Unmanned Robotic Vehicles for Demining

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1 Introduction

Application of robotic technology for performing risky tasks to prevent human life, big economical as well as ecological damages became a big challenge for research in several domains; mainly in robotics. Within most dangerous operations can be included: cleaning terrain from landmines, fire fighting, solving nuclear accidents or physical catastrophes (earthquakes, sea or river debacles, etc.). As human safety is the highest priority, the best option is to remove the human operator from the hazardous scene and/or totally to substitute him with “an intelligent” agent, which is expected to provide the operator such means that would enable carrying out the same mission safety. These application fields require mobile robotic systems having specific features and exhibit limited level of autonomy as to mobility and functions.

New research achievements that have been reached in robotics and other related domains provide a new qualitative base for further development of more sophisticated approaches that can be applied for solving problems related to all risky operations. There are especially achievements in following disciplines:

- Microelectronics and microengineering. New materials and technologies enable to construct of robotic devices smaller, lighter and more reliable in operation.
- Elaboration of new sensing principles and detection technologies. Sensors are more precise and sensitive, smarter and fusing sensory data results in more reliable information. Compact and integrated solutions of sensory systems enable their applications in harsh environments.
- Computer and information processing technologies. Nowadays, there are practically no limits as to amount of data processing and computing complex problems.
- The precise GPS localization/navigation together with sophisticated control algorithms give possibility of higher level of autonomy for mobile robotic vehicles.
- Communication technologies enable to shear and transmit information data on very long distances.

Naturally these results go together with achievements in elaboration of related theoretical and technological problems. Examples are new sophisticated concepts applying principles of on artificial intelligence (AI), sensory devices for target recognition based on neural networks (NN) or new methods for navigation and control using sensory information.

The overviews of existing research projects, techniques and equipment have been developed for performing particular tasks are listed in several databases (www.gichd.ch; GICHD, 2006; www.hdic.jmu.edu; www.eudem.vub.ac.be) and in several conference proceedings. The task oriented research is especially desired in the following domains: mobile out-door robotics, explosive/mine detection technology, tools and special neutralization equipment (Ide *et al*., 2004; Wetzel & Smith, 2003; Mori *et al*. 2005; Hae *et al*. 2005).

Many research projects and lot of research work has resulted in design of several concepts as well as development of robotic machines and especially detection systems (Habib 2007). Unfortunately, despite this effort and promising performances in laboratories, several sophisticated robotic solutions and systems did not find such acceptance in practical use as was expected. There are several reasons:

- Cost of these systems, including service, is too high.
- De-mining process is too complex and practically there is no 100% repeatability in performing particular tasks.
- Danger of explosion is very high. For this reason some robust techniques, as for instance flailing, are more preferred.
- To achieve desired performance (safety, reliability, cost, robustness, etc.) there are still problems that should be solved.
- Economy. Market in the domain of robotic technology for de-mining, comparing to manufacturing robotics, is relatively small. On the other hand; problems to be solved are very complex.
- Practically, there is no unification or standardization of parts. For these reasons big manufacturers of industrial robotic technology have very limited interest to be engaged in this domain.

This chapter deals with application of robotic vehicles for performing risky tasks, mainly for de-mining operations. Most important problems related to the de-mining procedure are analyzed in more details, conditions and desired performance specifications that such robotic vehicles with task-related equipment should satisfy are discussed. The current state of this technology and development of the remotely controlled family of "Božena" machines is presented, as illustrative example.

2 Robotic approach

2.1 General considerations

When intend to apply a robotic technology for performing risky operations the first idea is to construct some universal all terrain robotic system, highly mobile, lightweight, that could be immediately set to risky/de-mining works all around the globe. Although such an idea could be maybe realizable, when one considers the current state of technology, there is no reason to spend so much money and enormous human effort to develop such a complicated high-tech and enormously expensive system. The robotic system should satisfy specific conditions directly related to the process and its local application.

It is obvious that all parts of the system should be adequately robust to sustain not only harsh working and climatic conditions and possible accidental explosions too. It should be said that any complex repair to be made on place is very limited. Beside acceptable performance parameters the robotic system should exhibit a "self- recovery" capability. This means that it could be removed from the dangerous place/minefield without access or interventions of humans. Performing any risky operation the general requirement is that all tasks should be made by safe ways in order to reduce any risk for humans as well as material with minimal negative impact on economy and environment.

Let us analyze two similar operations from the point of view application robotic technology and problems for research.

2.1.1 Humanitarian De-mining

As the de-mining operation represent dangerous works in hazardous environments the safety of human beings and/or valuable equipment then, the emergency management application should take place. The first step is to provide the operator by such means that would enable him to perform the same mission safely, i.e. without direct entrance on dangerous terrain or contacts with explosives. Considering large polluted areas and drawbacks of actual de-mining technologies main contributions by using robotic technologies are expected in three main crucial tasks of the de-mining process:

- Searching large areas and localization of mines and any explosives (UXO) by fast and reliable way.
- Fast and reliable neutralization/destruction of mines without the need of personal assistance to be inside, or close, to dangerous places.

Both these tasks are directly related to the problem and solving the next - very important task.

- Preparing infected terrain for reliable detection as well as for neutralization procedures, i.e. removing vegetation and any obstacles that could prevent detection or safe neutralization.

Comparing to other, mainly military devices, the robotic system for humanitarian de-mining should respect some specific aspects and rules that should be taken into account and directly influence the choice of adequate technology. There are:

- **Minefields are not laboratories.** Robust and reliable constructions as well as control techniques should correspond to harsh working conditions and environment. This includes solving so called "self-recovery strategies" in most crucial situations that could arise (occasional explosions, errors in systems/operators, lost of communication, etc.). This means that it could be removed from the minefield without access or interventions of humans. It is obvious that all parts of the system should be adequately robust to sustain not only harsh working and climatic conditions but some possible accidental explosions too. It should be said that any complex repair to be made on place is very limited.
- **The reliable detection and localization of mines (UXO) as targets is the task of primary importance.** If mines are reliably detected and exactly localized, then the neutralization procedure could be directly addressed to the place of their occurrence.
- **Any new de-mining technology should be easily accepted by local authorities and people.** The robotic system should satisfy specific conditions related to its local application demands (country people and their education experiences, infected terrains, climatic conditions, type of mines, maintenance, etc).
- **There are no universal solutions.** Robotic technology cannot totally replace humans in all phases of de-mining process. Some robotic approaches should replace some most dangerous searching/neutralization methods. Automatic ways are especially suited for primary detection and cleaning large areas under some homogenous conditions (terrain, obstacles, mines, vegetation, etc.).

- **Economy.** Mines are deployed in post – battle regions where mainly local materials, local manufacturing and local manpower should be used to perform de-mining operation and to maintain all technology. Technical knowledge of people is very limited and access to high-technology components is almost nonexistent. Usually the economy of such regions does not work, or, it is totally destroyed. It is obvious that under such conditions using low-cost de-mining equipment, including standard hand searching and neutralization technologies are more preferred. Sophisticated robotic equipment, comparing to standard de-mining technology, is mostly complicated and much more expensive.

- **Psychological aspects.** Humanitarian de-mining requires the high level of confidence that all mines have been detected and neutralized. This naturally results that any technology should guarantee practically 100% reliability of cleaning. When consider that de-miners (professionals or locally engaged) doing this dangerous task are always under psychological pressure, usually, they are not able to master a complex robotic system including its operation, maintenance and possible repairs. Otherwise specialists should be trained what considerably increases cost of de-mining woks. It should be said that the confidence of de-mining personals to the technique plays an important role otherwise it can be hardly accepted.

- **Any new solution should minimize risks for people; as well as for the damage of relatively expensive technology.** This risk of the damage, or, the lifetime by using new technology should be calculated in the expected comparable total cost for de-mining the surface area.

2.1.2 Firefighting

Firefighting represents harsh conditions in the operation space: toxic gases, high temperatures, possibility of explosions/breaking down of any constructions or trees, poor/no visibility, obstacles - bad accessibility, etc. An intended robotic system should exhibit some similar principal features as for demining operations:

- Mobility in complex terrain with unknown obstacles. The vehicle can move on wheels, belts, or depending on obstacles, on legs.

- Sensory equipment. Principal requirement is positioning the vehicle in a global/local reference system. For measuring actual position in global world coordinates can be used GPS devices able to ascertain position within resolution of 1m, or less, The other problem is to navigate the vehicle according to actual situations (obstacle avoidance, thermal navigation to source of fire, solving recovery situations, etc.). The navigation should be frequently done under poor visibility conditions i.e. without visual feedback when an additional thermal imaging system can be applied only.

- The board of the vehicle is equipped by an active system for fire intervention (water/foam/sand gun, placement explosives to extinguish the fire, removing objects/obstacles, etc.

- Control and communication should reliably work and such an agent should exhibit a given degree of autonomy to solve some unexpected situations.

2.2 Robotic vehicles for de-mining. Expectations and reality

Following the development of robotic technology, especially for humanitarian de-mining, the acceleration and progress can be seen after 1980s. Some existing technologies could be used for robotic de-mining were more exactly elaborated and, beside yet known techniques, new principles were designed and widely studied. Within technologies for cleaning large areas the most frequently used are mechanical systems (Habib, M.K. 2002, 2007a, b; Baudoin, Y. 2008). This concept of neutralization applies technique of mechanical activation of explosion and includes a remotely controlled vehicle with the mine neutralization tool, mainly rotating flails (Habib, 2002, 2008; Licko & Havlik, 1997; Havlik 2008 a, b; GICHD, 2004; Lindman & Watts, 2003; Ide *et al*., 2004; Stilling *et al*., 2003). Main drawback of these purely mechanical techniques is that they should mechanically effect on large areas, frequently, without any occurrence of mines. More, no such system can satisfy desired 100% reliability and frequently manual verification of yet cleaned area is need. Actually, there are more then 40 manufacturers of machines for this purpose listed in catalogue (GICHD, 2006). For performance evaluation of particular machines the common criteria and test conditions were accepted on the international level (CEN, 2004). According to these standards it is possible to compare machines available on market.

After more then 15 years of development of robotic tools for de-minig one can briefly evaluate the state in application of robotic technology in this field (Ide, 2004; Mc Donald, 2003; Santana, 2007; Wetzel, 2004; Tojo, 2003). New locomotion systems as for example: multi-legged walking platforms (Baudoin 2008), swarm-like mechanisms (Cepolina, E.E. 2002; light weight wheel vehicle ARES (Santana *et al*. 2008) have been studied and tested in laboratories. Together with mechanics using sophisticated sensor based navigation and control systems have been studied (Wetzel 2006). Naturally, main attention has been devoted to searching and detection (Mori, 2005; Faust, 2005; Baudoin, 2008). As result of this originally academic research several promising solutions of robotic vehicles with detection systems have been tested in real minefield conditions and still are under development (Nonami, 2007; Masunaga, 2007; Baudoin, 2008; Habib, 2008). Beside the development of unmanned mobile vehicles with robotic mechanisms for scanning terrain and localization of mines some special tools for cleaning/cutting vegetation, neutralization or removing mines were developed (Wojtara, 2005). It should be said that the key problem of de-mining lies and will be solved if mines are reliably detected and localized. Then the neutralization procedure is directly addressed to this place of mine occurrence.

Although all these systems represent a very good impact and progress in de-mining technologies, till now, they did not find more extended use. Mines, after several years of deployment are usually covered by layers of soil or sand and, except of desert conditions, mainly vegetation. Natural vegetation (shrubberies, bush, grass, trees, etc.) and time changing terrain (sand dunes, changing mud, etc) are still limiting factors for using sophisticated, but relatively fragile and expensive robotic devices.
Results of this research are in several databases:

- http://www.eudem.vub.ac.be
- http://www.hdic.jmu.edu
- http://www.state.gov/t/pm/rls/rpt/
- http://www.de-mining.brtrc.com/r_d

- http://www.demining@mech.uwa.edu.au
- http://www.dervish.org
- http://www.mineaction.org
- http://www.port.ac.uk/research/c&r/robotics
- http://www.rma.ac.be
- Several proceedings from conferences "HUDEM" dealing with humanitarian de-mining organized within the "IARP" community.

Some samples that represent the state in the development of small robotic vehicles for de-mining tasks bring Figures 1 to 3.

COMET III The Six Legs Robot (Nonami 2007)

Gryphon IV Mobile System (Fukushima 2008)

The MR Mime Detection Robot (ESI 2005)

Vehicle Mounted Detection System VMDS (Nonami 2008)

Sensor Arrays Attached to HD Robotic Platform Nemsis (GICHD)

The ILDS Remote Detection Vehicle (RDV) (Faust 2005, GICHD 2006)

Figure 1: Robotic vehicles for detection.

Figure 2: Robotic vehicle for cutting vegetation (Nonami 2008).

(a) DOK-ING MV-4 (GICHD 2010)

(b) Božena 4 (Havlik 2008)

Figure 3: Remotely controlled flailing vhicles.

2.3 Specific Features and Requirements

As mentioned above, performing any risky operation in dangerous environment requires three principal features to be satisfied by an intervention robotic agent: self-recovery capability, minimal risk assessment and maximal reliability in all actions.

2.3.1 Self-Recovery

This is an important and specific feature directly related to particular tasks. Its main purpose is to prevent/to avoid loses or self-destruction of the agent and to finish a given action in risky environment without serious damages. The self-recovery strategies should start especially in unwanted situations as follow:

- The failure of technique (communication, engine, control system, sensory system, etc…).
- The problem is to remove the vehicle from the dangerous terrain without any risk for persons. In cases of fault decisions made by the operator where there are no/not exact information for further action and it seems to be too risky for the agent to stay or to continue action, as planed.

Consider an agent performing de-mining operation in the minefield. Each motion of the vehicle in this dangerous terrain should be carefully judged. Otherwise any wrong movement could result in its destruction. The principal strategy should be based on following rule: "Any motion/action of the vehicle could be realized in such direction where no accident could arise (mines were reliably detected, or, all mines were destructed/removed)".

Another situation arises in case of any failure and the vehicle cannot perform desired activities. The problem is to remove it from the dangerous terrain without any risk for persons. One of the simplest way, how to solve this situation, is using a cable and pull it out by the winch mechanisms. The other possibility enables using another vehicle, which helps to remove the first one from the minefield.

2.3.2 Minimal Risk

Solving any situation brings for operator/operation system the decision problem: to decide for the next action if any unexpected situation arose. The general rule is: the operator decides for the next paths of the agent in order to minimize any risk of damages for the agent itself. This procedure represents the standard decision algorithms according to the risk assessment routine: next action : <STOP/CONTINUE/GO BACK/ … > if < CONDITION: SENSOR xx >. On the other hand; operator's decisions require much more complex assessment of possible risks with respect to given criteria. Such a typical situation arises during automatic de-mining operation when available mine detection systems give not reliable information about the presence of mines and there is only a suspicion if "something is inside". Then, the operator should decide if to continue the same task, or, some other techniques of searching by using other detection systems and fusion are need.

2.3.3 Reliability

The reliability of performing a task should be considered with respect to criteria given for a particular operation. Naturally, particular dangerous missions exhibit specific tasks and working conditions results in different approaches to solving robotic technology. To compare different tasks, actions and criteria that are given for performing particular risky operations are given on examples in Table 1.

3 Robotic tools and technology

3.1 Analysis of the de-mining process

The classic definition of the mobile robotic system says that it is "a machine" able to move in more or less structured environment and perform some given operations automatically, or, according to a given plan. The functionality of such a robotic agent then includes three principal performance features of the cognitive process: perception, recognition and decision making. It is obvious that the autonomy of the whole robotic system then directly corresponds to sensory equipment, processing sensory information and decision algorithms. As to robotic de-mining there is one principal question: what level of autonomy is need and such a robotic agent should exhibit.

To answer this question let us compare the de-mining process with other technological or service processes where advanced robotic systems were successfully applied. Consider some principal criteria and working conditions as follows:

- **Safety.** Because of during all activities: preparing terrain, detection and neutralization, there is always a serious danger of explosion that results in destruction of robotic equipment. For this reason all decisions/actions have to prevent any risk of explosions. Comparing to robotic operation for liquidation of dangerous objects, as in cases of explosives hidden in public places, explosion prevention in de-mining is much more complex due to unknown environment and types of mines (dimensions, terrain, unforeseen obstacles, vegetation, etc.).

Operation	Task description (example)	Description of the action	Criteria
Humanitarian de-mining	Steps of de-mining: Cleaning vegetation, if any exists Detection of mines and localization Destruction of mines on place or removing	Robotic agents for performing particular tasks are operated from the center. Agents are equipped by detection systems and tools for destruction/neutralization.]	High reliability of cleaning (up to 100%) Safety Cost/speed
Fire fighting	Active intervention: (water/foam/sand gun, placement explosives) to extinguish the fire, removing objects/obstacles, etc.	Mobile robot is carrying extinguish material and tools to put material into fire, or other actions. Poor/no visibility, unknown obstacles, toxic gases, high temperature, navigation problem, recovery. Sensory equipment: GPS, vision and thermal imaging.	Robustness to work in harsh conditions
Nuclear power plant actions	Surveillance and manipulations with nuclear materials.	The robot hand executes manipulations with dangerous materials. The detection – measuring system verifies level of radiation. The operation space is visible and quite well defined. Equipment: Remotely-operated transport platform with on board robot- manipulator, tools, vision system, gamma-detector (gamma locator)	Reliability
Antiterrorist action	Airport action: Remove an object as potential/suspected explosives or other dangerous materials inside. The agent should remove dangerous object from the space as soon as possible.	The remotely-operated mobile robotic agent will approach to the object, takes it by an arm and inserts the object into a container on its platform. The object is then carried out into a safe space for further recognition. The environment is quite well defined as to terrain, visibility and weight of objects. Equipment: Mobility system, robotic arm, vision, hand held camera, remote control (~200m), other sensors/detectors	Minimum time Prevention of accidental explosion

Table 1: Description and criteria of some risky operations

- **Safety.** Because of during all activities: preparing terrain, detection and neutralization, there is always a serious danger of explosion that results in destruction of robotic equipment. For this reason all decisions/actions have to prevent any risk of explosions. Comparing to robotic operation for liquidation of dangerous objects, as in cases of explosives hidden in public places, explosion prevention in de-mining is much more complex due to unknown environment and types of mines (dimensions, terrain, unforeseen obstacles, vegetation, etc.).
- **Reliability.** Humanitarian de-mining process should guarantee practically 100% reliability that all mines were neutralized.
- **Complexity.** The de-mining process is practically not, or very poorly, defined in all three principal phases: detection, preparing terrain and neutralization. This includes environment, target objects, positions, and sequence of particular operations. Large variety of objects to be manipulated as to form, weight or positions (mines, stones, terrain, vegetation, etc.) requires complex recognition and evaluation of actual situation that can be hardly specified in advance. It can be said that practically there is no repeatability in performing particular tasks. Naturally, the system cannot exhibit a higher level of autonomy. The development robotic machines and detection systems should focus on technologies that are able to acquire as much information as possible about the minefield prior to clearance. These machines need a variety of information-gathering tools to investigate a range of explosive-risk.
- **Accuracy of positioning.** When analyze main tasks of the de-mining process from the position/motion control point of view, all positions are related to the base – field reference coordinates. Then, for displacements, two characteristic categories of motions can be distinguished. There are:
    - Gross motions of the vehicle usually measured by GPS or other measuring system; for instance laser. As to the accuracy of positioning, as well as recording targets into digital maps it should correspond to the resolution of GPS positional measurement.
    - Fine motions are performed by on/board tools fixed on flanges of the robot arm or platform. These motions are related to the vehicle reference system

  When consider the requirements on positioning accuracy of a robotic system when performing de-mining tasks with respect to the range of the operation space the order difference is 5 ÷ 6. In standard manufacturing technologies this order difference is 4. Because of the robotic de-mining process requires at least two mutually dependent positioning mechanisms, obviously, it is not possible to reach such accuracy under uncertainties and possible errors that can arise. For this reason adaptive approaches have to be applied in control.

  It should be noted that some operations procedures require more precise positioning of tools then the others. For instance: flailing destruction technique does not need so exact coordinates of targets for its successful function. On the other hand, removing mines requires relatively precise positional information for any control action. Some characteristic features of particular motions are in next Table 2.

	Gross motions	Fine motions
Tasks	-global positioning of the vehicle -searching/scanning motions -mapping targets -marking -flailing	Fine motions scanning by the robot (removing mines/obstacles)
Tools	vehicles	on-board robot arm sensory platform
Desired positional resolution	~ 5-10 m for air vehicles ~ 0,5 m for ground vehicles (in field/global references)	~ 5 mm (relative) in vehicle/local references
Sensing -primary control -adaptive control	GPS, laser, camera Sensors for vehicle-environment interaction (mine detection, obstacle detection, etc..)	Internal sensor in joints of mechanisms Sensors for tool-environment interaction (hand-held mine detectors, camera, force/haptic sensors, etc.)

Table 2: Motion characteristics of de-mining tasks.

- **Similarity.** Numerous common features and similarities between robotic systems for de-mining and other out-door mobile robots that could be adopted, or, partially integrated in a common solution. There are especially: mobility mechanisms, arms for manipulations, communication, navigation/control, general sensory equipment, cognitive features, etc. Beside these general purpose systems there are several specific de-mining tools directly oriented to particular tasks as for instance: prodders, grippers, shovels, sand suckers, cutters, detectors, etc.

  It is obvious, that any robotic system can effectively work under some standard and expected conditions/environment. Performing de-mining activity then means that there are given some limit capabilities as to maneuvering of the mobility system, reliable detection of mines and desired confidence level of neutralization equipment. This practically results in fact that automatic de-mining technology will be preferably used for cleaning large homogenous terrains without complex obstacles (vegetation, terrain, trenches, etc.). Beside such complex automatic equipments several task oriented semi - automatic, or remotely controlled devices can effectively work.

  Thus, as to the autonomy of robotic systems for de-mining operation when evaluate the state of the art in development robotic technology and complexness of the de-mining process the only one and relatively simple rule can be adopted: *"Any activity of the robot that could result in danger of explosion should be consulted with operator monitoring the whole de-mining process".* This naturally requires transmission and monitoring all relevant information from the de-mining scene. This fact practically means that all most dangerous actions are performed in the "master-slave" control mode, as figured on the information – control scheme in Figure 4.

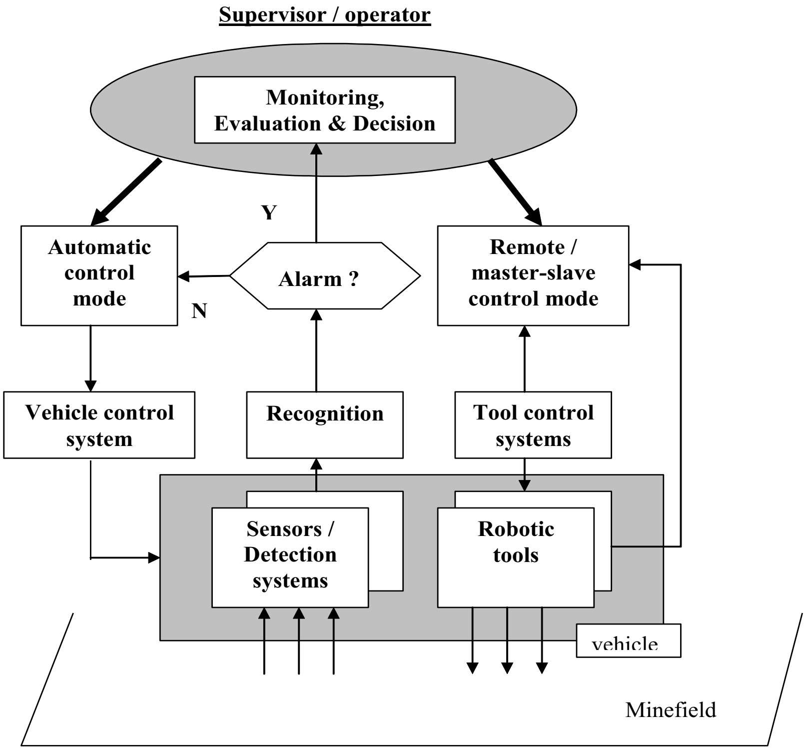


Figure 4: Information – control scheme of the semi-autonomous de-mining system.

As follows from the observations the time need for performing particular tasks, about 20 - 30 % of time is spent for detection, 50 – 60 % for cleaning vegetation and preparing terrain and only 10 – 30 % of the total time is spent for neutralization. Naturally, these data are strongly dependent on regions and kind of vegetation. Another statistical data (Mc Donald, J.A. et al. 2003) say that from 200 million items excavated within a period only about 500 00 items (less then 0,3%) were anti- personnel mines or other explosive devices. Thus more then 99 % of the total working time of the de-mining crew was spent for confirmation, excavation of scrap items that resulted false signals of metal detectors.

When combine the above data one can deduce an important fact that the most significant time savings in de-mining can be expected if the rate of false alarms be reduced. Because of the safety rules, any false alarm should be considered as potential mine or any explosive object/UXO and, the procedure that follows, should be organized as in the case of a mine occurrence. Thus, reliable detection and verification is one of the most time consuming procedure. It can be said, that if a mine, or any explosives on the field are reliably detected/recognized and localized the problem of de-mining is practically on 90 – 95 % solved. For this reason, performing reliable detection and recognition of hidden explosive objects by an automatic way is the most important task of the whole de-mining process.

Based on above discussion one can state priorities in solving and development of devices as parts of robotic de-mining technology:

- **Priority 1. Development of devices for detection and localization of mines/targets**

  Beside detection systems there are mainly robotic arms, as porters of various sensory systems that enable to scan/search dangerous terrain. In principle, the sensory systems can be situated on a special platform of a mobile vehicle performing scanning dangerous terrain, or, on the end of a robotic arm. As obvious, some principles are more suited for searching large areas to detect the existence of minefields (infrared, chemical, bacteria) and the others should enable precise localizations of particular targets (metal detectors - MD, ground penetrating radar - GPR, camera, tactile prodder, and others). Positional data of detected targets can be directly set into minefield (GIS) maps. Beside tools used together with detection systems other tools for marking positions of targets are need. There are for instance most frequently used color sprayers.

- **Priority 2. Development of tools for preparing terrain**

  These tools represent relatively broad class of devices can be used in large variety of situations according to terrain conditions. There are especially: tools for removing obstacles or cleaning vegetation because of mines, after some years of deployment, are covered by sand (in desert conditions), ground, vegetation, masking means, etc. For removing these obstacles different remotely operated tools with sensory feedback should be developed, as for instance: saws, sand suckers, cutters, shovels, special grippers, diggers and probes, etc.

- **Priority 3. Development of technologies and equipment for neutralization/removing mines**

  Beside mechanical systems as for instance: rollers, ploughs, flails, rakes, hammers, etc., several other principles with tools that activate explosion of mines can be used. There are: explosive hoses, fuel air mixture burners, air – sand cutting jets, directed energy systems, lasers, microwave sources or sniper rifle. For the mine removal tasks there are special end-effectors in forms of double shovels, diggers, soil separators, etc. Input data for these systems are positions/coordinates of mine targets as well as actual sensory information (vision, proximity, tactile, force).

3.2 The global concept

When one talk about robotic technology for de-mining we have in mind a robotic agent with appropriate equipments that exhibit features, as follows:

It is unmanned vehicle/platform able to move and work in the minefield automatically, semi-automatically, or, remotely controlled. On board of the vehicle are manipulation systems and tools (robot arm, manipulator) with some desired motion and sensing capabilities for performing prescribed tasks: preparing terrain (removing obstacles, cutting vegetation, etc.), scanning terrain during detection and mine-cleaning (removing, neutralization, flailing, etc.). The vehicle is equipped by detection systems for its mobility control and mine detection/localization as well as the sets of special task-related tools for performing various tasks related to the de-mining process. Main parts of such a complex robotic system shows scheme in Figure 5.

In principle, advanced robotic technology could be applied for performing specific tasks in all three phases of the de-mining process:

a) **Searching large areas and localization of mines and any explosives (UXO) by fast and reliable ways.** Scanning terrain, detection and localization of mines has a crucial importance in whole de-mining process. Considering great number of types of produced mines (different forms, plastic materials, colors, etc.), variety of terrain, as well as possibilities of hiding mines in various terrains, the reliable detection equipment working on different sensing principles and fusing sensory information should be applied. This naturally includes elaboration of fast and reliable object recognition algorithms. Special robotic devices/vehicles are intended to use as carriers of detection systems for performing searching/scanning motions in the minefields and precise localization of detected targets.

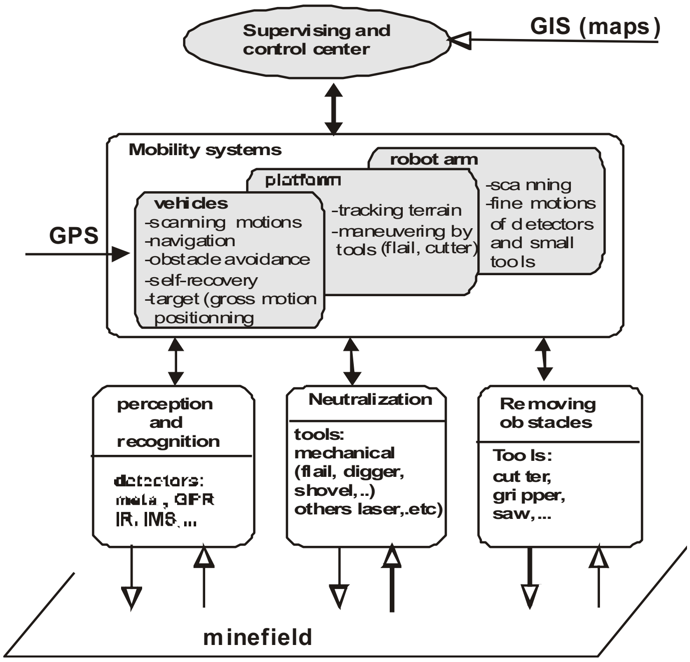


Figure 5: Parts of the robotic system for de-mining.

b) **Preparing infected terrain for reliable detection, as well as for neutralization procedures**, i.e. removing vegetation and any obstacles that could prevent detection or safe neutralization. When analyze activity of the human – de-miner, preparing terrain represents a very big portion of the time he spends under high psychological pressure. The principal problem is that after years of mine deployment the terrain is frequently covered by soil and vegetation or other mechanical objects. This is one of the most critical and dangerous task that require application of special tools and procedures. This fact naturally results in hard decision which technique will be used in particular cases. Applying robotic techniques for this kind of operations brings serious problems due to large possibilities of unknown objects and unforeseen situations. Anyway, performing such complex tasks require a multi d.o.f. robotic arm, sets of exchangeable tools together with additional sensory equipment, as for instance: haptic – tactile and force/torque sensors, proximity and position sensors, cameras in the hand, etc. Further development of techniques together with exchangeable task/oriented tools for removing different objects and cleaning vegetation are highly desirable. Naturally, much more sophisticated interface and feedback control system is need.

c) **Neutralization/destruction of mines.** In principle, there are three ways of neutralization. The first way results in activation of explosion of mines directly on places of their occurrence. For this purpose the most frequently used is the flailing technology. The second way lies in neutralization/destruction of mines on place without explosions. Several techniques as burning, abrasive water jet cutting, etc. have been, or, are under development. The third way is removing mines from terrain and safe transport on places of further neutralization. For this purpose special grippers are need.

Several global concepts of humanitarian de-mining were proposed in past. One of the most general concepts "ANGEL" considers activity of two missions: aerial and ground, having a common operation/information center (Project EUREKA 1889!). Main function of this operation center is to collect information, planning activities and evaluation of actual situations as well as controlling agents for detection and neutralization. The system should operate with GPS data over digital GIS maps. The agents for performing these tasks can be, in principle, aerial or ground vehicles that satisfy desired mobility features and are provided by adequate technology equipment, depicted in Figure 6.

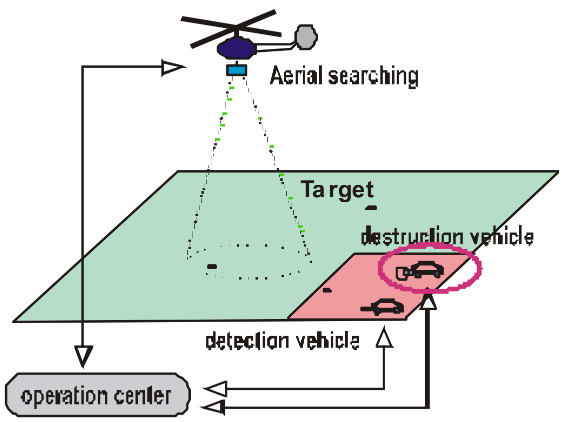


Figure 6: The global concept of de-mining.

Flying vehicle
Aerial searching is especially suited for first scan of large areas. Unmanned flying vehicle – small helicopter for this purpose is equipped by a special platform with several detection systems. The helicopter performs scanning motions over the terrain and as soon as any suspicion on mine (UXO) will arise coordinates of this place are saved into operation map. More precise localization of particular mines is doing by ground detection vehicle in next searching.

Land vehicle for detection

The vehicle automatically moves to address coordinates according digital map where an explosive was observed/detected by aerial searching. Its task is to localize exact position of targets, and/or to mark them by a visible color. The vehicle as porter of multi-sensorial system should exhibit good maneuvering and control capability in various terrains as well as autonomy features that enables to avoid obstacles, using remote vision system, etc. To prevent any accidental explosion of mines automatic stop and further searching procedure are activated. From the point of view mechanical performance there are some several specific requirements that such a vehicle should satisfy (maximal pressure on the ground, velocity related to speed of detection systems, noise and temperature limitation, reliable power and communication systems, self recovery capabilities, etc).

Neutralization – mine destruction land vehicle

This vehicle with similar maneuvering and control capabilities has to approach to the position of a detected mine and to neutralize it by activation or removing procedure. For this reason it has to be protected against explosions of mines not only antipersonnel but anti-tanks too.

Main functional parts of both above vehicles represent the robotic arm with a set of tools for removing obstacles/vegetation or for neutralization procedure.

3.3 Parameters and performance criteria

The de-mining equipment beside maximal reliability, should guarantee some standards given for particular devices. The effort for standardization of main functional characteristics resulted in CEN workshop agreement "Test and evaluation of de-mining machines" (CEN 2004). Similarly, when consider a new robotic system there are several criteria should be taken into account. There are as follows:

- Operational criteria
    - Working efficiency/neutralization capability
    - Reliability of cleaning
    - Self-recovery capabilities
    - Working time to change and repairs, availability of spare parts
    - Diagnostics and maintenance
    - Way of the operation/control and level of autonomy
- Technical parameters
    - Performance characteristics of the mobility/positioning systems
    - Characteristics of detection systems (detectors and reliability of recognition)
    - Neutralization and cleaning tools (reliability of cleaning)
    - Control and communication systems (distance, data transmission, etc.)
    - Mines and protection against explosions
- Applicability
    - Working conditions (environment, terrain, types of mines could be destroyed, etc.)
    - Transport to minefields
    - Technical level/skills of operators
    - Integration with respect to other technologies

- Additional attachment/auxiliary equipment (the set of exchangeable tools)
- Acceptability (friendly) by local people/operators

- Cost and economy
    - Total cost of the system (including services)
    - Working costs (price/working hour, price/m^2 of cleaned area)

3.4 Modular approach

Following the above discussion the most effective way will be if the modularity approach in construction of robotic tools will be adopted. Typical examples are electronic systems, computer technology, or, bicycle solutions. A number of parts, mainly mechanisms, can be solved as “general purpose” mobility, or, manipulation systems. These systems can be combined with another - de-mining task related tools. The modularity approach should be applied in all functional parts: the mobile platforms, robotic arms, tool changing systems, some tools for grasping objects, etc. Majority of these parts are manufactured in big series and they are available on the market. On the other hand many specific devices for performing de-mining operations should be newly developed as some “task-oriented” tools. The modular concept is then based on separation of these functional parts, as shows Figure 7. Such approach could minimize cost of general (multi) purpose parts and the whole system, as well.

Principal feature of such a multi purpose machine is that it will be able to perform, beside de-mining tasks, some other activities. There are for instance: several civil engineering works (transport of materials, drilling, raking, manipulation with soils and loose materials, etc.) The general purpose parts could be used for other risky operation as follows: fire fighting, disaster rescue and anti-terrorist actions, etc.

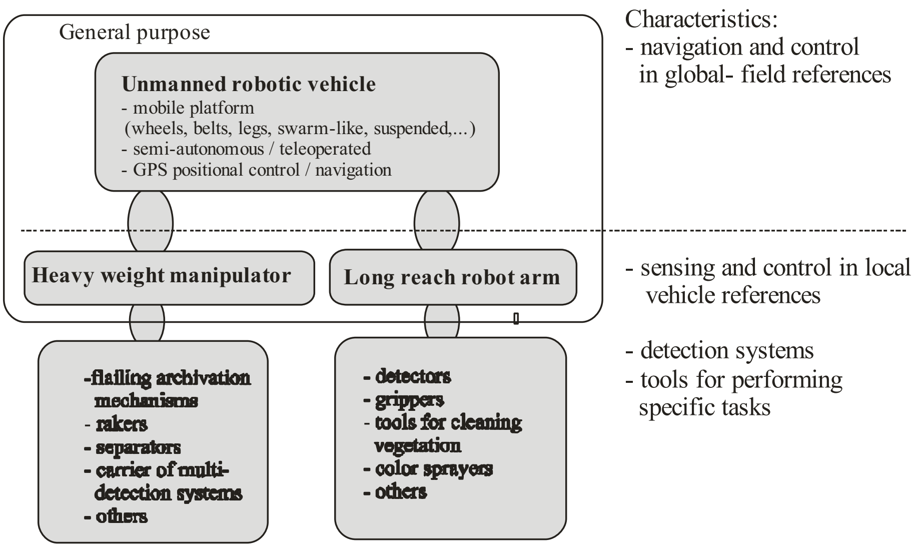


Figure 7: General purpose and task oriented parts of the de-mining system.

Following this concept and when consider actual state and availability of robotic and de-mining technologies the most general solution could include following functional parts:

- The mobility system represented by the ground vehicle, as mobile platform carrying various equipment, detection or destruction systems
- The heavy manipulator
- The long reach robotic arm
- Sets of exchangeable tools for removing obstacles/vegetation and marking positions of targets
- Neutralization/destruction tools
- Additional multi purpose tools and attachments
- Sophisticated sensing, navigation, control and communication systems

Based on analysis of de-mining problems, the robotic technology includes the multi-purpose mobile vehicle with on-board equipment, tasks and related tools, as given in Table 3.

Task in the minefield	**Equipment**	**Robotic tools**
Maneuvering in the dangerous terrain	Mobility system	The remotely controlled/autonomous robotic vehicle - carrier of tools
Searching dangerous terrain	Mine detection systems on platform (mainly metal detectors and Ground Penetrating Radar – GPR) Detectors on the end flange of the long reach arm Marking system of targets	Heavy manipulator Long reach robot arm
Neutralization by flailing	Flailing mechanism	Heavy manipulator
Removing mines, obstacles, …	Grippers, suckers,	Robot arm
Neutralization by using specific techniques: posing explosives, burning and others.	Grippers – special tools	Robot arm
Post – cleaning verification, removing metal parts, …	Detection systems Magnetic separator of metal elements	Heavy manipulator Robot arm
Cleaning vegetation	Cutters of vegetation, grippers, saws, sand suckers, etc.	Heavy manipulator, Robot arm
Manipulation with soil and loose materials: transport, loading, digging, drilling, etc.	Additional accessories/tools (rakes, soil loading tools, drillers, etc.)	Heavy manipulator

Table 3: Tasks for robotic tools.

Taking into account possible situations that could arise in de-mining process a most general solution of the ground vehicle that enables to combine several functional equipments can be adopted, as depicted the design study in Figure 8.

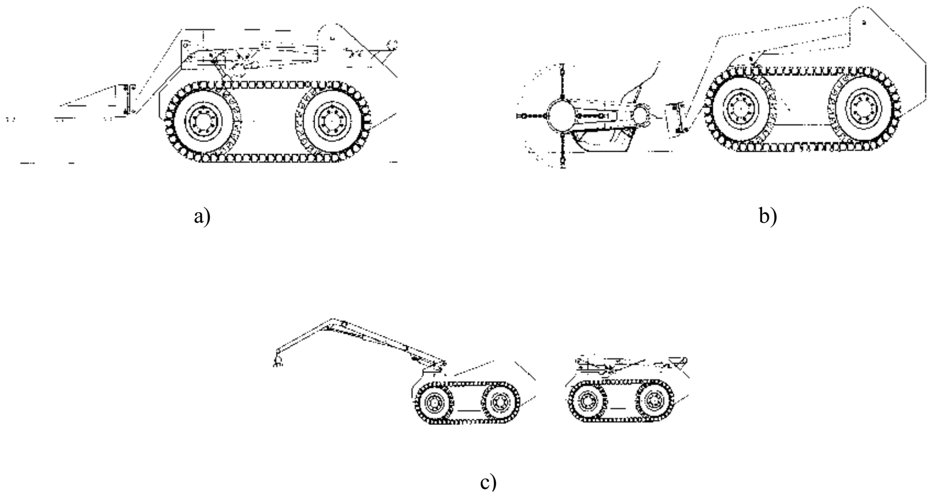


Figure 8: Modular concept of robotic vehicles. (a) The vehicle with front sensory platform. (b) The vehicle with flailing activation mechanism. (c) The long reach robot arm for tools.

Let us describe and specify requirements on particular functional parts.

- **The vehicle and its mobility system.** The vehicle and its mobility system should provide good maneuvering capability in various terrains. Tenths of mobile robotic devices moving on wheels, belts or legs have been developed. With respect to general requirements given, as discussed before, the mobility that combines wheels and belts seems to be one of the best and most widely used solutions (Havlík 2003a, 2005). The vehicle as carrier of multi-sensorial system and other robotic tools should exhibit some autonomy features, as collision avoidance, automatic stop in cases of detected mine and self recovery capabilities. For the security reason it has to be protected against explosions of mines (not only antipersonnel but anti-tanks too).
- **A heavy 3 - 4 d.o.f. manipulator.** The heavy weight manipulator in front of the vehicle with about 1000 - 1200 kg payload capacity is the main carrier of heavy sensory systems as well as other mechanisms (flail with protective cover), tools for cutting vegetation, tools for manipulation with soils, etc.). It is equipped by distance/proximity sensor what enables tracking terrain at a given vertical distance as well as range detectors for collision protection.
- **Neutralization/mine-destruction tools.** Referring to possible techniques of neutralization, i.e., removing or destruction, the set of exchangeable tools can be considered. When compare existing techniques from the safety point of view, the flailing technique seems to be a single way

which is relatively safe, fast and reliable. It can be used especially in cases when coordinates of targets are not exactly known and terrain is covered by vegetation. The verified configuration: the vehicle with flailing activating mechanism on the heavy manipulator is depicted in Figure 8(a).

In principle, explosions of mines are activated by the beating force of hammers on the ends of rotating chains. On order to satisfy reliability of the cleaning procedure this force should be keep above some given limit and every segment of the terrain should be bit several times. Naturally, the rotation speed (rpm) of the flailing shaft and advance speed of the vehicle are mutually related and depend on several factors, as shown in Figure 9 (left). This dependence can be experimentally tested and the simple mathematical model can be built. The output of this model is integrated into vehicle control system as desired value of advance speed during operation. Practically, the control system for the flail should guarantee that every local place of the terrain that corresponds to diameter of mines to be hit by a given minimal force/energy.

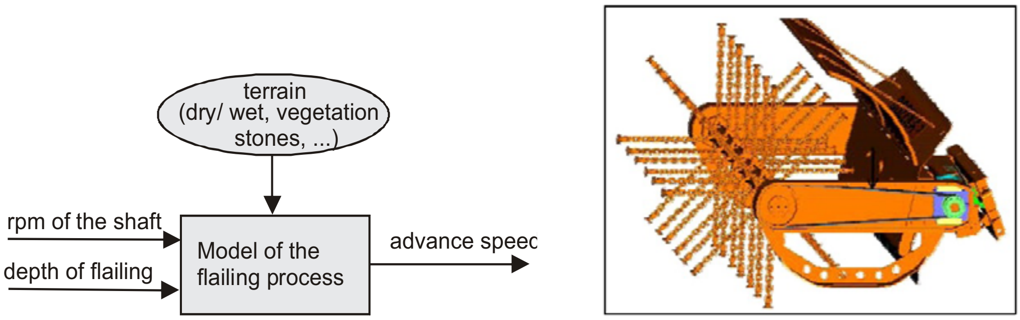


Figure: 9 Model of the flailing process and the flailing mechanisms

- **The long reach robotic arm (Figure 8c).** This robot performs specific tasks especially in situations as follows:
    - Targets are not exactly localized and further – more precise searching/detection procedures using hand held detectors should be made.
    - Targets are hidden by vegetation/stones, or, targets are in inaccessible positions for removing or other way of neutralization. In these cases special de-mining procedures and tools have to be applied.

In general, this 6 d.o.f. remotely controlled robot hand can exhibit the payload capacity about 20 -30 kg with the reach about 3m. It could be controlled in Cartesian hand references as well as in the vehicle reference coordinates related to camera systems. It is supposed that the vehicle is equipped by a set of exchangeable tools for performing fine operations. One of desired tasks can be laying additional explosives beside mines in situations when other neutralization procedure seems to be not reliable, or could be too dangerous.

- **Sets of exchangeable tools and attachment.** The set of tools consists of probes, cutters, various grippers, additional sensors for detecting explosives, etc. On the end of arm cold be the small camera what will allow more detailed views on the mine and place of its vicinity.
- **Vehicle navigation, control and communication systems.** As discussed above it is not expected that the system will work fully automatically. Nevertheless, searching and neutralization procedures made by mobile robotic vehicles should exhibit some level of autonomy. This fact naturally requires some unified approach to navigation and control. The general scheme of the control system, in Figure 10, shows some main components arranged in four control loops: global positioning, steering control loop, motor control loop and loops for control of various on board equipments (robot arm, manipulator, tools, and others).

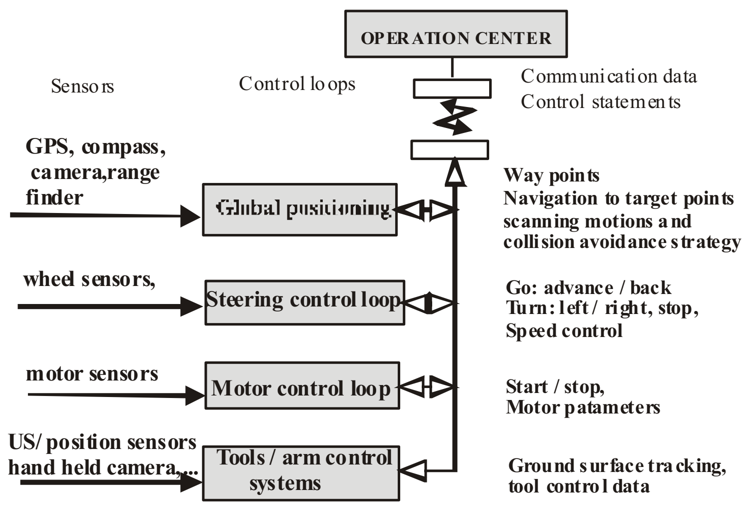


Figure 10: Components of the vehicle control system.

Specific working conditions and security reason require that the control system to work in two independent modes:

a) Automatic/programmable control mode through communication with operation center. This mode supposes normal operation of all systems as included scheme in Figure 5. Communication system for automatic modes transmit control and sensory data: way-points/trajectory, control statements for vehicle and motor, images from camera (remote vision), vehicle and motor states, warning error situations, etc.
b) Manual control using joystick/control panel/keyboard that allows maneuvering the vehicle without operation center. Manual control is used in cases as follows: removing the vehicle from the

minefield and recovery if any situation due to failure of any other system (programs, communication, etc.), loading/unloading the vehicles during transport, testing. This control mode directly operates steering and motor control loops. Communication is limited and corresponds to main statements for limited maneuvering motions.

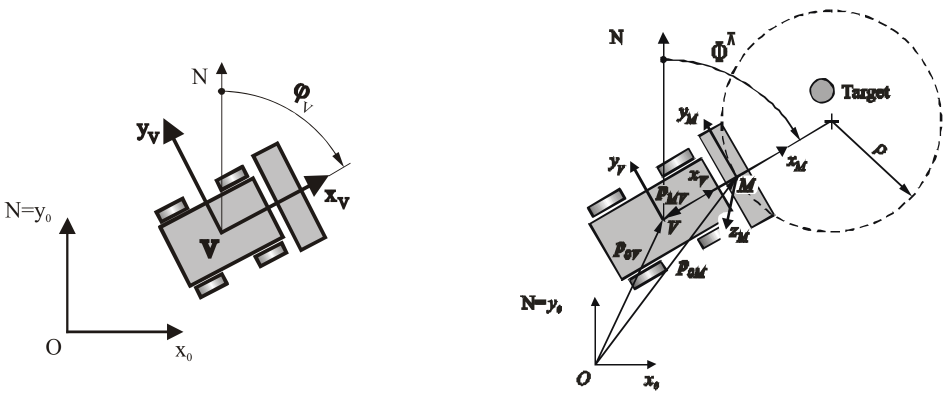
In general, any de-mining procedure includes some principal control routines. There are especially 3 basic tasks:

- **Task 1. Go to a given position and orientation.**

  Altitude and longitude of the vehicle is directly measured by on board GPS unit. The accuracy and resolution of measurements should correspond to accuracy of digital maps where all targets are recorded. As to orientation angle (azimuth φ) can be directly measured by digital compass. Then, three variables x_V, y_V, φ_V are controlled coordinates of the vehicle as can be seen in Figure 11a.

- **Task 2. Maneuvering to a given target. (Direct task).**

  The vehicle should move to a given coordinates of expected target in order to localize its position more precisely, or, to destroy it. For the security reason it is stated the security measure ρ and the approach trajectory/angle φ_{ap} to the expected target position. These parameters should guarantee that the first "sensory contact" of the vehicle and an expected dangerous target will be made in direction of the detection – sensory systems, or, the destruction mechanisms. The approach angle φ_{ap} expresses the direction of movement from an actual position of the vehicle to a specified distance to the expected position of the target. The security measure ρ represents the uncertainty of recording targets into digital maps as result of a limited accuracy of localization of previous aerial/terrestrial searching. Considering this uncertainty or security measure it is expected that the target be situated inside the circle given by coordinates in digital map. Then, the searching strategy of goal position depends on φ_{ap} and ρ parameters. Such a situation when the goal position is reached and next operation could start is depicted in Figure 11b.



(a) (b)

Figure: 11 (a) Position and orientation of the vehicle. (b) Approach to the target

- **Task 3. Precise localization of target position (inverse task).**

  The exact position of the target should be stated and recorded. Practically the vehicle should stop in some position where occurrence of target is expected. Searching dangerous terrain is performed within the reach of the robot arm by on board sensory equipment. There are, in principle, two possibilities:

  Detectors are on the sensory platform in front/beside the vehicle. The vehicle can slowly move in forward direction according to a given scanning strategy. Or, detectors are held in the robot hand and scanning motions and precise localization are made by detectors held in the robot hand as depicted Figure 12.

  The task is then to ascertain positions of targets using transformations that relate to actual position of particular detection system (Havlik, 2002).

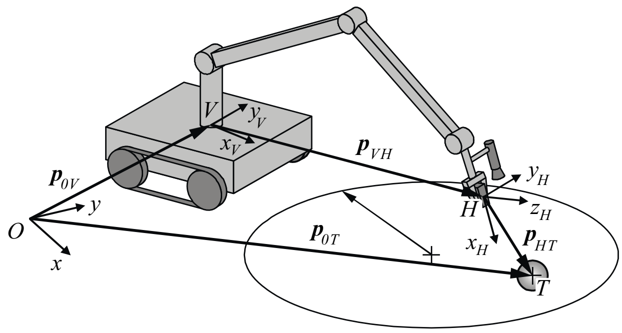


Figure: 12. Precise localization of the target by detectors held in robot hand

As obvious, further more sophisticated control routines that will correspond to sensory systems can be previously programmed. There are for instance:

- Obstacle avoidance algorithms
- Scanning motion strategies
- Self-recovery strategies
- Other routines that reduce psychological stress of the operator

When compare desired characteristics of above functional parts with respect to the actual state in development of manipulation/robotic technology the concept of modularity can be easily adopted.

4 Multi – purpose robotic vehicles

To keep the reality and in order to show the course of development of such kind of machines the "Božena" family machines are shown below; as one representative example (www.bozena.eu).

4.1 The “BOŽENA” machines

The primary concept of the vehicle was based on modification of the small loader i.e. machine for manipulation with loose materials, terrain works, etc. The flailing activation mechanism i.e. rotating shaft with chains and hammers on their ends is fixed on the end flange of the hydraulically powered manipulator in front of the vehicle. The radio communication system enables remote mobility control, manipulation with active mechanisms as well as monitoring relevant parameters of the whole system. Next generations of these mini-flail machines “Božena 2 and 3“, were constructed as task oriented machines have been produced within 2000-2002. They exhibit more powerful driving unit, better manoeuvring and control capabilities and, due to more power available for driving flailing mechanisms controlling the energy much more reliable activation by was reached. (Havlik, 2007a, b)

Further development of these machines represents important design changes, improvement of their performances to reach more applicability. New machines, except flailing mechanism, enable to use various additional attachments. The latest generations of these machines and more detailed description is given in next. The total number of these machines actually in active operation is more then 130, practically in all countries infected by landmines.

Results from more then fifteen years experience of using similar machines can be summarized into statements as follows:

Despite the fact that the vehicle with flailing mechanisms cannot guarantee 100% reliability of cleaning it is an effective tool especially in cases when positions of mines are not exactly know, or if the terrain is covered by vegetation. To satisfy more/maximal reliability the post verification procedure of the cleaning process can be realized using vehicles equipped by mine detection systems.

Using remotely operated vehicles minimizes psychological pressure and improves safety of persons. The useful help for operator is, if some functions are performed automatically, for instance flailing process with respect to advance speed, or, straight line control routines.

The efficiency of the whole de-mining process will be improved if mines are previously detected and localized. Then, the destruction vehicle could be directly navigated to these positions where mines are expected.

According to experiences from using these machines on many minefields the vehicle should be constructed as a “multi purpose” machine able to perform various activities. For this reason several additional attachments are need. The “Božena 4” in Figure 13, is the fourth generation of the mini-flail vehicles mainly oriented for clearing large areas from antipersonnel mines (AP) as well as from anti-tank (AT) mines up to 9 kg of TNT equivalent.

The last generation machine of this family, “Božena 5”, belongs to category of midi-flail systems. This much more powerful machine exhibit about two-times higher productivity of cleaning comparable terrains. To reach a good manoeuvring capability in various terrains the solution that enables to combine wheels and belts was adopted.

As to control this vehicle and all its mechanisms are controlled from the cabin where all data and information from the process, about the machine and its environment are transmitted. The operator can use the special portable control box with keyboard and joystick. Some principal control routines can be pre-programmed.

Figure 13: "Božena 4" (left) and "Božena 5" (right) in de-mining action.

To improve controllability of de-mining actions the on-board remote vision system has been developed and is installed. In the most complex configuration it consists of two stable cameras for observation the environment in front and in rear of the vehicle and one adjustable camera system in Figure 14. This robust camera is fixed on the 2 d.o.f. mechanism which enables adjustable observation within the whole area 360^0 around the vehicle and +/- 20^0 of tilting. Pictures from cameras are digitally transmitted on screens into the operation centre. Thus, combining the visual images with GPS data it is possible to recognize actual situation on the minefield (terrain, obstacles, trenches, trees, etc.) and to make correct decisions.

Figure 14: Robust camera and visual monitoring - control box.

4.2 Flailing mechanism and additional attachments

Concept of the multi-purpose machine includes two categories of tools and attachments:

a. Equipment directly related to the de-mining process, as platform for detection systems, flailing mechanism, target marking system, saw/cutter of vegetation, system for removing metal parts, grippers, etc.
b. Equipment for engineering works as digging, drilling, loading and transport of soil or loose materials, removing obstacles, etc.

Principal tools from the set of attachments have been developed for Božena machines are given in next.

4.2.1 Flailing mechanism

The well known flailing principle consists of the rotating shaft with the set of chains and hammers on their ends. The crucial problem is to design such a flailing system which keeps maximal efficiency and quality together with high productivity of cleaning process. To achieve this performance many parameters and characteristics should be studied and experimentally verified. Some of them are: length of chains, forms and material of hammers, positions of chains on the shaft, speed of rotation, impact energy of hammers, advance speed with respect to depth of penetration, soil, etc. Beside technical criteria, the mechanism should be very robust to resist explosions of AP mines and possible AT mines too.

The flailing mechanism in Figure 15 is designed as an independent system powered by two hydromotors with reverse rotation possibility. The flailing process, including advance speed, shaft rotation speed, depth, copying the terrain, is fully controlled by pre-programmed routines.

Figure 15: Flailing mechanism.

4.2.2 Collector of Magnetic Parts

On each minefield, before and after cleaning process there are usually spread great numbers of metal elements, such as shells, ammunition cartridges, mine fragments, or other ferromagnetic parts such as wires, screws, etc. Obviously, these spread parts result in false signals of metal detectors when the verification procedure is doing. To pick up small ferromagnetic parts the special attachment - magnetic collector, in Figure 16, is shown

4.2.3 Soil Separator

Another useful attachment is the mechanism for sifting and recycling soils where AP mines and UXO are expected. This attachment enables to take up the material (soil, waste) and, after closing the drum, by turning motion the content is sifted. The objects, as AP mines, remain inside the drum and may be dumped afterwards after opening the jaw. Grated form of jaws is as well the best solution enables to spread the blast wave in case explosions inside the drum. As the procedure is remotely controlled the safety for operator is provided.

Figure 16: Magnetic collector

Figure: 17: Separator for sifting and recycling soil

4.2.4 Other Attachment

Beside direct de-mining process, there are many dangerous works should be made in remote operation mode. Main reason is to protect persons if any suspicion on explosion or other possible hazard situation could arise. There are several useful accessories that can be directly attached on the end flange of the heavy load manipulator, frequently applied for most principal works are in Figure 18.

5 Conclusion

There is one of principal instruction from the history: one cannot expect that people in war conflicts will not use any available ways or things that could give them an advantage over the other side. This fact naturally includes using mines too. The single solution lies in development of fast, effective and reliable de-mining technologies that will result in useless application of these weapons. The advantages that give

Figure 18: Accessories for remotely operated de-mining machines

their deployment for one side of the conflict should be eliminated by the availability of fast and reliable detection and neutralization technologies. Then, reasons for their use will be reduced.

As can be seen problem of de-mining crossed borders of infected countries and research is doing in many laboratories in cooperation on the international level. The single way which reduces risk for people doing this dangerous operation and, contemporary, improves productivity of cleaning operations is application of advanced robotic technologies. As discussed in this chapter there are some several specific requirements that a robotic system for performing risky operations, especially de-mining, should satisfy. Beside technical parameters, operational performance and cost criteria, better applicability can be reached if all functional parts will be robust and relatively simple.

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References

Baudoin, Y. (2008). Mobile Robotic Systems Facing the Humanitarian Demining Problem State of the Art (SOTA). In 7th IARP International WS HUDEM' 2008, AUC.

Doroftei, D., Colon, E., Baudoin,Y. (2006). A modular control architecture for semiautonomous Navigation. Proceedings of the 9th International Conference on Climbing and Walking Robots.

CEN (2004). Workshop Agreement Test and evaluation of demining machines. CWA 150 44.

Cepolina E.E. (2002) Progress in devices for lacalization of antipersonal mines. PhD rep. Genova Univ. Italy

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

Fukushima, E.F., Freese, M., Matsuzawa, T., Aibara,T., & Hirose,S. (2008).Humanitarian Demining Robot Gryphon – Current Status and an Objecitve Evaluation., Intnternational Journal on Smart Sensing and Intelligent Systems.1(3).

Fukuda,T., Hasegawa,Y., Kosuge,K., Komoriya,K., Kitagawa,F., & IKEGAMI,T. (2011) Environment-Adaptive Antipersonnel Mine Detection System: Advanced Mine Sweeper. Using robots in hazardous environments. Woodhead (pp. 285-298).

Faust A. A., et al. (2005). Canadian tele-operated landmine detection systems Part I: The improved landmine detection project. International Journal of Systems Science, 36(9), pp. 511-528.

Fukushima E.F. et al. (2008). Humanitarian demining robot gryphon – current status and an objective evaluation. Int. J. on Smart sensing and intelligent systems, 1(3).

Geneva International Centre for Humanitarian Demining (GICHD), (2005). A Study of Manual Mine Clearance. (Books 1-5). Geneva International Centre for Humanitarian Demining, .Geneva, Switzerland.

Geneva International Centre for Humanitarian Demining (GICHD), (2010). Mechanical demining equipment Catalogue. Geneva International Centre for Humanitarian Demining, Geneva, Switzerland.

Geneva International Centre for Humanitarian Demining (GICHD), (2008). A Handbook of Mechanical Demining Geneva International Centre for Humanitarian Demining, Geneva, Switzerland.

Geneva International Centre for Humanitarian Demining (GICHD), (2006). Guidebook on Detection Technologies and Systems for Humanitarian Demining. Geneva International Centre for Humanitarian Demining, Geneva, Switzerland.

Geneva International Centre for Humanitarian Demining (GICHD), (2008). Proc. Second Mine Action Technology Workshop, Geneva.

Habib, M. K. (2007). Humanitarian Demining: Reality and the Challenge of Technology -The State of the Arts. International Journal of Advanced Robotic Systems, 4. (2), 151-172.

Habib. M. K. (2008). Humanitarian Demining: The Problem, Difficulties, Priorities, Demining Technology and the Challenge for Robotics. In book Humanitarian Demining Innovative Solutions and the Challenges of Technology, ed. Maki K. Habib, Vienna, Austria, I-Tech Education and Publishing, (pp. 1-56).

Habib,M. K. & Baudoin, Y. (2011) Mechanical Mine Clearance Development, Applicability and Effectiveness. In Book Using robots in hazardous environments. Woodhead publ. (pp.299-326).

Havlik, S. & Licko, P. (1998) Humanitarian demining: The challenge for robotic research The Journal of Humanitarian Demining, USA.

Havlik, S. (2002). Mine clearance robots. In International Advancet Robotics Program - IARP International Workshop on Robots For Humanitarian Demining, HUDEM '02, (pp. 33-38).

Havlik, S. (2003). A concept of robotic vehicle for demining. In EUDEM2-SCOT –2003 International Conference on Requirements and Technologies for Detection, Removal and Neutralization of Landmines and UXO, (pp. 371-376).

Havlik, S. (2003). Some concepts and design consideration in building robots for humanitarian demining. In Proc. 2003 IEEE ICRA 03, International Conference on Robotics and Automation, Workshop "The State of the Art of Robotíce in Humanitarian demining.

Havlik, S. (2004). Robotic agents for dangerous tasks. Features and Performances. In Proc. International Workshop Robotics and Mechanical assistance in Humanitarian Demining and Similar risky interventions, IARP.

Havlík, Š. (2005). A modular concept of robotic vehicle for demining operations. Autonomous Robots, 18, 253-262.

Havlik, S. (2008a). Some Robotic Approaches and Technologies for Humanitarian Demining. In Maki K. Habib, Humanitarian Demining Innovative Solutions and the Challenges of Technology, I-Tech Education and Publishing, (pp. 289-314).

Havlik, S. (2008b). Land Robotic Vehicles for Demining. In Maki K. Habib, Humanitarian Demining Innovative Solutions and the Challenges of Technology, I-Tech Education and Publishing, (pp.315-326).

Havlik, S. (2011) Robotic tools for demining and risky operations. In Book Using robots in hazardous environments. Woodhead publ. (pp.327-352)

Ide, K .et al. (2004). Towards a semi -autonomous vehicle for mine neutralization. In International Workshop Robotics and Mechanical assistance in Humanitarian Demining and Similar risky interventions, IARP.

Masunaga, S & Nonami, K. (2007) Controlled Metal Detector Mounted on Mine Detection Robot, In International Journal of Advanced Robotic Systems, 4,(2), 237-245.

Mc Donald J A et al. (2003) 'Research plan for a multi-sensor landmine detector'. Proc. Int. Conf. Requirements and Technologies for the Detection, Removal and Neutralization of Landmines and UXO. Sept. 15-18, 2003, Brussels, Belgium, 625-632

Mori Y., et al. (2005) Feasibility Study on an Excavation-Type Demining Robot. Autonomous Robots, 18, 263-274.

Nonami, K. et al. (2008). Mine Detection Robot and Related Technologies for Humanitarian Demining. In book Humanitarian Demining Innovative Solutions and the Challenges of Technology, ed. Maki K. Habib, Viena, Austria, I-Tech Education and Publishing.

Santana, P. et al. (2008). Developments on an Affordable Robotic System for Humanitarian Demining. In book Humanitarian Demining Innovative Solutions and the Challenges of Technology, ed. Maki K. Habib, I-Tech Education and Publishing.

Tojo, Y. et al.: (2004). Robotic System for Humanitarian Demining - Development of Weight-Compensated Pantograph Manipulator. In Proceedings of the IEEE International Conference on Robotics and Automation (ICRA'2004), (pp. 2025-2030).

Wetzel, J.P. & Smith, B.O. (2003). Landmine detection and neutralization from a robotic platform. In Proc. EUDEM2-SCOT –2003 International Conference on Requirements and Technologies for Detection, Removal and Neutralization of Landmines and UXO, (pp. 365 – 370).

Wetzel, J. P. et al.: (2006).Modular Robotic Control System for Landmine Detection. In Proceedings of the 6th Annual Intelligent Vehicle Systems Symposium & Exhibition.

Wojtara T. et al.: (2005) Hydraulic master–slave land mine clearance robot hand controlled by pulse modulation. Mechatronics 15, 589–609.