of ppm, ppb or ppt. Such concentrations are proportional to the true vapour pressure. The vapour pressure increases quite rapidly with temperature. In the case of solid TNT near room temperature for example it approximately doubles every 5°C [Brus01].
The manufacturing process of explosives produces many chemical compounds, some of which may remain in the explosives as contaminants at up to several percent by mass. Several of the contaminants have vapour pressures greater than the explosive which is contaminated. For this reason it is sometimes more useful to search for these contaminants than looking for the explosive itself.

2.2.2.17 Biosensor

Biosensor systems are used to develop portable vapour detection systems, sometimes called "artificial dog noses". The systems consist of a collection system and a biosensor with sensitivity capable of detecting pictogram levels of TNT molecules.
The collection system collects air and the air sample passes a filter which absorbs the molecules of the target substance. The collected molecules are then dissolved in a fluid. Because of their extremely low concentration in air, the target molecules are concentrated in a large volume of air. About 100 litres of air are concentrated into 10 microlitres solution [MaGa99].
The biosensor is based on the weight loss in a Quartz Crystal Microbalance system. This system consists of a piezoelectric crystal connected to an electrical circuit. The surface of the crystal is covered by antibodies. They are attached in such a way that they will be released when reacting with the molecules in the solution. The quartz crystal oscillates at its natural frequency. Releasing antibodies alters the weight of the crystal and this decrease of the oscillating mass changes the frequency of the crystal, which can be measured easily.

2.2.2.18 Micro Electrical Mechanical System

The basic concept is to ultrasonically stimulate a target area in order to detach and then collect explosive particles on a cantilever. The particles are then irradiated with selected IR radiation causing them to deflagrate and release heat. The heat change causes a measurable change in the capacitance set-up that is characteristic of the weight of explosive collected. Detection occurs when there is sufficient explosive to generate a measurable change.

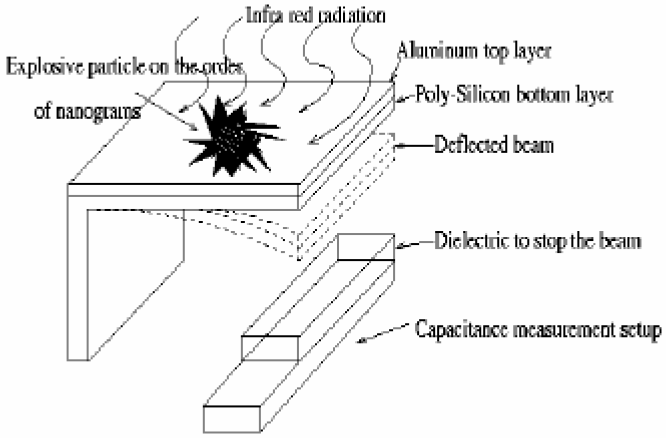


Figure 35: Schematic of MEMS trace explosive particle detector [BrGr97]

2.2.2.19 Ion Mobility Spectrometer

The IMS is a detection system capable of identifying and qualifying chemical vapours in minute traces. This technology was developed for the explosive-detection portal to check airline passengers.

IMS makes use of the different mobilities of ionised species in gases. Via an inlet membrane molecules enter in ambient air the ionisation region, where they are ionised by the means of UV radiation or beta particles. Short periodical pulses on a shutter grid allow the produced ions to move into the drift tube. Different charged particles drift according to their specific velocities and arrive at characteristic times at the collector electrode and cause current pulses forming the IMS spectrum. The drift time depends on the ion mass and on its molecular structure, and allows the identification of the substance. The current is a measure of the quantity of the substance. The presence of many different compounds in the probe sample increases the complexity of the IMS spectrum and makes the interpretation difficult.

All these trace explosive detection techniques have the same problems. It takes time to reach a detectable concentration of explosive molecules. The molecules are first blocked by the casing and then absorbed into the soil. Very little reaches the surface, so soil sampling may be required. The best conditions for detection are poorly sealed mine casings and mines buried in a porous medium.

Even though explosive may be detected, the precise location cannot be determined since molecules may migrate to the surface several metres away. The equipment is highly sensitive, requires a lot of maintenance and frequent calibration checks and is rather expensive.

2.2.2.20 Biochemical

Bacteria can be genetically engineered to glow in the presence of certain compounds including explosives. Biotechnologies using bacteria hinge on the tiny organisms ability to metabolize and break down organic compounds or transform heavy metals.
Chromosomes in bacteria can be modified to make the bacteria glow in the presence of TNT. The plan is to spray a solution of genetically engineered bacteria over a minefield. When the bacteria contact the explosives, which contaminate the soil, they start metabolizing it. They will scavenge the compound as a food source activating the genes that produce proteins needed to digest the TNT. Special genes that have been attached to the now activated genes produce the protein that emits extremely bright fluorescence when exposed to ultraviolet light.
Vegetation also tends to take up the chemicals, so the bacteria glowing on the vegetation could even localize the explosives more. It would be possible to detect land mines remotely from helicopters by looking for glowing microbes on soil illuminated with UV light.
Places they would not work are wet areas like rice paddies and rough jungle and snow. The method has been working in lab environment, there is a need to study the safety and effectiveness of using the bacteria in real mine infected area.

2.2.2.21 Equipping Robots with Sensor Technologies

There are several detection technologies in use respectively under development, but none of them is able to detect a mine alone by itself. The solution is to use two or more of these sensors simultaneously. The first logical step would be to mount several sensors on one robot. Since there are weight limits, and limits in the amount of available energy, this is probably not the best solution. Some of these technologies need strong power sources and some of them are relatively heavy constructed. These facts will not help to keep the weight of the robot low, so using for each type of sensor a single robot seems to be the better solution.

Unfortunately it will not be enough to simply mount the sensor system somewhere at the robot which only carries the sensor around. The detection robots should communicate with each other, change data and coordinate their work. If one robot with one distinct detection technology has found a possible target, the area should be verified by all other detection technologies before any further action is started. Therefore the different technologies must be compatible to allow coordination. At least the data from the sensors should be assessed by the same software. Combining results from different mine detection technologies is not easy and demands special strategies. These so-called sensor fusion technologies are not only of concern for mine detection. They are widely used in mobile robotics but mainly used to assess sensor data for navigation. Sensor fusion techniques are discussed later in this work.

Another important point is the power supply of the detection system. One possibility is to equip the detection system with an autonomous power source. But this could complicate the recharging of the system. There would be need for extra docking stations and at the worst for each detection technology a different docking station. And this would cost time because it is unlikely that the mobile platform and the sensor system need exactly the same time before recharging is necessary again.
Using the power source of the mobile robot platform would only alter the recharging process with regard to the operational time. In exchange compatibility problems could occur. Each detection technology may need power in a different way. And furthermore a modular system insists a quick exchange of the modules. Each sensor has to be mounted on every platform in a fast and easy way. It should be some sort of ‘plug and play’.

These problems could be largely disarmed if the different sensor systems would be constructed in consciousness of some constraints which are appointed by the possibilities of the mobile robot platform. Therefore the different development groups of the detection technologies and the modular mobile robot system would have to work together right from the beginning.

This cooperation during the development and design process of the modular robot system and landmine detection sensors is of greater concern than only for an appropriate modular interface. Some of these sensor systems are extremely sensible and may loose performance in presence of certain materials. Using these materials for parts of the robot system which has to carry the sensor technology has to be avoided. And many of the sensor techniques work by using radiation in some range of the electromagnetic spectrum. It has to be guaranteed that systems of the robot do not jam the sensor technology or the other way round.

2.2.3 Removal Robots

The removal of landmines is probably the heaviest work during the whole demining process. This is clearly a matter of the type of soil in which the mines are buried. But generally this task needs the highest forces and therefore the employed system has to be more stiff and heavy constructed.

The removal robots have also the most various tasks to fulfil. While the detection robots only transport the detection technology and the transportation robots have to accomplish an advanced pick and place task, the removal robots have to, in case of buried mines, dig out a highly sensitive device, which must be handled extremely carefully, but at the same time applying relatively high forces to penetrate the soil. In addition the excavation of a mine is every time a different procedure. The main parameters which differ for each buried mine are the type and shape of the mine, the position relative to the surface and the type of soil in which the mine is buried.

Some mechanical mine clearance devices used today can be compared in some ways with the considered removal robots. One difference is that the mechanical devices are brute and heavy compared to the robots. This means that it doesn't matter if they trigger off an explosion, because the explosion can not damage them. Putting aside the fact that explosions are undesired because of the environmental hazard, damaging a robot every time would be very costly and would delay the progress of the whole work. To avoid this negative effect, the excavation of a detected landmine must be carried out carefully rather than 'digging until hit upon something'.

Since the excavation is a complex task a dexterous robot arm with a high number of degrees of freedom is likely to be used. For the mine removal various end-effectors may be necessary.

The robot arm can be equipped with a variety of standard tools which are similar to tools used for manual excavation. All forms of shovels are doubtless of interest to remove foremost close grained material. Grippers may be used to sweep stones or other bigger obstacles. These tools are commercially available and well proven.

2.2.3.1 Sensors for Removal Work

Up to the present the most removal work performed at hazardous materials was executed teleoperated. For that the aid of sensors is mainly limited to force and torque sensors which ensure not to apply too high forces to the sensible object. But the whole process is controlled by an operator using video cameras to lead the tools.

Using a robot for autonomous removal of landmines presupposes the usage of sensors to compensate the teleoperator. Two broad classes of sensing technologies support earthmoving automation. One class allows determining the state of the robot itself, the other class concerns perception of the environment around the earthmover.

Local state is achieved by measuring displacements at the robots various joints. If the actuators are hydraulic cylinders the use of position transducers would be a good choice. An alternative is to use joint resolvers, like potentiometers, directly at rotary joints. Another form of state estimation is to locate the robot arm with respect to some fixed coordinate frame. Many sensing modalities have been used including, GPS, inertial sensors and reflecting beacons. Successful estimation schemes combine several of these techniques.

The other class of sensors perceives the robots immediate environment so that it can intelligently perform tasks such as avoiding obstacles or picking a place to dig. Two promising technologies for environmental sensing are laser and radar ranging. In both cases energy is transmitted into the world and range is determined by processing the reflected signal. Another active means of ranging uses ultrasonic sensors to determine distance to objects in the world. These sensors are often used for collision avoidance for autonomous vehicles. In contrast to active sensors transmitting energy into the world, passive ranging devices use available energy to calculate range.

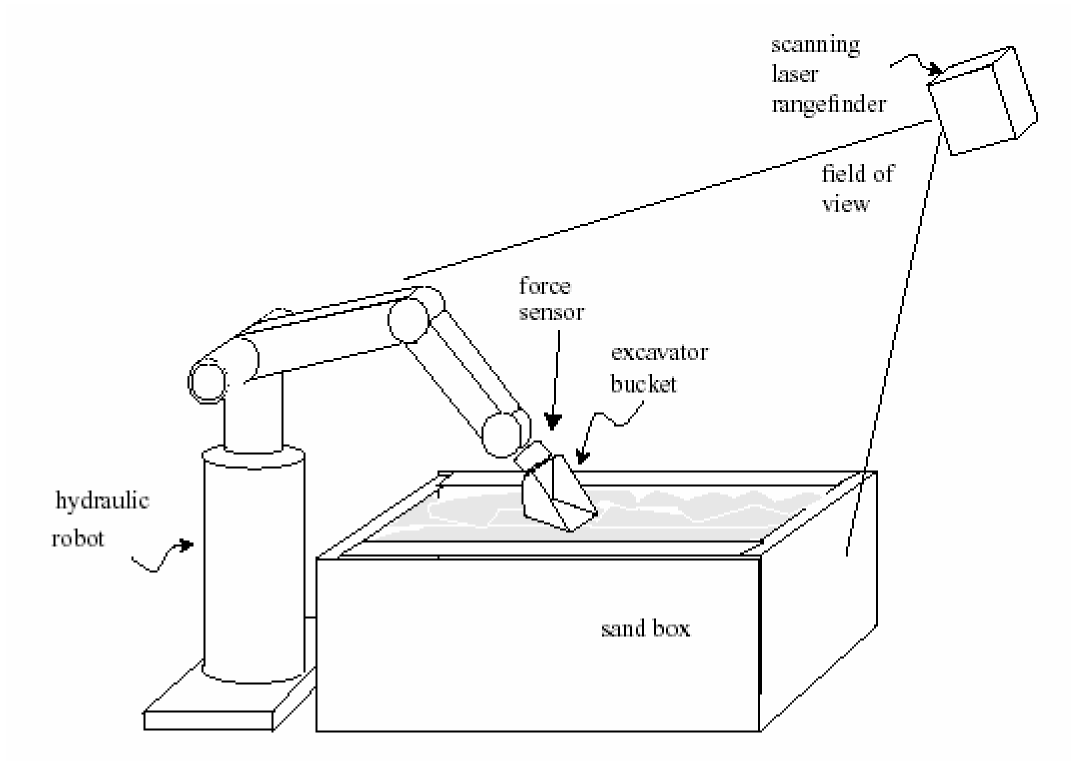


Figure 36: Excavation testbed [Singh97]

These sensors which are used to perceive the environment during the excavation work have interesting similarities to the sensors used to detect the landmines. In fact some of the excavation sensors mentioned above are almost identical with them. Therefore the idea to use the detection sensor also to support the removal work is self-evident. Some modifications of the software, filters or the bandwiths may enough to switch from detection mode to removal mode. Beside the possibility to install some of the detection modules on a removal robot there is also the opportunity of a detection robot and a removal robot working side by side simultaneously during the removal process. The detection robot can perceive the changes in the environment, monitor the progress of the excavation and transmit the obtained data to the removal robot. With this information the removal robot can plan and execute the next steps.

2.2.3.2 Removal Tools

A possible tool for the excavation of landmines could be a waterjet tool. Waterjet tools are capable of cutting even through baked clay at high speed and can remove dirt and soil at rapid rates. While waterjets are effective in removing soil there is a risk if the jets are used to flush

the soil away from the surface and to expose the mine. Some mines are very light and these can be thrown to one side by the action of a jet and recovered with dirt.
It is better to gently remove the soil from the area by using the jets only to liquefy the soil. The system (figure 37) consists of a set of three high-speed nozzles that rotate around a central suction tube. The jets fire down into the material and liquefy the soil. Concurrently a high pressure jet pump is used to remove the liquefied material (figure 38). This device has been tested for the removal of high level radioactive waste from underground storage tanks very successfully [DeHe98].

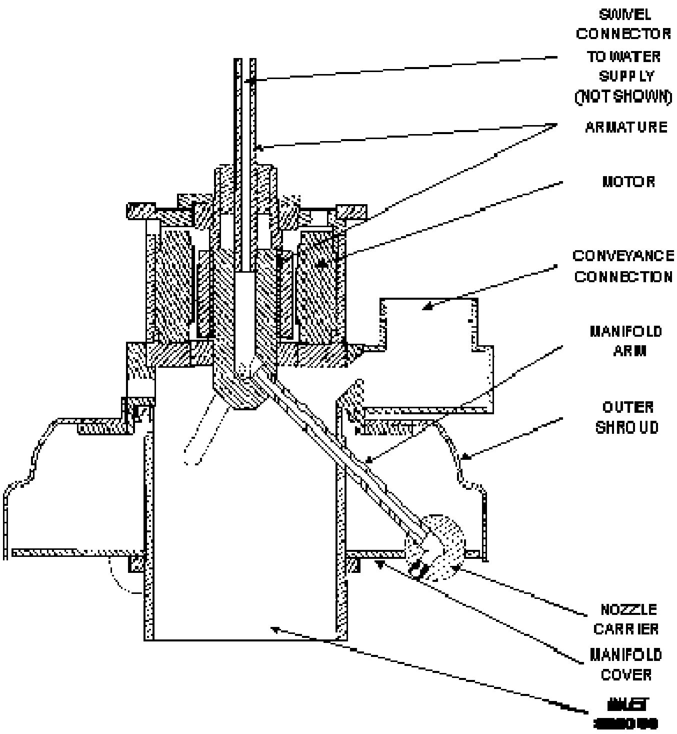


Figure 37: End effector used for removing high level waste [DeHe98]

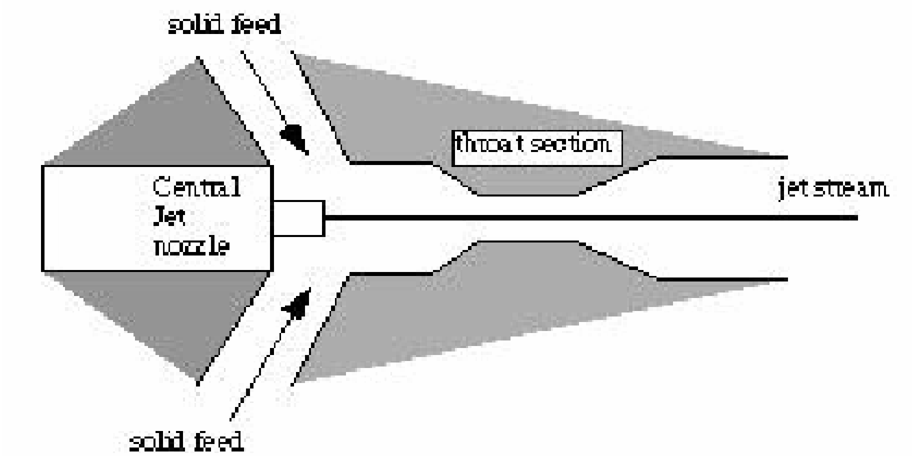


Figure 38: Schematic showing the operational mode of a jet pump [DeHe98]

In addition the waterjet can be used to neutralize the mine. This can be achieved by adding abrasive to the system which enables the jet to cut the mine into pieces. There have been a number of studies of the impact of abrasive on waterjets and the risks from sparks causing ignition [DeHe98]. Generally the level of force during cutting is relatively low which makes an ignition unlikely.

Figure 39: Inert AP mine cut by an abrasive waterjet system [DeHe98]

The AIR-SPADE Series 2000 [Airs02] is an air excavation tool. It is a very rugged and handheld durable tool that produces a ‘laser-like’ supersonic jet of air moving at approximately twice the speed of sound. The supersonic jet of air effectively penetrates and dislodges most types of soil, but is harmless to non-porous items like buried pipes or cables. Unlike the hard cutting edges of shovels, picks, digging bars, blades or buckets, only the high speed air of the jet contacts the soil.

The AIR-SPADE has been used for many different applications, among other things it has also been used by deminers and others working with unexploded ordnance.

Figure 40: AIR-SPADE Series 2000 Handtool [Airs02]

Rated Pressure	6.2 bar
Rated Flow	4.2 m^3/min
Barrel	High Strength Pultruded Fibreglass
Standard Length	Approximately 5 Ft.
Weight	6.5 lbs.
Nozzle	Machined Stainless Steel

Although the AIR-SPADE Series 2000 is a handheld tool, it is possible to adopt it for robotic application. A main problem of this technology is the need for a compressor. If the tool is installed onboard an autonomous robot, the compressor could either be installed on the robot as well, or the tool could be connected to an immobile compressor via a long hose.

Installing the compressor onboard a robot requires a pretty heavy constructed robot. The Series 200 tool is offered in a package including also a compressor.

Figure 41: VANAIR VIPER Compressor [Airs02]

Dimensions	42" X 33" X 25"
Weight	Approximately 500 lbs.

Considering the weight of the compressor it is probably better to use an immobile compressor. But this solution restricts the sphere of the robots’ action depending on the length of the hose. Being aware of the possibility to partition minefields and demine it part by part, this restriction is to tolerate.

The Shovel-shaped Gripper [HiKa02] is not a high specialized tool. But after all it was purely designed for demining applications. The developers argue that after detection of a mine two functions, digging and handling, are required. Thus the gripper has a pair of spade-shaped fingers.

Figure 42: Shovel-shaped gripper [HiKa02]

2.2.3.3 Tool changing systems

The variety of possible tools used for removal actions makes a tool changing system onboard a removal robot necessary. The system should be actuated by the same principle as the tools are actuated. That implies that a whole set of excavation tools should be actuated by the same principle. Employing more sophisticated removal tools like the presented waterjet system returns some problems for the use of only one robot arm. In that case the end effector has to be supplied with more than the standard tools need. The water supply of this device is generally a problem in mobile robotics. A simple solution could be the use of different removal robots, one type of robot unvarying equipped with such sophisticated removal devices and a general type of removal robot equipped with standard tools and a tool changing system. However, a tool changing system always requires an appropriate magazine for the tools. In outdoor applications it is important that the tool magazine protects sensible parts of the tools against dirt. Especially the interfaces for power and information supply should be kept clean to ensure a proper passing on when the tools are used. Therefore the magazine should be sealed off against the environment someway.

A RISTEC tool changer is shown below.

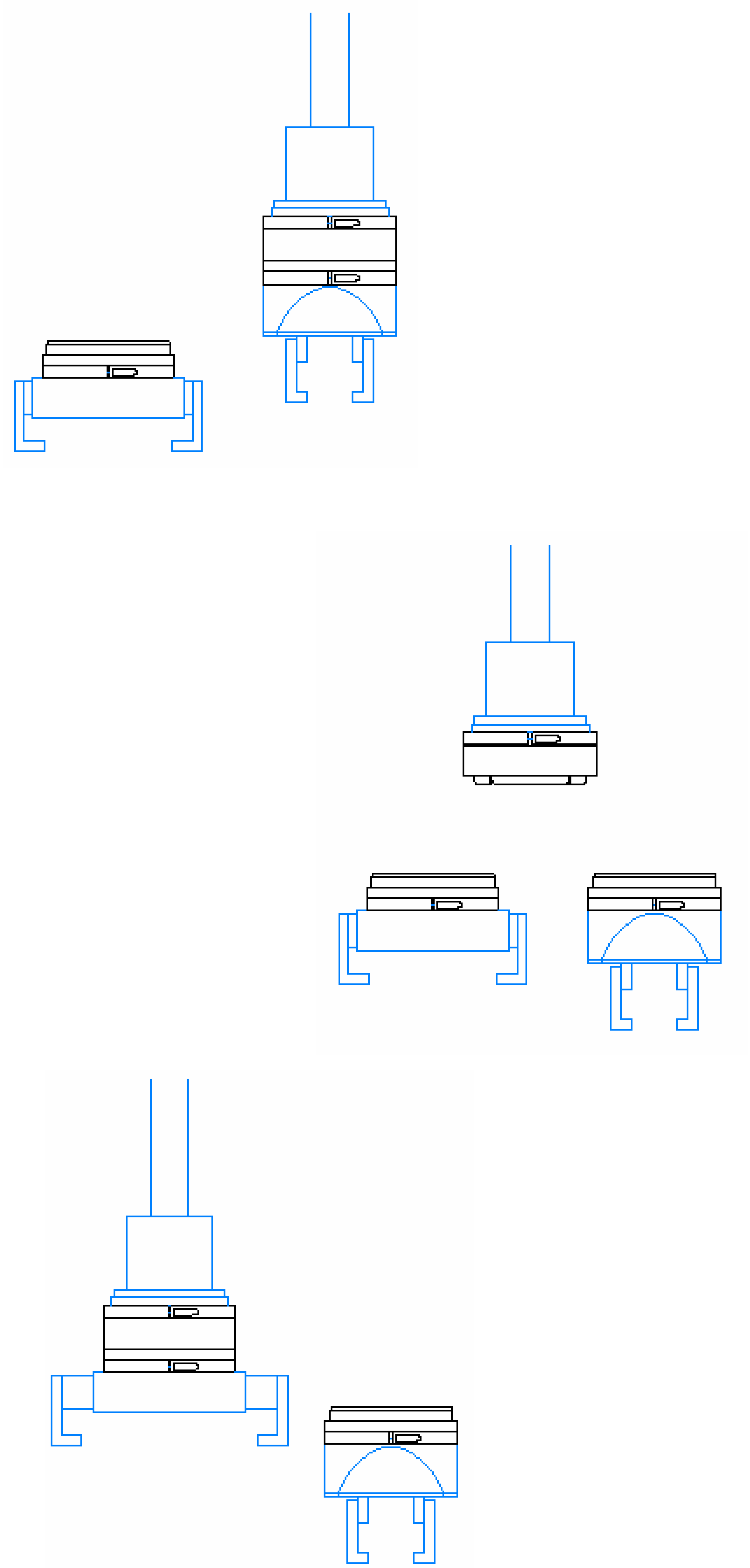


Figure 43: Tool changing system [Rist02]

- One half of the tool changer, known as the ‘robot module’, is attached to the robot.
- The other half, known as the ‘tool module’, is attached to the tooling, for every single tool one tool module is needed.
- When the robot module has brought into contact with the appropriate tool module, a signal is sent to the controller and the two modules are locked together by the use of air pressure.
- When the robot has finished using a particular tool, it sends another signal and the two modules are unlocked using air pressure, allowing the robot to go pick up the next module.

The tool changing system is completed by mounting modules. They make possible to connect RISTEC products to robots and tooling and consist of

- Adaptor plates specialized for nearly every SCARA robot on the market.
- Blank adaptor plates which can be customized for the users tooling.
- Clamp collar kits which hold it all together.

Another tool changer is offered by ATI Industrial Automation. Essentially, there is a master plate that is attached to the robot with an interface plate. The tool plate is then attached to the master plate. The attachment of the master plate and the tool plate is done via an air-actuated mechanism. The patented ball-locking device keeps the two plates together. Should there be a sudden loss of air pressure, there is a fail-safe mechanism that keeps the plates together.

Underneath the locking mechanism of the ATI quick changer is depictured [Atii02].

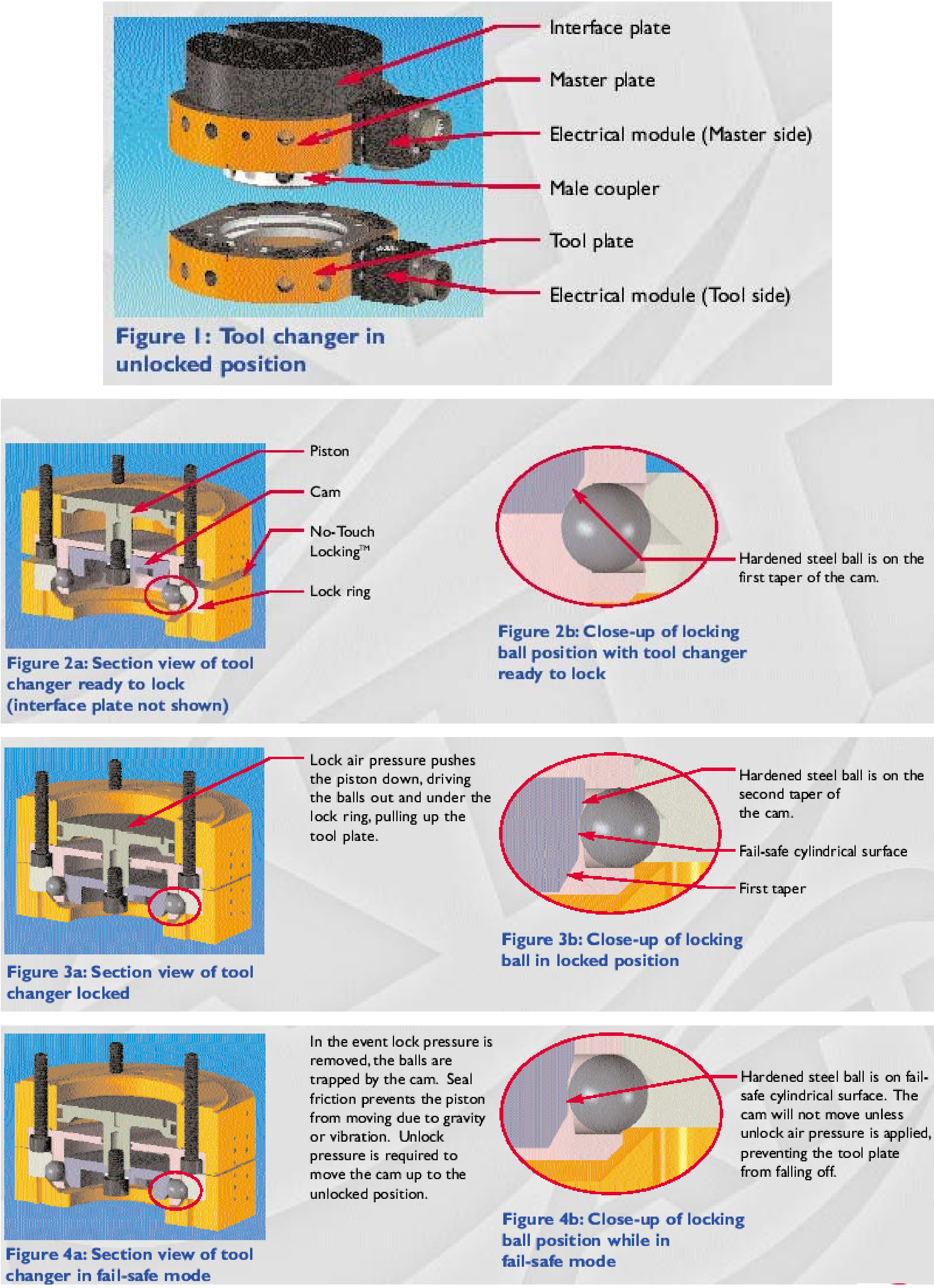


Figure 44: Tool changing system [Atii02]

Tool changer are designed with regard to

- Fail-safe Locking

  A fail-safe locking mechanism must keep the tool plate locked to the master plate in the event of pneumatic pressure loss.
- High Rigidity

  The mechanism must have a high moment capacity, in order not to rock during high-inertia moves, preventing locking failure and repeatability problems.
- Repeatability

  It must be designed for aligning master and tool with remarkable repeatability.
- Simplicity

  Simple interface plate design allows for easy robot mounting.

These tool changers are available in many different sizes and are designed for different payloads. Although they are intended for industrial applications they can be used for mobile robots as well.

2.2.4 Transportation Robots

The transportation seems to be quite simpler than the removal of a landmine. Basically the robot has to pick up the landmine, store it somewhere during the transportation and deliver it at the collection point.

An important decision in respect of the transportation robots is the number of mines the robots should be able to carry. Carrying only one mine would it make possible to use a rather simple robot. At the best it may possible to retrench the storing place for the landmine. The robot could pick up the mine with a gripper, lift it up somewhat above the ground and transport it to the collection area while holding it tight with the gripper. The use of a dexterous robot arm, like that one for the removal task, would be disproportionate. A simple 2 DOF lift onboard the mobile robot platform could be sufficient.

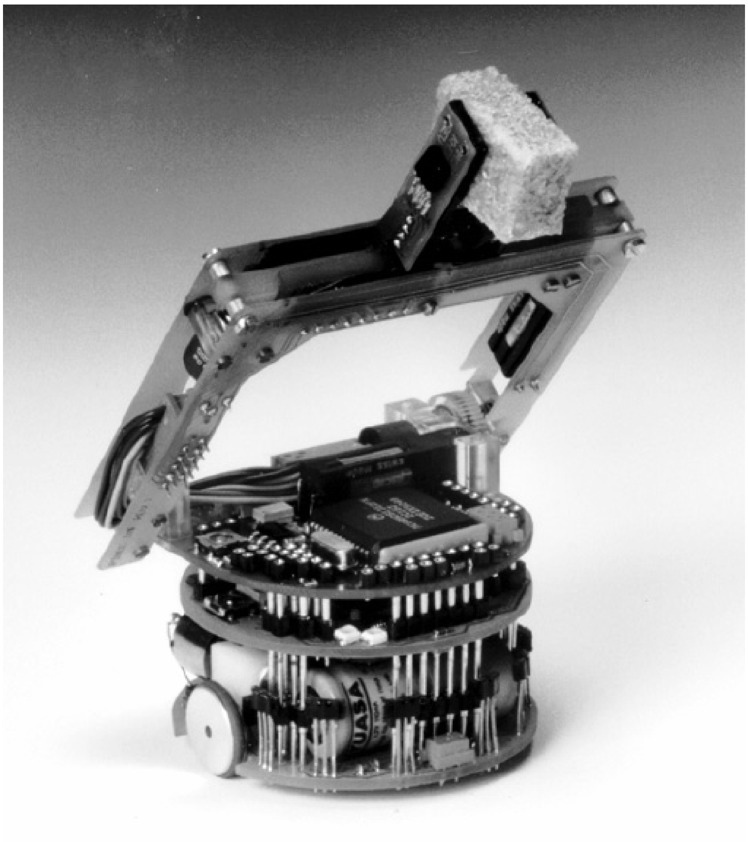


Figure 45: A gripper module with two degrees of freedom [NoPa95]

But the application of a transportation robot with the ability to carry more than one mine is in a manner useful too. Since transportation robots are likely to be rather slow this approach is much more timesaving. The volume of saved time depends on the amount and distribution of collection areas in proportion to the field of activity as well. But establishing lesser collection areas simplifies the further strategy for the disposal of the collected landmines. To give the robot the ability to transport more than one mine it must be equipped with some sort of storage device.

On principle it would be of use to make the storage device of protective material to mitigate accidentally explosions. One possibility is to use a lockable storage device. But therefore the device must be designed with regard to a maximal allowed load of explosives. An explosion inside a locked container exceeding the maximal allowed load may be worse than without any protective measures. Fragments of the blasting container could damage the robot in addition. For this reason it would be better to use a container which is opened upwards. This guarantees a way out for the blast wave in case of an accidental explosion.

The placement of the mines inside the storage device is of special interest. Storing the mines one upon the other increases the danger of the explosion of a mine during the transportation process. Contrarily storing the mines side by side presupposes a large base of the storage device. Furthermore the design of the storage device and the placement of mines inside should guarantee a simple load and unload process. A safe and space-saving storage device should not be installed at the cost of the lifting device. If for the loading and unloading a highly dexterous robot arm and a sophisticated end-effector are needed, it might be better to reduce the complexity of the storage device.

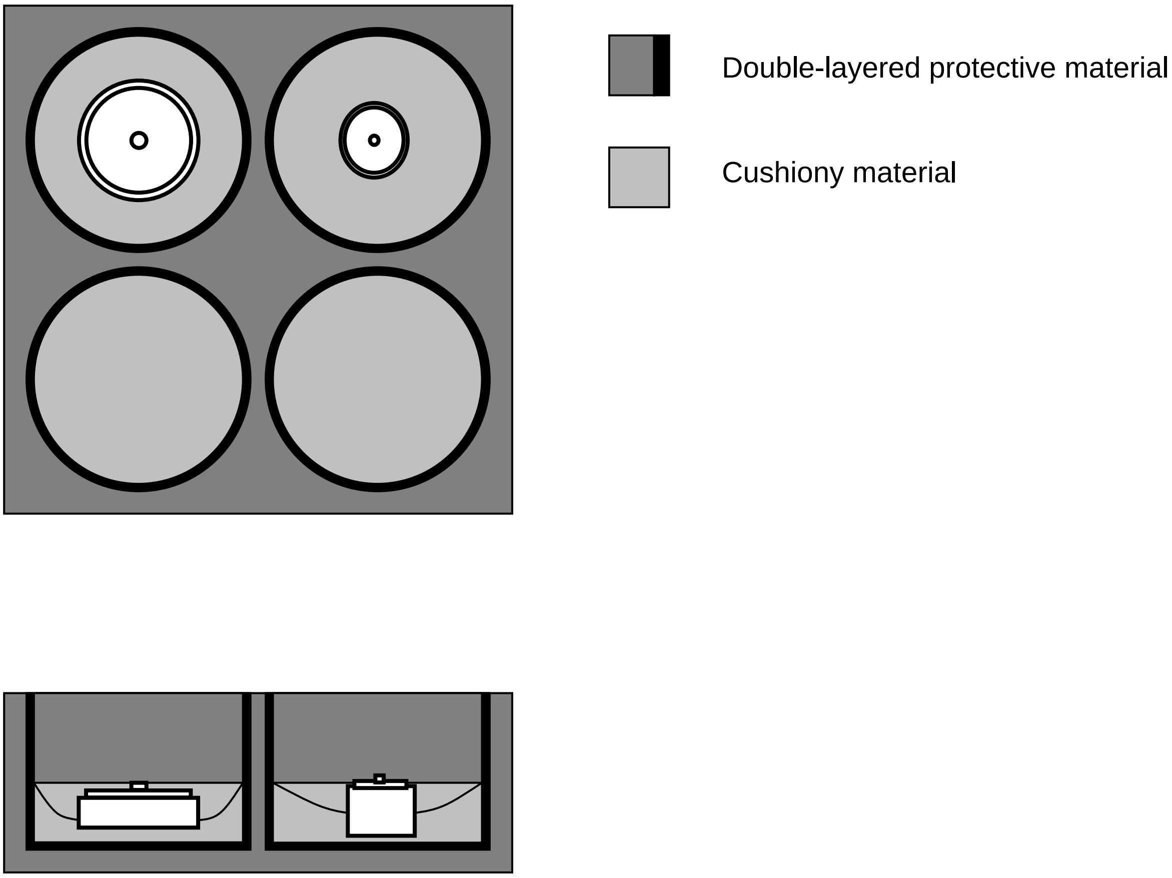


Figure 46: Scheme of a storage device for landmine transportation

Features

- Separate storage of each single landmine avoids a detonation of the full loading in case of an accidental explosion of one mine.
- Mines are transported in a horizontal position face upward. Since the explosion of nearly all landmines is directed upwards the main force of the blast wave can leave the container upwards, away from the robot carrying the storage device and vulnerable objects.
- Furthermore the container consists of a hard inner cylinder with good ballistic properties and an energy-absorbing outer material. This combination captures fragments and redirects the blast upwards.
- Mines are embedded in a soft material to guarantee a cushioned transportation. In addition the flexibility of the material allows simple and safe storage of various shaped mines.
- The construction of the device is simple and allows simple loading and unloading by a SCARA robot structure.

The storage device shown below stores the mines one upon the other. This time springs and flexible bands are used to fix the mines position.

Compared to the first storage device:

- The mines are not cushioned in vertical direction. This can be compensated by cushion the whole storage device against the robot.
- In case of an explosion of the bottom mine the other mines get in the way of the blast wave.
- The storage device must be locked which complicates the loading and unloading. Furthermore a locked container is a security risk when the explosion exceeds a certain extent.
- The edgewise loading and unloading is much more complicated and requires a more flexible robot arm.

In return the one-upon-the-other-storage of the mines saves place.

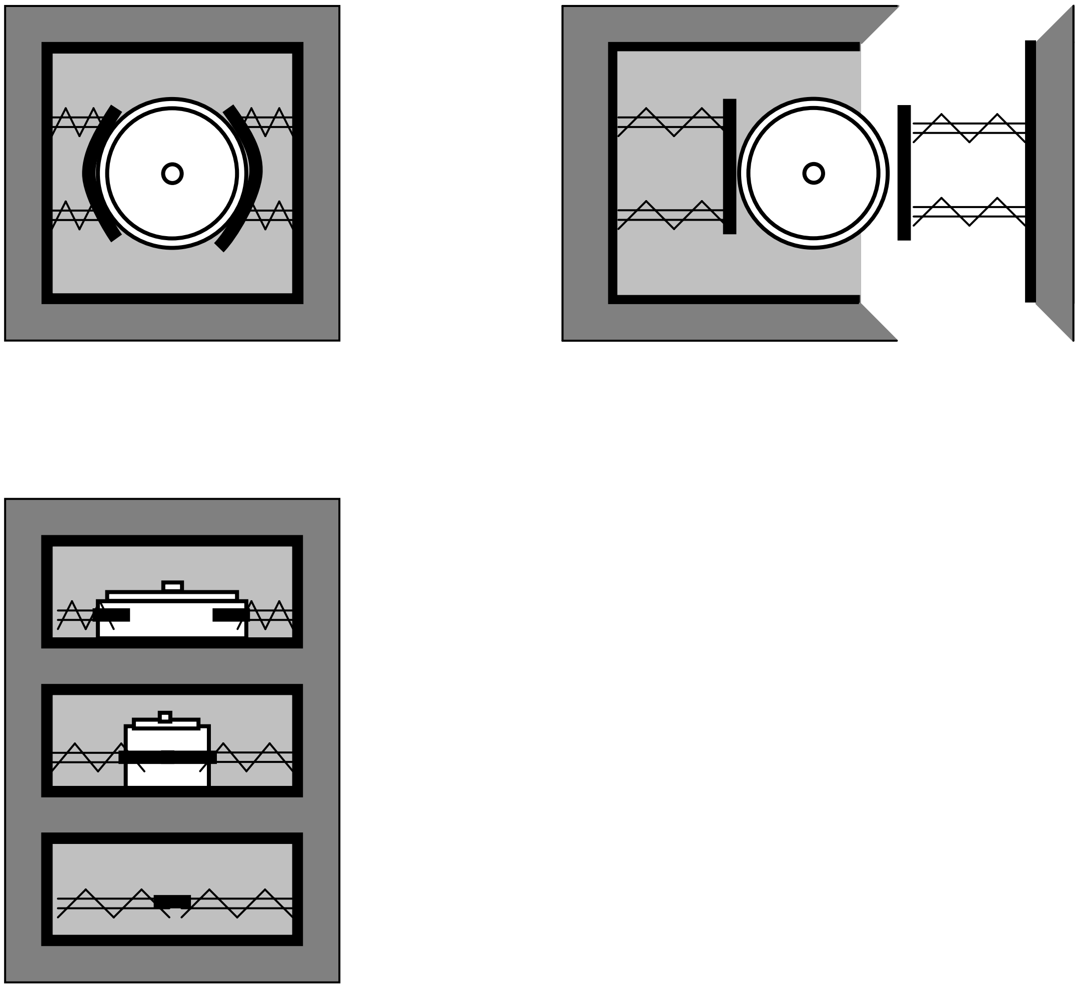


Figure 47: Scheme of a storage device for landmine transportation

An important factor for the decision of using single or multi transport robots is the density of the minefield. If there are only few landmines per surface unit, the application of single-mine transportation robots will be more likely. In this case the work quota of the detection robots is much higher compared to that of the removal and transportation robots. Therefore raising the working capacity of the transportation robots would not increase the overall efficiency perceptible.

2.2.5 Inventory of the ‘Tool Kit’

Each robot used for demining has to be assembled by using the modules of the ‘Tool Kit’. The goal of inventory design is to create the smallest inventory of modules that can be assembled into the largest diversity of robots. Although the task of humanitarian demining is clearly defined (i.e. detection, removal and transportation), you can never tell whether some tasks emerge which can not be foreseen. Because unforeseen problems should be solved with available resources, one of the design specifications should be adaptability. Therefore in inventory design, the level of modularity is important. A low-level inventory would contain very basic elements such motors, gears, bearings and nuts and bolts. A high-level inventory would contain complex elements such as limbs or arms. A low-level inventory offers more flexibility in the variety of robots to assemble. But the assembling is more sophisticated. Conversely a high-level inventory allows fewer robots but the assembly is simplified.

The review in the chapter ‘Modularization of Mobile Robot’ outlines definitely a concept based on high-level inventory. Robot arms for example appear as single modules. But that does not imply that a robot tool kit for humanitarian demining must categorical consist of high-level inventory.

When it comes to the realization of such a tool kit many different factors have to be considered and many decisions have to be made before even starting with the design. The decision about the level of modularity will depend on cost factors, technical feasibility, variety of performable tasks and many other things. The highest level of modularization would be the use of robots made from identical modules. These robots are in a prime state of development and their abilities have only been demonstrated to a less degree.

But apart from this it is absolutely imaginable to include in a tool kit translatorial and rotational modules which can be assembled to different robot structures (e.g. articulated, Cartesian, spherical, cylindrical, SCARA …) which can be attached to the mobile robot platform.

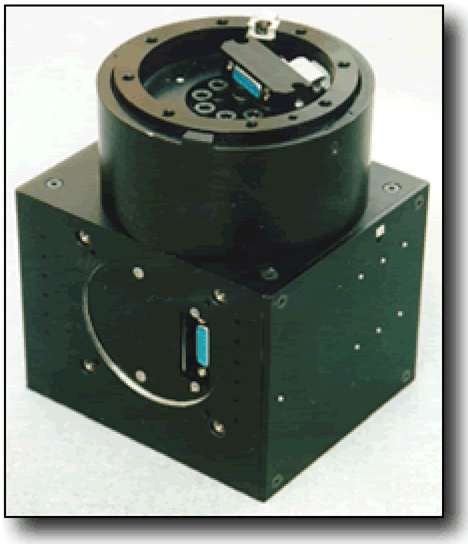


Figure 48: Example of a joint module [Esi02]

Such modules like in figure 48 are normally composed of a motor, precision reduction gear, position encoder, brake, motor amplifier, limit switches, on-board computer controller, and internal cabling. The fabrication of such modules should not be, in case of a reasonably number of pieces, too costly. This is quite important because the robot arm for removal actions is likely to be one of the most endangered parts to be damaged by an explosion.
Beside these actuation modules there is also need for kinematic modules. They are used to alter the dimension of the robot which means to change the distance between the robots joints. This greatly affects the capability of the robot in terms of strength, reach and accuracy.
If the tool kit consists of several actuation modules of different sizes there are also adapter modules required to link modules with differential interface sizes.

Figure 49: Scheme of an assembled robot structure [FaZh01]

2.2.6 Module Interface

To build functional robots each module must be capable of interfacing with all other modules. The interface can be broken into three categories:

- Mechanical Interface
- Power Interface
- Information Interface

It is necessary that the modules can be easily connected with each other to make the robots reconfigurable. This quality of the modules also reduces the maintenance effort and simplifies the exchange of defect modules. A quick-coupling mechanism with which a secure mechanical connection between modules can be achieved would be an excellent solution. At the same time the mechanical connection is made, power and information connection should also be made. There are many possible solutions for this problem. The following picture shows one of them.

Figure 50: A quick-coupling connector [PaBr96]

The transmission of power between modules depends on the power source. If pneumatic and/or hydraulic actuators are used an electrical bus for transmitting electrical power will not be sufficient. Especially for heavier tasks like the excavation of landmines hydraulic actuators may be used. Considering for example a simple translatorial or rotational module used for a robot arm it could be necessary only to link up the end effector with the hydraulic powering aggregate.

The necessary information transfer between modules can be done using electrical or optical connections. Information transfer can occur in many ways. Each module will need its own processor to handle communication between modules and local control (e.g. position joint control).

2.2.7 Software Architecture

Robotic software can be broadly categorized into two major levels. The first is the actuator control software. The second level is system control software. There are three levels within the system control software level.

The top-most layer of a robotic software system is the robot programming language. This layer provides the man-machine interface for human intervention. In this layer, programs written in the robot programming language are converted into appropriate commands for the middle layer. These commands are then translated into actuator position, velocity and torque commands by the middle layer and that are then sent to the lowest layer.

The middle layer is the operational software layer and it focuses on the intelligent control algorithms that include generalized kinematics, dynamics, fault-tolerance, and decision-making. Advanced robots are, unlike monolithic industrial robots, based on modularity, redundancy, fault-tolerance, condition-based maintenance, and performance. The operational software layer for these robots should be general and reconfigurable, and should support kinematics, dynamics, deflection modelling, performance criteria, fault-tolerance, and condition-based maintenance.

The third layer is the hardware-interfacing layer. The purpose of this layer is to interface with the servo control software, peripheral devices, and communication buses. Real-time constraints on this layer are the most stringent because it interacts with the external hardware. A parallel software execution environment is best suited for this layer. This is because the software in this layer has to handle multiple asynchronous events (both external and internal) in real-time (less than 1 millisecond).

2.2.7.1 Software Architecture Requirements

Software architecture is defined by the demands placed on it. As mentioned above the development of software architecture for modular robots focus on the operational layer. Design requirements for a software architecture that exhibits modularity, flexibility, redundancy, and fault-tolerance are [KaCe98]:

- Open System: An open system is one that allows user modification, extensibility, and integration with other systems.
- Reusable: The software must have a clear interface that gives the components a black-box 'look-and-feel.' Furthermore the user should be able to selectively modify, add, or constrain the functionality of a component.
- Application Independence: The software should be developed without any specific application in mind. This will lead to an architecture that is not biased towards a specific application.
- General: The software architecture should make no assumptions that limit the future integration of any conceivable manipulator.
- The architecture should be equally applicable to simulation and real-time control. This feature allows for algorithm testing in simulation before use on physical hardware. The user of the architecture should be able to test any extensions or modifications to the software before controlling a physical robot.

2.2.7.2 Architecture Development Process

There are two predominant software design methodologies. These are structured design and object-oriented design (OOD). Structured design is based on data-flow, where data flows from one subroutine (or procedure) to another, thereby undergoing transformations. In this design philosophy, data and instructions are kept separate. OOD allows the building of software as components with standardized interfaces and reuse capability. Reuse is a result of the generality and extensibility of these components. Extensibility is achieved in two ways. Specialization allows for the customization of an existing component by extending, constraining, or even changing the object without modifying the already existing code. This is also called inheritance. The second means of extensibility is through containment. In this, a set of components can be combined together to form a new component. Over structured design, OOD offers the advantages of modularity, reusability, and standardized interfaces. Due to these advantages, OOD is better suited to meet the defined design requirements mentioned

3 Robot Swarms

Worldwide scientific research is actually done to use so-called “robot swarms”. The appliance of these research efforts is not only limited to demining actions. Robot swarms are promising to improve the capacity of robotic application in different areas where robots are already used today.

Figure 51: Robot swarm [MaEa02]

Considering robot swarms leads to two possibilities:

1. Using mobile intelligent robots equipped with devices for mine detection, for mine removing and for transportation to a collecting point.
2. Using three swarms of robots equipped either with detection devices or removing devices or transportation facilities.

There are several reasons to decide for the second possibility.

Using different robots for different tasks reduces the weight of the robots working in the minefield. Therefore it is much easier to design robots which are light enough not to cause an explosion while crossing over a mine. If such an accident does happen after all the damage is not as bad as a robot equipped with devices for all three tasks would be affected.

As mentioned before the use of modular robots is perfect for the design of task-specific demining robots because of the similarities between the tasks.

Since the complexity of a system raises the susceptibility to trouble exponential, it is always better to keep devices as simple as possible and therefore the better choice is using simpler robots.
Using smaller robots extends the operational time before re-fueling or re-charging is necessary or at least prevents the use of bulky and heavy batteries or tanks.

But it should be noted that a decision for the second possibility means an increased effort in communication between the robots in the swarm. If every robot is able to perform the whole demining process by itself, the communication will be reduced making them not to disturb each other at all and ensure to cover all the area. However the task-specific robots have to exchange a lot more of data. The detection robots must work together since they are equipped with different detection technologies. When they have found a mine they must signal it to the removal robots and they have to inform after done work the transportation robots.
Using robot swarms for demining actions is similar to ‘Multi Agent Systems – MAS’. These systems are very well known in software engineering since more than twenty years. In the last years there are more and more works related to the application in robotics.

The characteristics of MAS are that [Syca02]

- each agent has incomplete information or capabilities for solving the problem and, thus, has a limited viewpoint
- there is no system global control
- data are decentralized
- computation is asynchronous

MAS consist of a number of intelligent, co-operative and communicative hardware agents getting a common task. Because of the intelligence they are able to divide the task in subtasks as long as at least one agent is able to fulfil one subtask. Repeating this procedure yields to the solution of the common task. Newest research leads to MMAS - Multiple Multi Agent Systems – different MAS are involved for the solution of a complex task.

This brief overview points out the similarities of MAS and humanitarian demining with the aid of robot swarms. Therefore the performed work in the field of MAS could be of great use for the establishment of such robot swarms.

3.1 Control Paradigms

In scientific papers are various approaches and denotations to subdivide control strategies for autonomous mobile robots in different types. In principal there are two fundamental ideas, the functional approach and behaviour based robotics.

In the functional approach the control system senses the environment through sensors, constructs an internal model of the environment, computes plans to fulfil its tasks, and acts on them. This is the so-called 'sense-think-act' cycle. The crux of this approach is the internal world model, which is ideally a true representation of the real world. However, modelling of the real world is difficult due to problems such as the dynamic nature of the real world, limitations of the sensors and so on. Another problem of the functional approach is constituted by the fact that it is extremely brittle. If any module failed, then the whole system would fail.

In behaviour based robotics this problem is avoided by using a parallel structure of control system, rather than a serial one. Here, the overall control task is decomposed into task-achieving behaviours which operate in parallel. Each behaviour module implement a complete and functional robot behaviour, rather than one single aspect of an overall control task, and has immediate access to sensors and actuators. The fundamental idea is that task-achieving behaviours operate independently of one another, and that the overall behaviour of the robot emerges through this concurrent operation. Although the system is more flexible and robust, this approach lacks performing complex tasks. A behaviour-based robot responds directly to sensory stimuli, it has no internal state memory and is therefore unable to follow externally specified sequences of actions.

Both of these approaches have advantages and limitations. Therefore most of the used control systems are a mix of them. Surely in each combination one of the two approaches is in some measure dominant. These combinations are usually called *hybrid* strategies. They separate the control system in two or more communicating but independent components. The lower levels are behaviour based while higher levels follow the functional approach. The goal is to provide quick responses in a dynamic environment while having the ability to plan and perform complex tasks.

Such a hybrid strategy seems to be practical for demining applications. The navigation of robots in a minefield is a task to be controlled by a behaviour based strategy. Obstacle avoidance for example is mainly a response to sensor perception, without engaging complex strategies. On the other hand the removal of landmine is a complex sequence of actions. It is hardly possible to solve this task without any predefined strategy.

Most likely the control strategy of detection robots is behaviour based dominated. Detection robots have to execute the most rudimentary tasks. They are mainly engaged in navigational tasks such as obstacle avoidance, holding a formation or trajectory following. Removal and transportation robots have to solve navigational tasks as well. But they have to solve some additional complex tasks. The removal process or the loading of a mine into a storage device are complex tasks which need planning.

3.2 Navigation

For a mobile agent, the ability to navigate is one of the most important capabilities of all. Staying operational, i.e. avoiding dangerous situations such as collisions, and staying within safe operating conditions (temperature, radiation, etc.) come first, but if any tasks are to be performed that relate to specific places in the agent's environment, navigation is a must.

Navigation can be defined as the combination of the three fundamental competences:

1. Self-localisation;
2. Path planning;
3. Map-building and map-interpretation.

Map in this context denotes any one-to-one mapping of the world onto an internal representation. This representation does not necessarily look like a map one can buy in the shop. In fact in robots it often takes the form of artificial neural network excitation patterns. Localisation denotes the agent's competence to establish its own position within a frame of reference. Path planning is effectively an extension of localisation, in that it requires the determination of the agent's current position and the position of a goal location, both within the same frame of reference. Map-building not only covers maps of the common known type, i.e. metric maps of the environment, but any notation describing locations within the frame of reference. The map charts explored territory within this frame of reference. Finally, to use a map, the ability to interpret the map is needed.

All navigation has to be anchored in some frame of reference. Navigation is always relative to this fixed frame of reference. Dead reckoning strategies estimate the agent's direction of travel and speed, and integrate the agent's movement over time, starting from a known location. Dead reckoning navigation systems are relative easy to implement, easy to interpret, and easy to use. They suffer, however, from the problem of incorrigible drift error, which is a serious problem for all but short range navigation tasks. For a dead reckoning system to work the robot has to measure its movement precisely – but this is impossible, owing to problems like wheel slippage, i.e. a movement that occurs to the frame of reference, but not in it. The robot can only measure it moves via internal measurements and is therefore unable to detect changes to the entire frame of reference. Navigation has to be achieved within the real world, however, not within the frame of reference, and therefore those drift problems, the drifting apart of frame of reference and position in the world, are a serious impediment.

The alternative to dead reckoning is landmark-based navigation, which is based on exteroception, i.e. the agent's perception of the environment. This strategy relies on the detection of unique features in the world – landmarks. Navigation with respect to external landmarks is referred to as piloting. The required course to a goal location is not determined trough path integration, as in dead reckoning, but through identifying landmarks or sequences of landmarks, and either following these landmarks in a specific order, or recalling the required compass direction from a recognised landmark, based on previous experience. Drift error is no problem here, but if the environment contains few perceptually unique clues, or confusing information, the performance of such systems will deteriorate. Landmarks are location-dependent perceptual features of the environment that can be detected by the navigator. They are not restricted to a physical body. Examples are the position of the sun, the direction of the wind or sound emanating from a specific direction. In order to fulfil its purpose as a guide to navigation, a landmark must be visible from various positions and recognisable under different lighting conditions, viewing angles, etc. If a landmark is not stationary, its motion must be known to the navigation mechanism. These requirements are rather high and not many things are employable as landmark. Another problem is that the assumption of unique perceptual signatures does not hold in many cases. Often there are many locations that look alike and the agent has problems to differentiate.

Each navigation principle alone is it dead reckoning or landmark-based navigation, has peculiar strengths and weaknesses, and only through the combination of systems the drawbacks of each system, while retaining their strengths, can be overcome.

Navigation for demining robots has some specialities. At first the main navigational task during the demining process should be considered.

- The robots have to move in a given area and must not leave it.
- Throughout the fulfilment of the whole task the robots have to avoid collisions with obstacles and other robots and they have to avoid all places where mines are already detected or expected.
- The detection robots have to search the whole area. To ensure that all mines are found no uncovered areas have to be left behind.

For demining actions the robots have to move only in a relatively small area. Most of the research work especially for outdoor robot navigation is related to wide area applications. Therefore at demining the navigational demands are at least in that case simplified. Considering dead reckoning strategies, unavoidable drift errors are because of the briefness of the travelled way not as bad. On the other hand it should not be forgotten that the movement inside the demining area has to be comparatively precisely. It is only a matter of centimetres if a robot bypasses a mine or causes an explosion. This geographical limitation is also an advantage for the use of landmark-based navigation. Normally a major problem for the practical application of this navigation strategy is the difficulty to find and perceive unambiguous landmarks. But for demining applications it would be no problem to use artificial landmarks. Artificial landmarks can be specially designed to ensure unique perception through the robots. And they can be easily placed from human operators since the operational area is known in advance. Considering a given minefield there is always the possibility to partition it with regard to optimal navigational and organisational conditions.

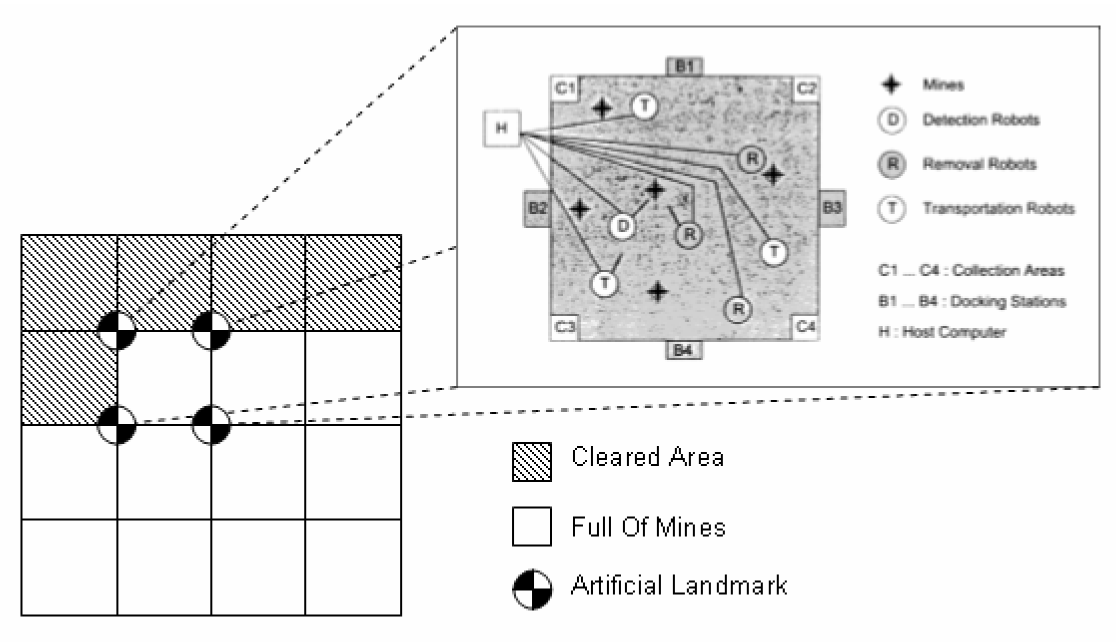


Figure 52: Partition of a minefield

3.2.1 Outdoor Navigation

Three main problems facing outdoor autonomous mobile robot navigation are:

- unstructured environment
- moving obstacles
- multiple sensors

Most autonomous mobile robots are designed to operate strictly in a linearly structured indoor environment with predominantly straight-line image features, with no obvious extension to an unstructured (lacking simple geometric shape or visual features) outdoor environment. Indoor environments exhibit a high degree of deterministic linear and non-linear visual features, providing robots with good structure and organization for image processing tasks. Outdoor environments tend to be unstructured and defeat computer vision solutions developed for the former. Only recently people have started to experiment with methods for autonomous navigation in outdoor environments. There are already practical solutions like a memory-based object recognition algorithm which requires a training phase where precise multiple views of each object must be stored in a database [Sing97].

Demining actions take place in outdoor environment. Therefore the problem of unstructured environment is of concern for demining. But demining robots never work in completely unknown environment. At least it is always known in which kind of terrain the robots will work and so there is the possibility to make some preparations to improve the performance. If the conditions in the minefield make an application impossible it has to be prepared. Today there are special designed vegetation cutters in use to prepare minefields before the real demining process is started. Perhaps it would be useful for robotic applications not only to cut vegetation but also to remove obstacles and prepare the minefield in regard to optimal work conditions.

Another source of uncertainty in mobile robot navigation is the presence of moving obstacles. Path planning refers to generating a route from one location in the environment to another, and path planning algorithm attempt to generate a collision free motion trajectory for the robot over a time period. One possible solution is to predict the movement of all obstacles and generate with this information a route which is collision-free. This approach is extremely constrained by the precise demand of prior knowledge about all obstacle motions and trajectories. A second group of approaches has been proposed to deal with unexpected obstacles and unknown trajectories. This approach, commonly called collision avoidance or collision detection, is based on reactive navigation. The robot reacts to obstacles which enter its surrounding by generating a new course to avoid a collision. The collision avoidance system can simply move the robot away of any appearing obstacle or, in a more sophisticated system, it can use long range sensors to predict the trajectories of obstacles and react appropriate.

In minefields it is extremely unlikely to encounter other moving obstacles than demining robots. Therefore it is dispensable to use sophisticated sensors and prediction algorithm to avoid collisions. If the robots can communicate with each other it should be possible to coordinate their movement.

Conflicts and inconsistencies between multiple sensors on the robot lead to uncertainty in the mobile robot navigation as well. Autonomous robots rely on numerous sensors to obtain a consistent and coherent view of the current world state. This inherently introduces uncertainties as different sensors may react differently to the same stimuli, or may provide incorrect or inconsistent data. These sensors discrepancies have to be handled in some framework to allow the robot to visualize a unified view of its environment. The sensor fusion literature can be broadly categorized into two main approaches:

- statistical fusion techniques
- probabilistic fusion techniques

Statistical fusion techniques are based on least-squares approximation methods. Least squares estimation is used for predicting the values of non-random variables in the system and makes no explicit assumptions about the probabilities involved in the process.

Probabilistic techniques like the Bayesian estimation use the sensor data from the individual sensors as inputs and a unified map representation as the single output. The weight of each sensor signal is calculated by using probabilities dependent on conditions under which the input was sensed.

Sensor fusion also concerns mine detection technologies. As mentioned before there is no current or emerging sensor technology which is universal able to detect mines. Therefore teamwork between different sensors is required. The theory of sensor fusion for detection technologies is the same as for navigation sensors.

Figure 53 shows a piece of ground containing a buried mine, together with a tin can, and bottle top, a rock and a piece of plastic. The three histograms show the metal detector, radar and chemical signals from each object. Only the mine returns a significant combination of positive signals from all three techniques.

Figure 54 shows from left to right, an area of ground containing several mines examined by (i) a metal detector, (ii) ground penetrating radar, (iii) the joint product probability, and (iv) the Bayes probability. In all cases the grey scale level indicates the probability with dark corresponding to low, white to high.

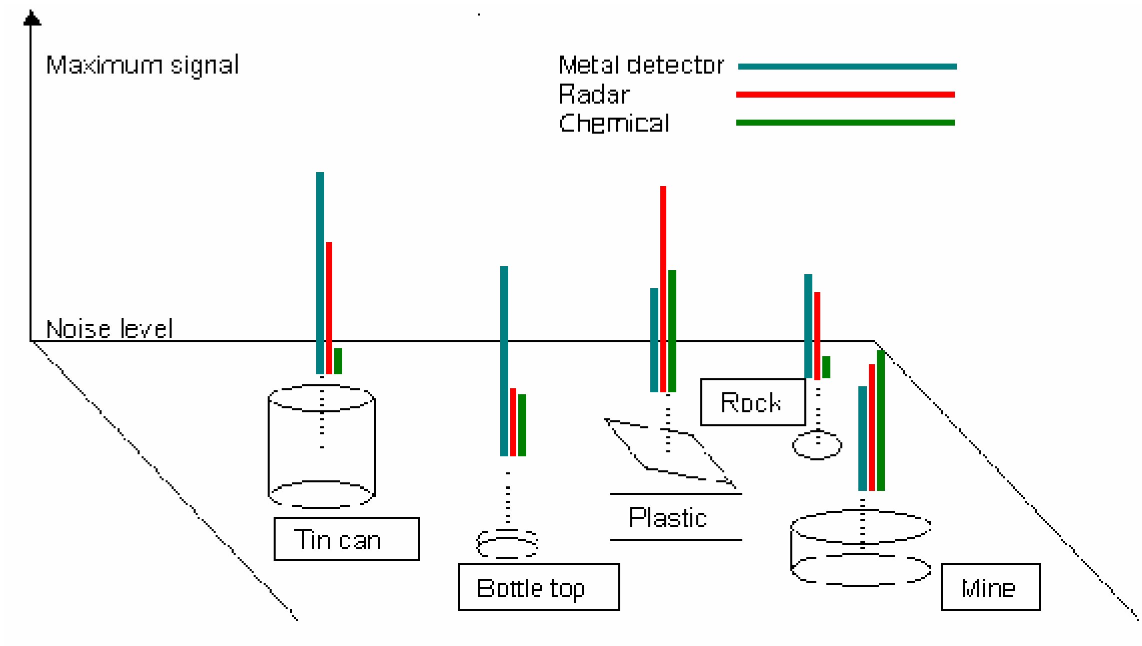


Figure 53: Sensor fusion for mine detection [WiCa99]

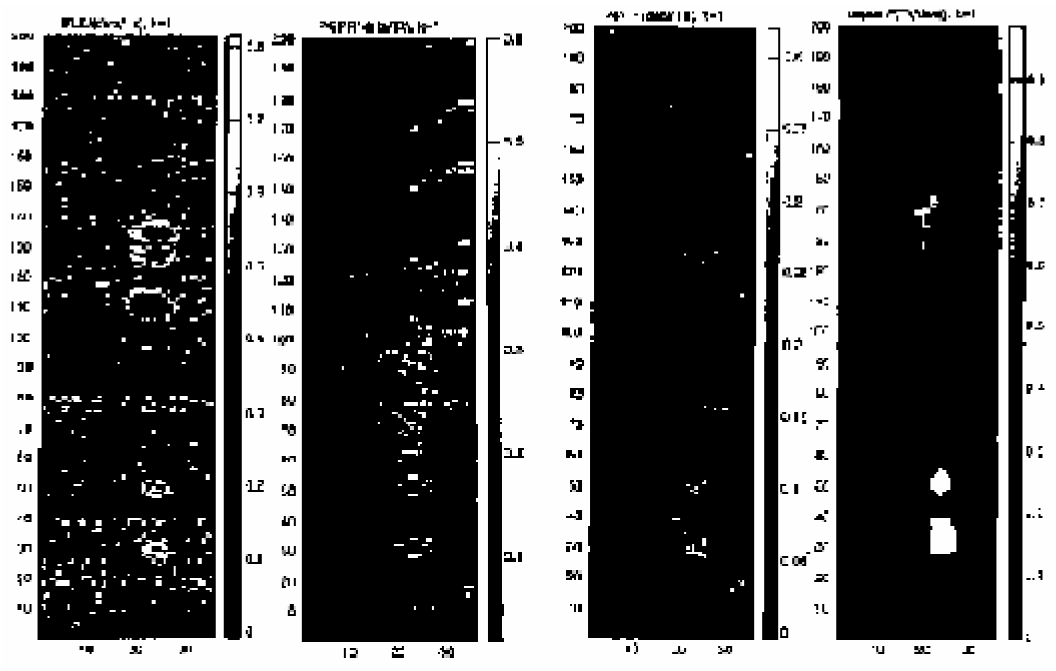


Figure 54: Bayes estimation of a minefield [WiCa99]

3.2.2 Global Positioning System – GPS

Many attempts for mobile robot navigation systems do not use GPS because of the limited applicability to indoor solutions. But this deficiency can be ignored completely for demining applications.

Mainly GPS is used to determinate the actual position of a mobile robot. This is one of the three fundamental concepts (mentioned some chapters before) in navigation for mobile robots. Beside this, GPS is very valuable for the detection process of the landmines. The detection of landmines has to be performed in a way that ensures that no uncovered areas are left behind. Independent whether a single robot or a robot swarm is used for detecting, the robots have to know which areas are already scanned and which not. With a GPS system systematic navigation is theoretically easy.

Deficiencies of GPS

The errors in an uncorrected GPS signal come in many forms and arise from a variety of different sources. These errors can be divided into two broad categories:

1) High frequency noise and
2) Long-term drift.

The first category pertains to the errors that manifest themselves as high frequency noise or spikes. The difficulty arises from the fact that in some instances the position can jump several meters and then either jump back or maintain the new position for a few seconds or indefinitely. Experience has shown that the two main causes of GPS noise are satellites coming in and out of the view of the GPS receiver and multi-path effects. The magnitude of these errors varies from a few meters to hundred meters.

The second category of GPS error is classified as drift. These errors change over a period of hours rather than seconds like the noise errors. It is difficult to determine the exact cause of these types of errors, but they are typically attributed to atmospheric effects in the ionosphere, troposphere and satellite geometry. The magnitude of these errors can vary from no error at all to ten meters or more.

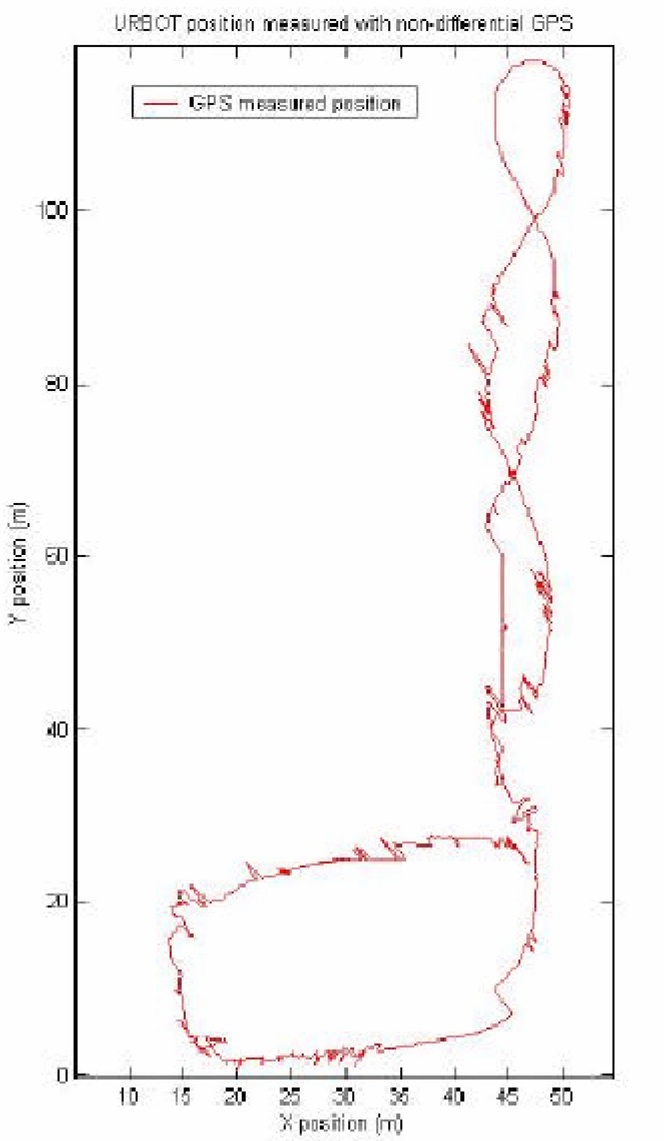


Figure 55: Non-differential GPS track of a robot with high frequency noise [BrGi02]

These errors are far too much for many applications especially for demining applications. For the monitoring of the detecting the resolution must be better than the size of the detector, in order to be sure to cover all the area. And for the self localisation the resolution should be better than the size of the robot. With several tens of meters error these requirements can not be fulfilled. To take remedial measures differential GPS could be used.

Differential Global Positioning System - DGPS

Differential GPS works by having a reference system at a known location which measures the errors in the signals and send corrections to users in the local area. These corrections will not be universal, but will be useful over a significant area. The corrections are normally sent every few seconds. The user is generally some mobile platform. Differential GPS is a solution down to one centimetre accuracy.

The costs of GPS receivers vary depending on capabilities. Small low-cost receivers can be purchased for a triple-digit euro sum, some of them can even accept differential corrections. Spending hundred times the sum of a low-cost receiver provides a receiver that can store files for post-processing with base station files. Receivers that can act as DGPS reference receivers (computing and providing correction data) can cost up to thousand times the sum of a low-cost receiver.

Fortunately only one reference receiver is needed for demining applications installed near the minefield. But each single robot working in the minefield needs an own receiver. Though these receivers are reasonably cheaper, DGPS is quite a costly system.

The biggest disadvantage of GPS is that it provides absolute coordinates (longitude, latitude and elevation) only and cannot be used without a geometric map of the environment. Another drawback is that GPS signals cannot be received indoors, making GPS a highly unlikely candidate for generalized robot localization.

3.2.3 Strategies for Navigation of Robot Swarms

The problem of controlling robot teams is very important and requires great attention. A publication about strategies for navigation of robot swarms to be used in landmines detection [CaBi99] gives an excellent overview.

The drawbacks of traditional centralized control are high computational and communication complexity, lack of flexibility and robustness. Therefore, a distributed control approach is more suitable for the control of systems that include a large number of robots. In such a distributed-control framework, each robot decides its own movements by observing the environment at the moment and applying some pre-defined control laws. The main idea is to design control laws such that the robot system as a whole will achieve the given goals, such as collision-free navigation or forming a spatial structure.

The similarities between distributed control of robot teams and the behaviour based control paradigm for single robots are obvious. In the latter the overall control task is decomposed into ‘task-achieving behaviours’ which operate in parallel. By comparison the distributed control approach works by achieving a task through the parallel work of the different members of a robot team.

Adopting decoupled planning means to see firstly each robot as independent from the others, while interactions among robots are evaluated at a later stage. The vectorial movement strategy described in the sequel can be regarded to as a decoupled planning. Robots are free to plan their own motions considering local and global information vectorially. The right configuration among them is effectively maintained by adding a swarm control vector.

The considered strategies for navigation of robot swarms are based on the assumption that there are robots present that are capable of some basic behaviour such as avoiding obstacles, finding the mines, following a specific path, maintaining the formation. In the simulation each robots has eight sonar sensors, one or more sensors for mine detection and a positioning system such as DGPS.

Generating a non-trivial behaviour requires effective use of multiple basic behaviours. Vectorial movement uses a specific vector for each of these basic behaviours. Four vectors have been designed:

- V1 used for avoiding obstacles: it can suppress all other vectors for the time necessary to move past the obstacle;
- V2, used for achieving a goal;
- V3, used for maintaining the position in a specific information;

- V4, for maintaining the robot direction.

Using this method, there have been defined, simulated and compared six strategies:

1. Random movement
2. Relay clustering
3. Flocking
4. Swarming
5. Formation maintenance
6. Comb movement

Random movement: Vectors used in this strategy are simply V1 and V4. V4 is used for the based random movement and V1 for avoiding obstacles and other robots.

Relay clustering: The movement of robots is initially random. When one robot finds a mine it transmits a signal to all other robots within communication range that a mine has been found. All robots receiving this signal move towards the place of the mine and at the same time they transmit a signal too to all robots in their communication range. In this strategy V2 is used, additional to the vectors used in random movement, to move towards the mine. This strategy has similarities to the way some ants behave when one of them discovers a food source.

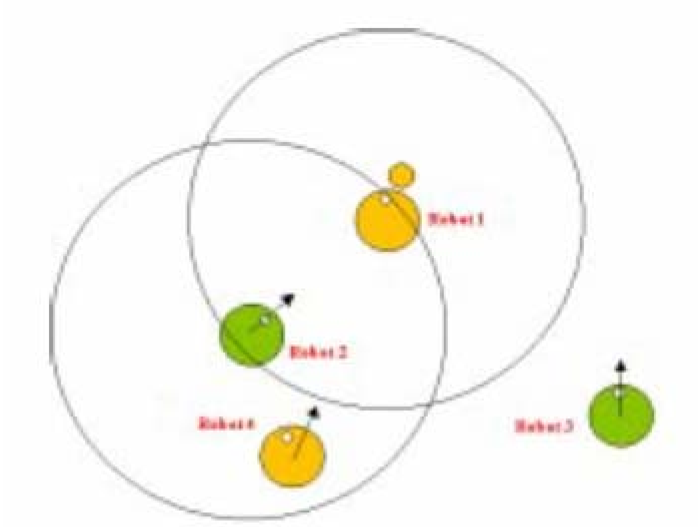


Figure 56: Relay Clustering [CaBi99]

Flocking: Flocking occurs in nature and is exhibited by birds, fish and some insects. Three rules of behaviour are added to obtain V3:

1. Cohesion: Each robot shall steer to move toward the average position of local flockmates.
2. Alignment: The robots will align to the same direction as their neighbours.
3. Separation: All robots in the flock will maintain a separation distance from their fellows.

The movement of the team is random so V2 in flocking is not necessary.

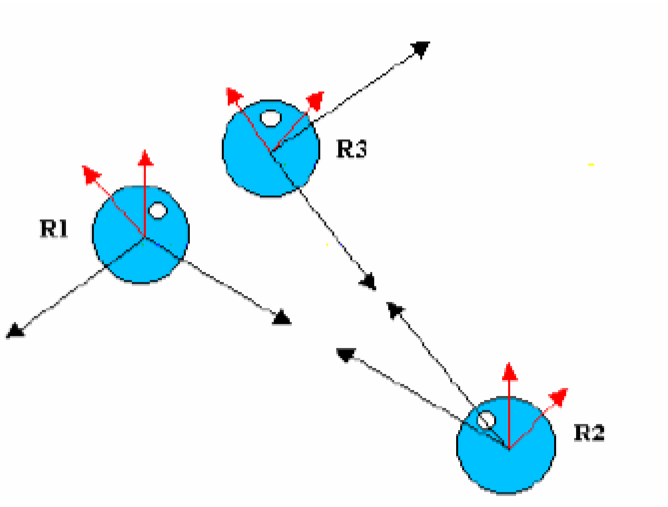


Figure 57: Flocking [CaBi99]

Swarming: This strategy works like flocking as far as robots belonging to the same team are concerned, but the flock is split in several teams. Different teams, to avoid each other, must follow these rules:

1. Attraction: Each robot is attracted to its fellows as the distance between them increases.
2. Alignment: The robots will align to the directions of their fellows.
3. Repulsion: Each robot is repelled by robots belonging to another team.

These three components are added to obtain V3. V2 here is not necessary again because the movement of the team is random.

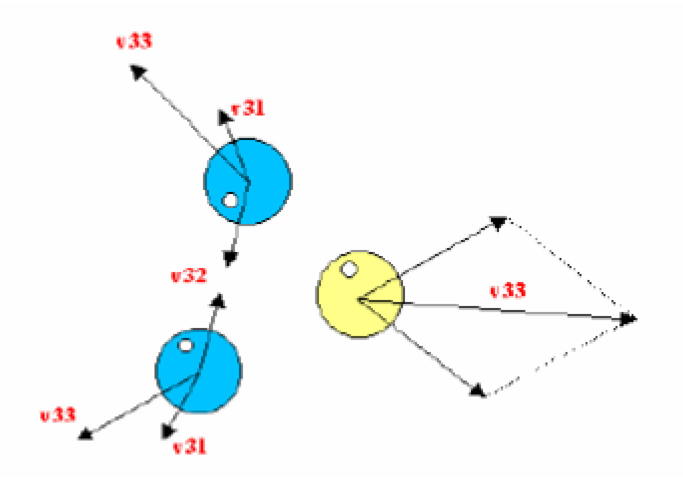


Figure 58: Swarming [CaBi99]

Formation maintenance: This is the first strategy that has a coordinated movement for all the teams. Each team can move using a different formation. There are three available choices: line, column and wedge. The position of each robot in the formation is fixed relatively to the team centroid, and V3 is used to keep this position. In this strategy, each team follows a specific path defined by an array of points. The movement of each team is obtained with the component V2 oriented from the actual team centroid to the next point in this array.

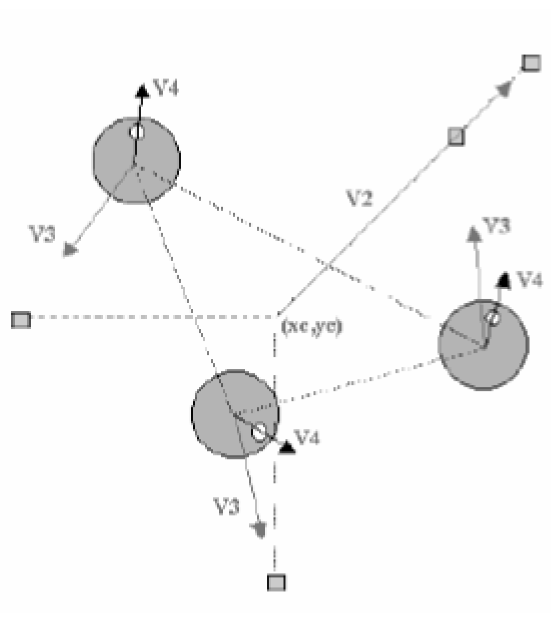


Figure 59: Formation Maintenance (Wedge Formation) [CaBi99]

Comb movement: This strategy is similar to formation maintenance, but the formation changes from line to column, and vice-versa, passing from a goal to another one. This change realizes a 'comb' movement.

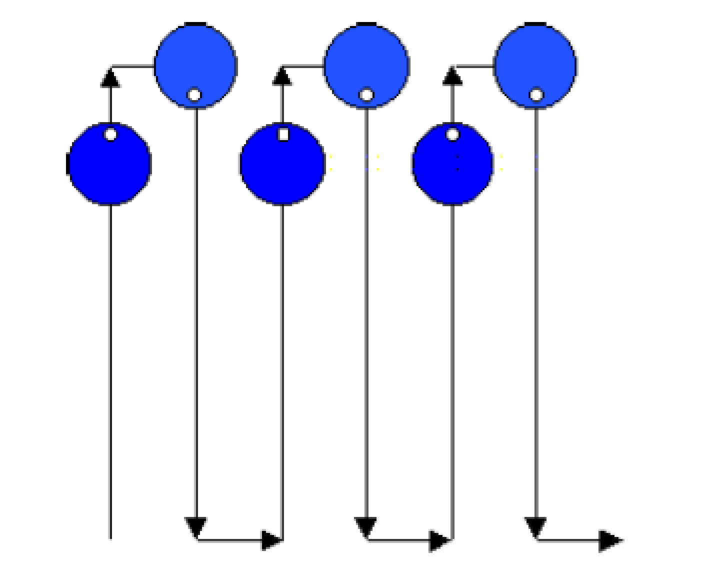


Figure 60: Comb movement [CaBi99]

After designating these strategies a simulator was used to test the performance of the different strategies in different environments. In the simulator the robots can sense their location in the environment, and detect obstacles, mines and other robots. The software package allows the use of multiple squads of robots and mines of different kinds can be laid in a field, along with obstacles such as walls, trees, etc.

In order to make comparison among different strategies possible, a performance metric has to be established. The time needed to complete the task was chosen as the primary performance index.

Tests performed differing in the design of the minefield and the amount of applied robots per team. The results in a minefield with less obstacles and randomly placed mines turned out heavily weighted in favour of the coordinated strategies because they had explored each point with a single robot, and only once during the whole process.
Tests in a world with just more obstacles turned out to be for all strategies worse then in the former test.

In test three, where mines of the same kind are gathered together in the field like in a real minefield, it is interesting that Relay Clustering performs much better then in the other test. Formation Maintenance and Comb Movement do not change because they are independent from the position of mines.
The results with regard to the number of robots per team are similar for all three kinds of minefields. The highest increase of performance occurs when the number of robots is changed form one to two. Each other increases of one team members results in an each time smaller enhancement of the performance.
An inspection of the time required to achieve a given number of found mines (all minefields contain 30 mines) shows that coordinated strategies find mines at a constant rate, while uncoordinated ones are more efficient when many mines are still undetected.

Even though many of the results of this simulation are not surprisingly, these tests point out great time-saving possibilities. Using the right strategy for each different environment the efficiency of the whole process of humanitarian demining can be increased noticeable. The main outcome is that clusters of well-organized robots work better than single machines, which is a strong argument for the coordinated use of robot swarms.

4 Conclusion and Outlook

This work presented the possibility to develop modular mobile robots suitable for humanitarian demining actions. The process of demining is a complicated and dangerous task. Mobile robots employed in a minefield have to meet most different requirements. On the one hand they have to perform highly accurate and sensitive tasks and on the other hand they have to withstand extreme environmental conditions. The use of robot swarms consisting of different types of robots which are assembled from modules is a possible way to meet these requirements. Especially the use of a modular system promises a low cost solution due to the applicability for many other purposes besides demining.

The first chapter provides a brief overview over the magnitude and effects of the landmine problem and over the most common types of landmines. In addition the state of art in humanitarian demining is presented which is essentially manual demining assisted sometimes by dogs and mechanical devices.

The second chapter explains at first the typical configuration of a modular mobile robot. Afterwards the discussion is focused on the question which of these modules could be of special interest for demining. The discussion is structured with respect to three different types of robots, each with other allocated tasks in the demining process. These three robot-types are detection robots, removal robots and transportation robots. Of course there are modules which are for all three types the same. Furthermore there are already useable existing modules, or at least solutions which are likely to be converted without too much effort into suitable modules, presented. Moreover the hardware aspect of a modular system is just as important as having modular software. A fast and simple connection in the hardware and software layer between all existing and possible future modules is an indispensable requirement for modular systems.

The third chapter deals with the manner of application of the different mobile robots. The disposition of the mobile robots in different swarms has many advantages. On the other hand a robot swarm implies new difficulties. Especially the coordination and navigation in the swarm is important. In addition demining robots have to navigate outdoors which can not be compared with navigation in indoor environments. An important assistance could be GPS. But for accurate tasks like marking a detected mine standard GPS is still to inaccurate.

Therefore expensive upgrades are needed. At last it is shown how important a coordinated working strategy in a robot swarm is. A comparison of different moving strategies for mine detection demonstrates the possibilities to enhance the work progress and to save time.

Outlook

Research and development in robotics for humanitarian demining is carried out mainly by universities, military and single persons. Even though military mine clearance requirements are approaching humanitarian standards, the acceptability of expensive equipment technology mean that military research is unlikely to provide useful equipment for humanitarian demining. Furthermore new discoveries which lead to major breakthrough in sensing mines are unlikely to be provided to civil demining groups.

It is expected that commercial companies could enhance the R&D process because it is abundantly clear that they are the most productive and cost effective of all organisations. Therefore it is important to create general conditions to attract commercial companies into the demining market.

A topic of recent interest in the field of robotics is the development of motion planning algorithms for robotic systems composed of a set of modules that change their position relative to one another, thereby reshaping the system. A robotic system that changes its shape due to individual module motion has been called self-reconfigurable or metamorphic.

A self-reconfigurable robotic system is a collection of independently controlled, mobile robots, each of which has the ability to connect, disconnect and move around adjacent robots. Metamorphic robotic systems, a subset of self-reconfigurable systems, are further limited by requiring each module to be identical in structure, motion constraints and computing capabilities. Typically, the modules have regular symmetry so that they can be packed densely, i.e. packed that the gaps between adjacent modules are as small as possible. In these systems, robots achieve locomotion by moving over a substrate composed of one or more other robots.

It is quite possible that metamorphic robots are the future of mobile robots. But that does not have to mean that they are the future of humanitarian demining as well. Some people are of the opinion that less emphasis should be put on development of new technologies. Rather the improvement of existing technology will resolve the problem faster, so that the political commitments of a mine free world within a decade could be achieved. The discussion on this issue is ongoing, and the many visions do not always coincide.

References

[Acti02] ActivMedia Robotics
http://www.activrobots.com/ROBOTS/core.html, 2002-10-20.

[Airs02] Air-Spade
http://www.air-spade.com/air-spad.htm, 2002-10-14.

[Altm01] Altmann, Jürgen: Neue Technologien für die Minensuche. In: Physik in unserer Zeit 32. Jahrgang 2001 Nr. 1, pp. 26-32.

[Atii02] ATI – Industrial Automation
http://www.ati-ia.com/quickchg.htm, 2002-10-12.

[BeAn02] Bennett, Phil C.; Anderson, Rober J.: Robotic Mobile Manipulation Experiments at the U.S. Army Maneuver Support Center. SAND 2002-1779, Intelligent Systems & Robotics Center, Sandia National Laboratories, 2002.

[BeKh00] Bererton, Curt; Khosla, Pradeep K.: Toward a Team of Robots with Repair Capabilities: A Visual Docking System. In Proceedings of the ISER '00 Seventh International Symposium on Experimental Robotics, December 2000.

[BoPo99] Boryssenko, A.; Polishchuk, V.: Passive Mine Detection by Estimation of Statistical Properties of the Natural Electromagnetic Background Radiation. Proceedings MINE’99, Sensor systems and signal processing techniques applied to the detection of mines and unexploded ordnance, Firenze, 1999. See also http://demining.jrc.it/aris/events/mine99/start.htm, 2002-07-10.

[Bory99] Boryssenko, A.: Ultra-Wide Band Impulse Radar for Stand-off and Stand-over Searching of Land Mines and UXO in Subsurface Region and Vegetation. Proceedings MINE’99, Sensor systems and signal processing techniques applied to the detection of mines and unexploded ordnance, Firenze, 1999. See also http://demining.jrc.it/aris/events/mine99/start.htm, 2002-07-10.

[BrGi02] Bruch, M.H.; Gilbreath, G.A.; et al: Accurate Waypoint Navigation Using Non-differential GPS. AUVSI Unmanned Systems 2002, Lake Buena Vista, 2002.

[BrGr97] Bruschini, Claudio; Gros, Bertrand: A Survey of current Sensor Technology Research for the Detection of Landmines. Proceedings SusDem’97, Sustainable Humanitarian Demining: Trends, Techniques and Technologies, Zagreb, 1997, pp. 6.18-6.27.

[BrKe00] Brooks, J.; van Kempen, L.; et al: A Primary Study in Adaptive Clutter Reduction and Buried Minelike Target Enhancement From GPR Data. Proceedings SPIE, Detection and Remediation Technologies for Mines and Minelike Targets V, Orlando, 2000, Vol. 4038, pp. 1183-1192.

[Brus01] Bruschini, Claudio: Commercial Systems for the Direct Detection of Explosives for Explosive Ordnance Disposal Tasks. In: Subsurface Sensing Technologies and Applications Vol. 2, No. 3, July 2001.

[Brus99] Bruschini, Claudio: Metal Detectors for Humanitarian Demining: from Basic Principles to Modern Tools and Advanced Developments. Proceedings MINE’99, Sensor systems and signal processing techniques applied to the detection of mines and unexploded ordnance, Firenze, 1999. See also http://demining.jrc.it/aris/events/mine99/start.htm, 2002-07-10.

[BrZa99] Bregman, Yuri; Zafrir, Hovav; et al: Handheld Magnetic System for Standoff Real Time Mine and UXO Detection. Proceedings MINE’99, Sensor systems and signal processing techniques applied to the detection of mines and unexploded ordnance, Firenze, 1999. See also http://demining.jrc.it/aris/events/mine99/start.htm, 2002-07-10.

[BuHi98] Butterfass, J.; Hirzinger, G.; et al: DLR's multisensory articulated hand, part I: Hard- and software architecture. In Proc. of the 1998 IEEE Int. Conf. on Robotics and Automation, pages 2081-2086, 1998.

[BzKu00] Bzostek, Andrew; Kumar, Rajesh; et al: Distributed Modular Computer-Integrated Surgical Robotic Systems: Implementation Using Modular Software and Networked Systems. In Proceedings of Third International Conference On Medical Robotics, Imaging and Computer Assisted Surgery, Pittsburgh, 2000. pp.969-978.

[CaBi99] Cassinis, R.; Bianco, G.; et al: Strategies for navigation of robot swarms to be used in landmines detection. EUROBOT'99, Third European Workshop on Advanced Mobile Robots, Zürich, 1999.

[ChDr99] Chernokalov, A.G.; Druchinin, S.V.; et al: Detecting of anti-tank mines having dielectric sheath under curved rough surface by ground penetrating radar with long pulse duration. Proceedings MINE'99, Sensor systems and signal processing techniques applied to the detection of mines and unexploded ordnance, Firenze, 1999. See also http://demining.jrc.it/aris/events/mine99/start.htm, 2002-07-10.

[ChGa99] Christensson, Magnus; Gardhagen Peter; et al: A New Portable Biosensor Technology for Vapour Detection. http://www.whitehousedrugpolicy.gov/ctac/ctac99/pdfs/c_g_s.pdf, 2002-07-11.

[ChPh98] Chambers, William B., Phelan, James M.; et al: Chemical Detection of Buried, Unexploded Ordnance. UXO Forum '98, Anaheim, 1998.

[ChYa97] Chen, I-Ming; Yang, Guilin: Automatic Generation of Dynamics for Modular Robots with Hybrid Geometry. Proceedings of the 1997 International Conference on Robotics and Automation, Albuquerque, 1997.

[CoKo99] Coutsomitros, Constantin Th.; Kokonozi, Athina; et al: Target identification in Humanitarian demining using weak activation IR methods. Proceedings MINE'99, Sensor systems and signal processing techniques applied to the detection of mines and unexploded ordnance, Firenze, 1999. See also http://demining.jrc.it/aris/events/mine99/start.htm, 2002-07-10.

[DaBo01] Datema, Cor P.; Bom, Victor R.; et al: Landmine Detection With the Neutron Backscattering Method. In: IEEE Transactions on Nuclear Science, Vol. 48, No. 4, August 2001.

[Dani99] Daniels, David J.: An overview of RF sensors for mine detection. Proceedings MINE'99, Sensor systems and signal processing techniques applied to the detection of mines and unexploded ordnance, Firenze, 1999. See also http://demining.jrc.it/aris/events/mine99/start.htm, 2002-07-10.

[DeHe98] Denier, R.; Herrick, T.; et al: The Use of Waterjets in the Location and Exposure of Landmines for Humanitarian Demining. Proceedings of the 14th INTSYMP Jet Cutting Technology, Brugges, 1998.

[DeTe02] DeTeC Demining Technology Center http://diwww.epfl.ch/lami/detec/rodemine.html, 2002-11-04.

[Dinc01] Dinc, Mustafa: Modelling Bluetooth Radio Technology Simulation Using Multi-Agent Based System and Genetic Algorithm Design Paradigm. Thesis, Naval Postgraduate School, Monterey, California, 2001.

[Dons98] Donskoy, D. M.: Nonlinear Seismo-Acoustic Technique for Land Mine Detection and Discrimination. Conference Publication No.458 © IEE 1998 Detection of abandoned Landmines, 1998.

[DuBr01] Dudenhoeffer, Donald D.; Bruemmer, David J.; et al: Modeling and Simulation for Exploring Human-Robot Team Interaction Requirements. Proceedings of the 2001 Winter Simulation Conference, B. A. Peters, J. Smith, D. Medeiros, M. Rohrer, eds. IEEE.

[Ebne98] Ebner, Marc: Evolution of a control architecture for a mobile robot. In Proceedings of the Second International Conference on Evolvable Systems: From Biology to Hardware (ICES 98), Lausanne, pp. 303-310, 1998.

[Esi02] Engineering Services Inc. http://www.esit.com/automation/mrj.html, 2002-09-30.

[FaDu01] Farritor, Shane; Dubowsky, Steven: On Modular Design of Field Robotic Systems. Autonomous Robots, Vol. 10, No. 1, pp. 57-65, January, 2001.

[FaZh01] Farritor, Shane; Zhang, Jun: A Reconfigurable Robotic System to Support Planetary Surface Operations. IEEE ICRA Workshop on Re-configurable Robots, Seoul, 2001.

[Frit01] Friezsche, Martin: Anwendung von Verfahren der Musterekennung zur Detektion von Landminen mit Georadaren. Dissertation, Fachbereich Höchstfrequenztechnik und Elektronik, Universität Karlsruhe, 2001.

[GeMa01] Gerkey, Brian P.; Mataric Maja J.: Sold!: Market methods for multi-robot control. Technical Report IRIS-01-399, Institute for Robotics and Intelligent Systems, University of Southern California, March 2001.

[GePe99] Georgson, Mikael; Pettersson, Lars; et al: Mine Detection Using Infrared Imaging Technique. Proceedings MINE'99, Sensor systems and signal processing techniques applied to the detection of mines and unexploded ordnance, Firenze, 1999. See also http://demining.jrc.it/aris/events/mine99/start.htm, 2002-07-10.

[Habi02] Habib, Maki K.: Mechanical Mine Clearance and Humanitarian Demining Applicability and Effectiveness. Fifth International Symposium: Technology and the Mine Problem, Naval Postgraduate School, Monterey, 2002.

[Habi01] Habib, Maki K.: Mine Detection and Sensing Technologies – New Development Potentials in the Context of Humanitarian Demining. IECON'01: The 27th Annual Conference of the IEEE Industrials Electronics Society, Denver, 2001.

[HaSa02] Ha, Quang; Santos, Miguel; et al: Robotic Excavation in Construction Automation. IEEE Robotics & Automation Magazine, pp. 20-28, March 2002.

[HaSc99] Havlík, `S.; `Scepko, P.: Searching dangerous terrain. Proceedings MINE'99, Sensor systems and signal processing techniques applied to the detection of mines and unexploded ordnance, Firenze, 1999. See also http://demining.jrc.it/aris/events/mine99/start.htm, 2002-07-10.

[Hong02] Hong, Mun Li: Hybrid Control System Development for Autonomous Mobile Robots. http://www.ntu.edu.sg/sce/Link00/cs00-4.pdf, 2002-10-02.

[HiFu02] Hirose, Shigeo; Fukushima, Edwardo F.: Snakes and Strings: New Robotic Components for Rescue Operations. Proc. of the Eight Int. Symp. on Experimental Robotics ISER-02, Sant'Angelo d'Ischia, 2002.

[HiKa02] Hirose, Shigeo; Kato, Keisuke: Study on Quadrupe Walking Robot in Tokyo Institute of Technology. http://www-robot.mes.titech.ac.jp/staff/kato/papers/ICRA00T9.pdf, 2002-09-30.

[Hiro00] Hirose, Shigeo: Super Mechano-System: New Perspective for Versatile Robotic System. Proc. of the Seventh Int. Symp. on Experimental Robotics ISER-00, Waikiki, 2002.

[HuKe98] Hu, Huosheng; Kelly, Ian; et al: Coordination of Multiple Mobile Robots via Communication. Proceedings SPIE'98, Mobile Robots XIII Conference, Boston, pages 94-103, 1998.

[KaCe98] Kapoor, C.; Cetin, M.; et al: A Software Architecture for Multi-Criteria Decision Making for Advanced Robotics. Proceedings of the 1998 IEEE ISIC/CIRA/ISAS Joint Conference, Gaithersburg, MD, pp. 525-530, 1998.

[KeDe99] Kerner, David; Deni, John; et al: Anti-Personnel Landmine (APL) Detection Technology Survey and Assessment, Technical Report TR-98-3. Defense Threat Reduction Agency, 1999.

[Khep02] K-Team http://www.k-team.com/robots/khepera/radioturret.html, 2002-10-13.

[KnSa99] Knapp, E.A.; Saunders, A.W.; et al: Direct Imaging of Explosives. Proceedings MINE'99, Sensor systems and signal processing techniques applied to the detection of mines and unexploded ordnance, Firenze, 1999. See also http://demining.jrc.it/aris/events/mine99/start.htm, 2002-07-10.

[Kopa02] Kopacek, Peter: Robots for Humanitarian Demining. Proceedings of the 33rd ISR (International Symposium on Robotics), Stockholm, 2002.

[Krau02] Kraut, Jay: An Autonomous Navigational Robot. Thesis, University of Manitoba, 2002.

[Land02] Landmine Monitor Report 2002 http://www.icbl.org/lm/2002/, 2002-11-13.

[MaEa02] Martinoli, Alcherio; Easton, Kjerstin: Modeling Swarm Robotic System. Proc. of the Eight Int. Symp. on Experimental Robotics ISER-02, Sant'Angelo d'Ischia, 2002.

[MaPa99] Mantini, Alessandro; Paolesse, Roberto; et al: How far can we push the chemical resolution of solid state gas sensors? Proceedings MINE'99, Sensor systems and signal processing techniques applied to the detection of mines and unexploded ordnance, Firenze, 1999. See also http://demining.jrc.it/aris/events/mine99/start.htm, 2002-07-10.

[McLe02] McLean, Ian G.: What the Dog's Nose Knows. http://maic.jmu.edu/journal/5.3/features/ian_mclean/ian_mclean.htm, 2002-11-10.

[MgMi02] Menschen gegen Minen http://www.mgm.org/, 2002-11-10.

[MiSc99] Milisavljevic, N.; Scheers, B.; et al: 3D visualization of data acquired by laboratory UWB GPR in the scope of mine detection. Proceedings MINE'99, Sensor systems and signal processing techniques applied to the detection of mines and unexploded ordnance, Firenze, 1999. See also http://demining.jrc.it/aris/events/mine99/start.htm, 2002-07-10.

[MoGu02] Mondada, Francesco; Guignard, Andrè; et al: SWARM-BOT: A New Concept of Robust All-Terrain Mobile Robotic System. Technical report, LSA2 - I2S - STI, Swiss Federal Institute of Technology, Lausanne, 2002.

[MoLe00] Moody, K. A.; LeVasseur J. P.: Current and Emerging Technologies for Use in a Hand-Held Mine Detector. Course Project Report, Royal Military College of Canada, 2000.

[NeFa99] Nebbia, G.; Fabris, D.; et al: EXPLODET: advanced nuclear techniques for humanitarian demining. Proceedings MINE'99, Sensor systems and signal processing techniques applied to the detection of mines and unexploded ordnance, Firenze, 1999. See also http://demining.jrc.it/aris/events/mine99/start.htm, 2002-07-10.

[NeVo01] Nesnas, I. A. D.; Volpe, R.; et al: Toward Developing Reusable Software Components for Robotic Applications. Proceedings of the International Conference on Intelligent Robots and Systems (IROS), Maui, 2001.

[NoPa95] Nolfi, Stefano; Parisi, Dominico: Evolving non-Trivial Behaviours on Real Robots: an Autonomous Robot that Picks up Objects. Proceedings of the 4th Congress of the Italian Association of Artificial Intelligence. Berlin: Springer-Verlag, 1995, 243-254.

[PaBr96] Paredis, Christiaan J. J.; Brown, Benjamin H.; et al: A Rapidly Deployable Manipulator System. Proceedings of the 1996 IEEE International Conference on Robotics and Automation, Minneapolis, 1996.

[PaNi99] Pardo, M.; Niederjaufner, G.; et al: Towards an Electronic Nose for Demining Based on Semiconductor Thin Films. Proceedings MINE'99, Sensor systems and signal processing techniques applied to the detection of mines and unexploded ordnance, Firenze, 1999. See also http://demining.jrc.it/aris/events/mine99/start.htm, 2002-07-10.

[PaPa02] Panzieri, S.; Pascucci, F.; et al: An Outdoor Navigation System Using GPS and Inertial Platform. IEEE/ASME Trans. on Mechatronics, vol. 7, n. 2, pp. 134-142, 2002.

[PeKw02] Pettinaro, Giovanni C.; Kwee, Ivo W.; et al: Swarm Robotics: A Different Approach to Service Robotics. Proceedings of the 33rd ISR (International Symposium on Robotics), Stockholm, 2002.

[PePi01] Pereira, G. A. S.; Pimentel, B. S.; et al: A simple testbed for cooperative robotics. In Anais do Simp´osio Brasileiro de Automa¸c ao Inteligente (submitted), Canela, RS, 2001.

[PiDo99] Pichot, Ch.; Dourthe, C.; et al: Sensor systems and near-field inversion algorithms for microwave imaging of buried objects. Proceedings MINE'99, Sensor systems and signal processing techniques applied to the detection of mines and unexploded ordnance, Firenze, 1999. See also http://demining.jrc.it/aris/events/mine99/start.htm, 2002-07-10.

[Rist02] Ristec – Robotic Interface System Technologies http://www.ristec.com, 2002-10-12.

[RoDo01] Rosengard, Ulf; Dolan, Thomas; et al: Humanitarian Demining Nuclear Techniques May Help the Search for Landmines. In: IAEA Bulletin, 43/2/2001.

[Sava99] Sai, B.; van Genderen, P.: On the Design of the UWB Front-end of GPR for Landmine Detection. RADAR'99, Brest, 1999.

[ScPi00] Schenker, P. S.; Pirjanian, P.; et al: Reconfigurable robots for all terrain exploration. In Proc. SPIE Sensor Fusion and Decentralized Control in Robotic Systems III, Vol. 4196, Boston, 2000.

[Sing97] Singhal, Amit: Issues in Autonomous Mobile Robot Navigation. Computer Science Department, University of Rochester, 1997.

[Singh97] Singh, Sanjiv: The State of the Art in Automation of Earthmoving. In ASCE Journal of Aerospace Engineering, 10(4), October, 1997.

[SiSi00] Simmons, Reid; Singh, Sanjiv; et al: First Results in the Coordination of Heterogeneous Robots for Large-Scale Assembly. Proc. of the ISER '00 Seventh International Symposium on Experimental Robotics, Honolulu, 2000.

[Shiv01] Shivarov, N.: A 'Tool Kit' for modular, intelligent, mobile robots. PhD. Thesis, Vienna University of Technology, 2001.

[Syca02] Sycara, Katia: Multi-Agent Systems. http://www.aaai.org/AITopics/html/multi.html#ks, 2002-10-02.

[Szyn99] Szyngiera, Piotr: A Method of Metal Objects Identification by Electromagnetic Means. Proceedings MINE'99, Sensor systems and signal processing techniques applied to the detection of mines and unexploded ordnance, Firenze, 1999. See also http://demining.jrc.it/aris/events/mine99/start.htm, 2002-07-10.

[TNMA01] TNMA Technical Notes for Mine Action: Guide to mechanical mine clearance/ground preparation using commercial tractors and front loaders. Technical Note 09.50/01 Version 1.0 http://www.gichd.ch/publications/index.htm, 2002-11-04.

[USDo98] U.S. Department of State: Hidden Killers: The Global Landmine Crisis. Report released by the U.S. Department of State, Bureau of Political-Military Affairs, Office of Humanitarian Demining Programs, Washington, DC, September 1998.

[WaHo02] Watson, Dave; Hoag, Vicky; et al: Robotic Landmine Vehicle. Senior Project Final Report. Dr. Pratt and the Messiah College Engineering Department, May 2002.

[Walk02] Walker, John: Common anti-personnel mines. http://www.fourmilab.ch/documents/minerats/figures/mines.html, 2002-11-10.

[WiCa99] Windsor, Colin; Capineri Lorenzo: Combining results from different mine detection techniques. Proceedings MINE'99, Sensor systems and signal processing techniques applied to the detection of mines and unexploded ordnance, Firenze, 1999. See also http://demining.jrc.it/aris/events/mine99/start.htm, 2002-07-10.

[YuVl01] Yuan, Jian Y.; Vlacic, Ljubo: Suitability of Bluetooth Technology in Communication Between Autonomous Mobile Robots. Microelectronic Engineering Research Conference 2001, Brisbane, 2001.