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Some Robotic Approaches and Technologies for Humanitarian Demining

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1. Introduction

Landmines, especially anti-personnel, are more-less psychological weapons. The advantages that result from their deployment for one side of the conflict should be eliminated by the availability of fast and reliable detection and neutralization technologies. Then, reasons for their use could be reduced.

Classic methods for detection and removing mines, used at present, are dangerous, too costly and considering the number of mines, are very slow. Within technologies for cleaning most frequently used are mechanical systems (Habib, M.K. 2002). Main drawback of these purely mechanical techniques is that they should mechanically effect on large areas, frequently, without any occurrence of mines. More, no such system can satisfy desired 100% reliability and frequently manual verification of yet cleaned area is required. It should be said that the key problem of demining lies and will be solved if mines are reliably detected and localized. Then the neutralization procedure is directly addressed to this place of mine occurrence.

The overviews of existing research projects, techniques and equipment have been developed for performing particular tasks are listed in several databases (www.gichd.ch; GICHD, 2006; www.hdic.jmu.edu; www.eudem.vub.ac.be) and in several conference proceedings.

The demining tasks represent dangerous works in hazardous environments the safety of human beings and / or valuable equipment then, the emergency management application should takes place. As human safety is the highest priority, the interest is to remove the operator from the hazardous scene and / or either totally to substitute him by an onboard "intelligent" agent - which is expected to provide the same or similar functionality. The first step is to provide the operator by such means that would enable him to perform the same mission safely, i.e. without direct entrance on dangerous terrain and contacts with explosives.

Considering large polluted areas and drawbacks of actual demining technologies main contributions by using robotic technologies are expected in following topics:

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

Source: Humanitarian Demining: Innovative Solutions and the Challenges of Technology, Book edited by: Maki K. Habib, ISBN 978-3-902613-11-0, pp. 392, February 2008, I-Tech Education and Publishing, Vienna, Austria

Performing these tasks by a "robot" is a big challenge for research in all domains of robotics. Oriented research is especially desired in the following domains (Ide et al., 2004; Wetzel & Smith, 2003; Mori et al. 2005; Hae et al. 2005). There are especially:
- *Mobile robotics.* Such a robot should be autonomous or semi-autonomous vehicle, easily transportable, and cheap. It should be able to move in various terrains (holes, slopes, stones, etc.) with possible obstacles (trees, weed coppice, wickets, waters, etc.) and to resist accidental explosions of mines. For neutralization of mines it is equipped by one or several appropriate mine removing or / and explosion activating systems.
- *Sensing technology.* Detection and localization of mines in terrain has a crucial importance in demining operations. Considering great number of types of produced mines (different forms, plastic materials, colors, etc.), variety of terrain as well as possibilities of hiding mines in various terrains the reliable detection equipment is highly desirable. Such a detection system should perform using more sensing principles and fusing sensory information. This naturally includes elaboration of reliable recognition algorithms.
- *Control and communication system.* The perception and information system includes several smart sensors need for the mobility control, searching dangerous terrain, localizations of targets, obstacle avoidance and navigation. All these functions suppose large amount of transferred data via wireless communication.
Much research work has been yet done in the domain of detection and localization of mines. Beside known methods new sophisticated sensing principles able to detect and recognize mines, as hidden objects, are under development. This is the most crucial task in the whole process. Because of automatic demining process is based on using special robotic vehicles / agents further research is oriented to the development mobile agents able to operate in, or, above the dangerous and partially unknown terrain as porters of detection systems and other tools used for preparing place of occurrence of mines and their neutralization, as well. Some robotic concepts and problems related to terrestrial demining are discussed below.

2. General Considerations

2.1. Robotic Approaches

Many research projects and lot of research work has resulted in design of several concepts of demining technologies as well as development new machines and especially detection systems. But, despite this effort and promising performances in laboratories, several sophisticated solutions and systems did not find such acceptance in practical use as was expected.
Designing a robotic technology the first idea is to construct the universal all terrain robotic system, highly mobile, lightweight, that could be immediately set to demining works all around the globe. Although such an idea could be realizable, when one considers the current state of technology, there is no reason to spend so much money and enormous human effort to develop such a complicated high-tech and enormously expensive system. Any robotic system should satisfy specific conditions directly related to its local application (Antinić, et al., 2001). Let us mention some reasons that directly influence the choice and use the adequate technology:

Principal requirements
When analyze actual situation in technology for humanitarian demining and compare its application one can deduce some principles:
Mechanics and mechanisms. Reliability and light-weight robust mechanics is preferred and desirable. The equipment should be easy, or, self – deployable directly on the minefields.
Electronics. HW and SW parts need not to be built on the most sophisticated technology. More important is that all systems should resist any possible actions due to errors of operators, shocks during transport, etc.
Sensors/detection systems. Development and availability of cheap, light-weight and reliable sensors can certainly solve the majority of searching problems.
Control. Remote or semi-autonomous control that reduces the risk of human operator is desired. The complexity and level of training for local operators should correspond to their local talent and technical education. An understandable and robust system with minimum training effort is preferred.
It is obvious that all parts of the system should be adequately robust to sustain not only harsh working and climatic conditions but some possible accidental explosions too. It should be said that any complex repair to be made on place is very limited. Beside acceptable performance parameters the robotic system should exhibit a "self- recovery" capability. This means that it could be removed from the minefield without access or interventions of humans.

Economy.
Mines are deployed in post – battle regions where mainly local materials, local manufacturing and local manpower should be used to perform demining operation and to maintain all technology. Technical knowledge of people is very limited and access to high-technology components is almost absent. Usually the economy of such regions does not work, or, it is totally destroyed. Demining operations are then usually financed by donor organizations. It is obvious that under such conditions using low-cost demining equipment, including standard hand searching and neutralization technologies are more preferred.

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

2.2. Main Rules and Criteria

Before consideration about a robotic system to be in use on the minefields there are some main rules have to be respected yet in conceptual design. Let us mention some main rules that should be taken into account before starting a new development of any equipment:

- **Minefields are not laboratories.** Robust and reliable constructions as well as control techniques should correspond to harsh working conditions and environment. This includes solving so called "self-recovery strategies" in most crucial situations that could arise (occasional explosions, errors in systems / operators, lost of communication, etc.).

- **The cost and availability of detection as well as neutralization technologies** is a very important factor that could limit their mass use in post conflict areas. Robotic cleaning should be faster (as to productivity in m^2/hour), cheaper (as to total cost/m^2) comparing to standard hand methods, reliable and safe.
- **Any new demining technology should be easily accepted by local authorities and people.** The robotic system should satisfy specific conditions related to its local application demands (country people and their education experiences, infected terrains, climatic conditions, type of mines, maintenance, etc).
- **There are no universal solutions.** Robotic technology cannot totally replace humans in all phases of demining process. Some robotic approaches should replace some most dangerous searching / neutralization methods. Automatic ways are especially suited for primary detection and cleaning large areas under some homogenous conditions (obstacles, mines, vegetation, etc.).
- **The reliable detection and localization of mines** (UXO) as targets is the task of primary importance. It can be said: "As soon as the mine is found and localized more then 90% of problem is solved".
- **Any new solution should minimize risks for people**, as well as for the damage of relatively expensive technology. This risk of the damage, or, the lifetime by using new technology should be calculated in expected comparable total cost for demininig the unit of surface.

2.3. Requirements on a Robotic System

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

Operational criteria

- Working efficiency / neutralization capability
- Reliability of cleaning
- Self-recovery capabilities
- Working time to change and repairs, availability of spare parts
- Diagnostics and maintenance
- Way of the operation / control and level of autonomy

Technical parameters

- Performance characteristics of the mobility / positioning systems (positioning accuracy, speed, allowable slopes, payloads, masses, maneuvering capabilities, etc.)
- Characteristics of detection systems (detectors and reliability of recognition)
- Neutralization and cleaning tools (reliability of cleaning)
- Control and communication systems (distance, data transmission, etc.)
- Mines and protection against explosions
- etc.

Applicability

- Working conditions (environment, terrain, types of mines could be destroyed, etc.)

- Transport to minefields
- Technical level / skills of operators
- Integration with respect to other technologies
- Additional attachment / auxiliary equipment (the set of exchangeable tools could be used not only in demining process)
- Acceptability (friendly) by local people / operators

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

2.4. Some Specific Features

When characterize main functions of a robotic system for demining: it should be a remotely / programmable controlled general porter of several detection systems able to perform searching dangerous terrain, localize and neutralize dangerous targets. It should exhibit excellent mobility and maneuvering capabilities in various terrains. General demand is for such an agent working in risky environment is that it should exhibit three following features: self-recovery capability, minimal risk assessment and maximal reliability in all actions.

The self-recovery performance is an important and specific feature directly related to particular tasks. Its main purpose is to prevent / to avoid loses or self-destruction of the agent and to finish a given action in risky environment without serious damages. The self-recovery strategies should start especially in unwanted situations as follows:
- In cases of any failure of technique (communication, engine, control system, sensory system, etc.). The problem is to remove it from the dangerous terrain without any risk for persons. One of the simplest ways how to solve such situation is using a cable and to pull it out by the winch mechanisms. The other possibility enables using another vehicle, which helps to remove the first one from the minefield.
- There are no / not enough information for further action. It seems to be risky situation to continue any motion; otherwise there is a probability that it could be destroyed. Solving such situation brings for operator / operation system the decision problem: to decide for the next action if any unexpected situation arose. The general rule is: the operator decides for the next paths of the agent in order to minimize any risk of damages for the agent itself. Naturally he should use all available sensor readings and information. This procedure represents the standard decision algorithms according to the scheme for risk assessment in Fig. 1.

It is obvious that some decisions can be represented by relatively simple routines working over a given set of options: Action : <STOP / GO BACK / … > if .< CONDITION: SENSOR ->. On the other hand, other operator’s decisions require much more complex assessment of possible risks with respect to given criteria. Such a typical situation arises during automatic demining operation when using mine detection systems give not reliable information about the presence of mines and there is only a suspicion if “something is inside”. In such cases the general rule is usually adopted: “the risk is minimized if one considers that there are always expected some mines”.

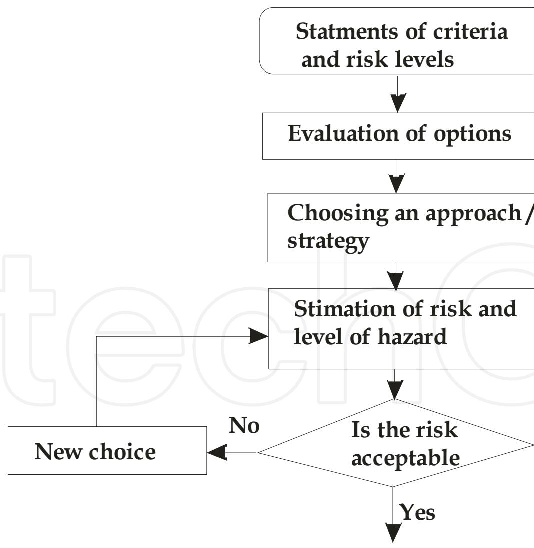


Fig. 1. The general risk assessment and decision procedure

3. Approach to Robotic Demining

3.1. Desired Performance

In general, the mine cleaning procedure consists of two main tasks:

- Detection and localization of land mines.
- Neutralization i.e. removing or destruction of mines on place.

These both tasks are usually directly related to the common problem and third important task:

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

Considering large polluted areas and drawbacks of actual demining technologies main contributions by using robotic technologies are expected in following topics:

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

As obvious, any robotic system can effectively work under some standard and expected conditions / environment. Performing demining activity this means that there are given some standard working environment and its capability as to maneuvering of the mobility system, reliable detection of mines and desired confidence level of neutralization equipment. This practically results in fact that automatic demining technology will be preferably used for cleaning large homogenous terrains without complex obstacles (vegetation, terrain, trenches, etc.). Beside such complex automatic equipments several task oriented semi - automatic, or remotely controlled devices can effectively take place. There are especially robotic vehicles and tools for searching dangerous terrains, robotic tools for neutralization of explosives / mines and tools for preparing terrain for demining. Naturally, a principal role in the whole demining process is given to the development of reliable detections techniques and technology.

3.2. Parts of the Global Robotic System

When consider a most general robotic mine clearance technology an advanced system consists of following parts. See Fig.2. (Havlik, 2004)

Mobility system. It is represented by remotely controlled / autonomous / semiautonomous mobile (robotic) vehicle, as general porter of sensory platforms and other manipulation systems for performing three principal tasks: detection, preparing terrain and neutralization. In principle, there are following possibilities:

- Free flying vehicles with suspended platform i.e. airborne mission mainly for searching especially large areas.
- Ground vehicles (wheeled / belt or walking / legged machines)
- Cable suspended platforms moving over the dangerous terrain

Multi-sensorial system for detection and recognition of mines. As to sensing principles automatic detection techniques should satisfy reliable detection / recognition of mines and to mark them into maps (assign them coordinates) as targets. In principle, the sensory systems can be situated on a special platform of a mobile vehicle performing scanning dangerous terrain or on the end of a robotic arm.

As obvious, some principles are more suited for searching large areas to detect the existence of minefields (infrared, chemical, bacteria) and the others should enable precise localizations of particular targets.

Tools for neutralization / destruction of mines. Beside mechanical systems as for instance: rollers, ploughs, flails, rakes, hammers, …etc, other principles that activate explosion of mines can be used. There are: explosive hoses, fuel air mixture, directed energy systems, laser, microwave sources or sniper rifle. For the mine removal tasks there are special end-effectors in forms of double shovels, diggers, etc. Input data for these systems are positions / coordinates of mine targets as well as actual sensory information (vision, tactile, force and other available sensors).

Tools for removing obstacles / vegetation and preparing terrain. Mines after some years of deployment are covered by sand (in desert conditions), ground, vegetation, masking means, etc. For removing these obstacles different remotely operated tools with sensory feedback should be developed. There are: sand suckers, cutters, shovels, special grippers, diggers and probes, etc.

Control and communication systems. Principal requirement is that the system should operate in remote control mode, or, semi-autonomously. As to the control a general system includes: mobility navigation / control, target positioning for detection, as well as neutralization systems.

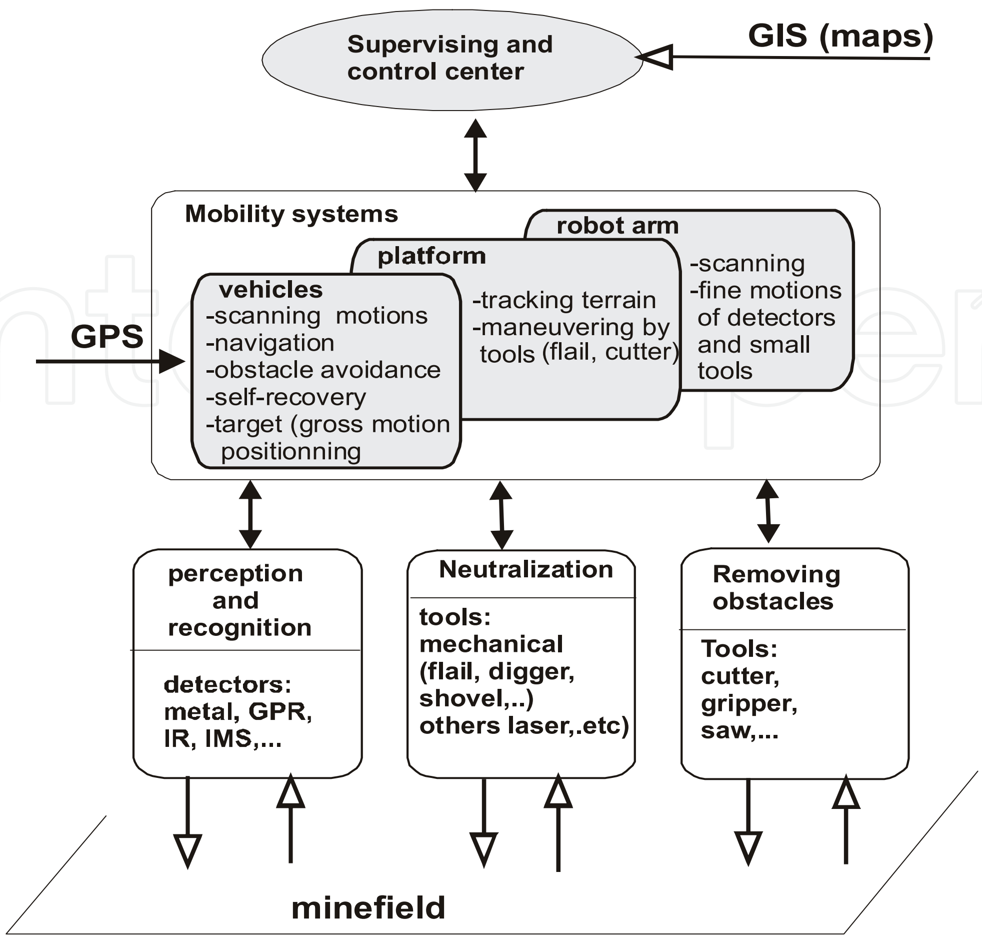


Fig. 2 Parts of the robotic demining system

3.3. Analysis of Motions and Functionality

When analyze main tasks of the demining process from the position / motion control point of view, positions are related to the base – field reference coordinates. Then, for displacements, two characteristic categories of motions can be distinguished. There are:

Gross motions, of the vehicle usually measured by GPS or other measuring system; for instance laser. As to the accuracy of positioning, as well as recording targets into digital maps it should correspond to the resolution of positional measurement.

Fine motions are performed by any of on/board tools (robot arm, platform). These motions are related to the vehicle reference system.

Some characteristic features of particular motions are in next table.

	Gross motions	Fine motions
Tasks	- Global positioning - searching/scanning motions - mapping targets - marking - flailing	- Fine motions scanning - removing mines /obstacles
Mechanisms	vehicles	- on-board robot arm and tools, - sensory platform
Desired positional resolution	< 10 m for aerial vehicle 0,3 - 0,5 m for ground vehicles (in global references)	< 2-5 mm (relative coordinates)
Sensing - primary positional control - adaptive positional control	GPS, laser, camera, etc. Sensors for vehicle-environment interaction: (mine detectors, obstacle detectors, etc..)	Internal sensor in joints of mechanisms. Sensors for tool-environment interaction (hand-held mine detectors, hand camera, force-tactile sensors, etc.).

Table 1. Motion characteristics of robotic systems

It should be noted that some operations procedures require more precise positioning of tools, then the others. For instance: the flailing destruction techniques must not so exact coordinates of targets for successful function. On the other hand removing mines requires relatively much more precise positional information for any control action.
Compare now some different performance requirements between particular tasks and classic robots used in manufacturing (see table 2). Let the characteristic measure be *m* - meter.

	Manufacturing	Demining
Range of the operation space	m	m. 10^2 ($\div 10^3$)
Positioning Accuracy / Accepted resolution	m. 10^{-4}	m.10^{-3}
Order difference	4	5 (6)

Table 2.

Because of there are considered two dependent positioning mechanisms, obviously, it is not possible to reach such an accuracy under all possible errors that could arise. For this reason the approach that includes elimination of possible uncertainties should be applied in control. Some robotic concepts some principal motion routines for control of robotic vehicle are given below.

4. The Global Concept "ANGEL"

One of the most general concepts "ANGEL" considers activity of two missions: aerial and ground, having a common operation / information center (ANGEL, 1998). . Main function of this operation center is to collect information, planning activities and evaluation of actual situations as well as controlling agents for detection and neutralization. The system operates with GPS data over digital GIS maps.

The agents for performing these tasks can be, in principle, aerial or ground vehicles that satisfy desired mobility features and are provided by adequate technology equipment, depicted in Fig.3.

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

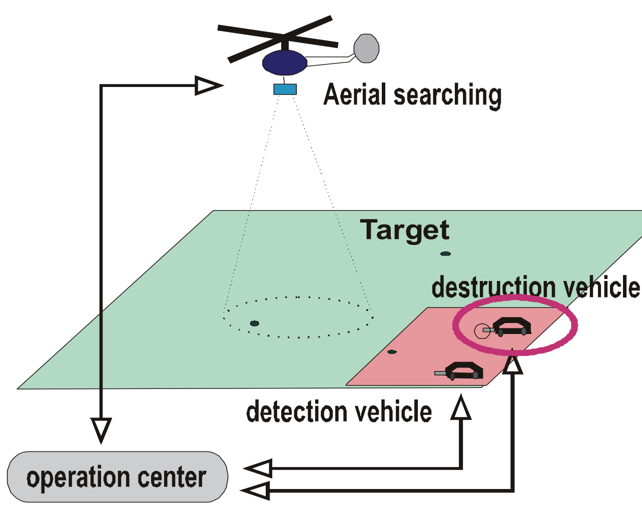


Fig. 3. The global concept of demining

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

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

Functional part of both above vehicles is the robotic arm with a set of tools for removing obstacles / vegetation or for neutralization procedure.

5. The Cable Suspended Searching Platform (Conceptual Study and Analysis)

5.1 The Principle and Main Parts

For searching dangerous terrain and relatively large operation space the concept of the cable suspended robotic platform was designed (Havlik, 1993, Havlik & Licko 1998).

In principle the system, as schematically illustrated in Fig.4, consists of three cable winches fixed on mobile columns. The ends of cables from particular winches are connected on the platform moving above the working place. Each winch mechanism is equipped by the cable length measuring sensor and the position / velocity control system. Thus for such a parallel mechanical structure any actual position of the moving platform determine three distances i.e. measured lengths of cables between the platform and end pulleys of winch mechanisms. The central control system performs transformations and coordinated motion control of the platform with respect to a world reference frame defined on place. Principal functional parts of the whole system are depicted in Fig. 5.

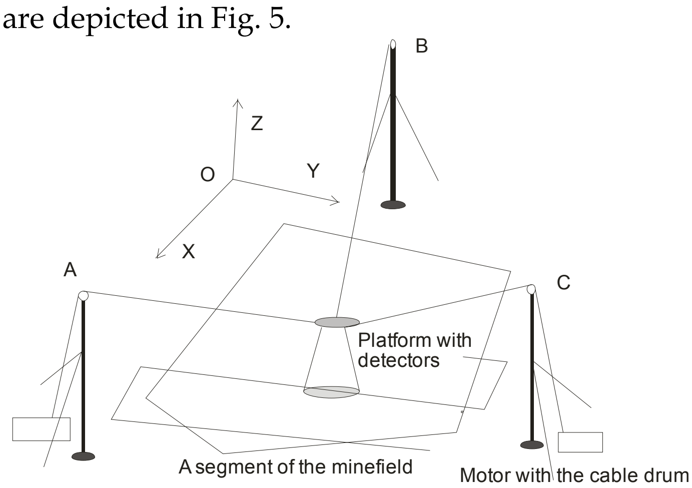


Fig. 4. Concept of searching dangerous terrain

This concept of scanning dangerous terrain by the suspended platform with detectors exhibits some advantageous features as follows:

Large workspace of operation which is reconfigurable according to actual terrain conditions

Low weight and simple transport

Fast and simple installation on place

Operation / control in Cartesian coordinates defined directly on place.

Using joystick, or programmable control it is possible to move the platform in a given scanning distance over the terrain. The Cartesian positions, i.e. x, y coordinates of any target are set into map, or, can be directly marked by colors. It is obvious that the operation space is given by the triangle created by the fixation positions of the end pulleys. It is approximately above the ground projection of this fixation triangle. As can be seen later, the upper boundary surface is given by the limit force in particular cables / fixations.

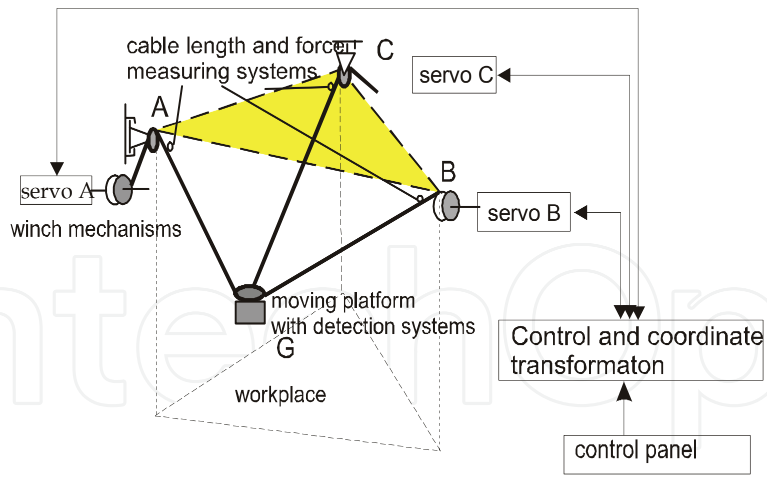


Fig. 5. Principal functional parts

5.2 Analysis of Motions and Control

Four main problems have been solved for this system. There are:

- ***Kinematic and force analysis.*** The task is to derive relations for motion and force transformation i.e. functions that relate actual motion and load values expressed in world reference coordinates and internal representation of control parameters i.e. cable length and internal forces.
- ***Coordinated motion control*** in world coordinates. This is a principal requirement to control and monitor scanning motions of the platform in Cartesian references mutually related to world references. Then, positions of targets are directly localized.
- ***Dynamic analysis and control****.* As follows from principal configuration the cable system exhibits limits that should be automatically adjusted.
- ***Calibration,*** i.e. to actualization of parameters in relations for motion and force transformations according to real configuration of the system and its spatial geometry.

Let us briefly explain solutions of these problems.

For the purpose of analysis following reference systems are stated on the geometrical scheme in Fig.6):

- O(x,y,z) the Cartesian world coordinate system of global positioning, Denote the fixation points A,B,C that create the triangle ΔABC above the working area. Each point of this triangle is given by three global coordinates $A(x_A,y_A,z_A)$, $B(x_B,y_B,z_B)$ and $C(x_C,y_C,z_C)$.
- A(x',y',z') the auxiliary Cartesian reference system where x',y' axes lie in the plane given by triangle ΔABC

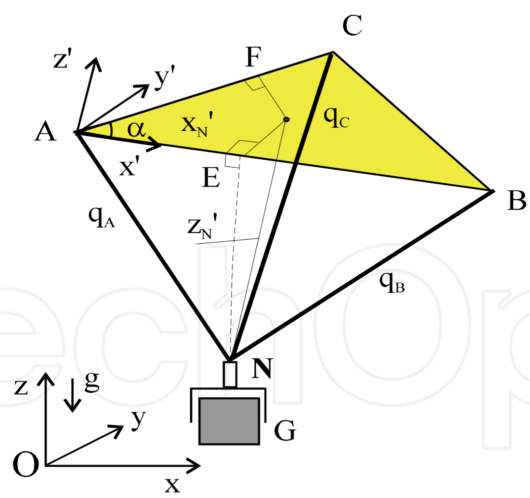


Fig. 6. Geometry of the cable support

Let point N be the reference on the moving platform. Its position gives the vector $\boldsymbol{p'}_N = [x'_N, y'_N, z'_N]^T$ in the A(x',y',z') local coordinate system or $\boldsymbol{p}_N = [x_N, y_N, z_N]^T$ in the global Cartesian references. These position vectors are mutually related using transformation

$$\boldsymbol{p}_N = \boldsymbol{p}_A + \boldsymbol{S}.\boldsymbol{p}_N^{'} \tag{1}$$

where $\boldsymbol{S}$ is the 3x3 rotation matrix of local coordinates into global references..
Denote by symbols: q_A, q_B, q_C ; the lengths of cables as controllable values. For the simplicity of calculations we will consider dimensions of the moving platform with respect to triangle ABC to be relatively small and negligible. Then, for such an actual tetrahedron ABCN one can write

$$\begin{aligned} q_A^2 &= (x'_N - x'_A)^2 + (y'_N - y'_A)^2 + (z'_N - z'_A)^2 \\ q_B^2 &= (x'_N - x'_B)^2 + (y'_N - y'_B)^2 + (z'_N - z'_B)^2 \\ q_C^2 &= (x'_N - x'_C)^2 + (y'_N - y'_C)^2 + (z'_N - z'_C)^2 \end{aligned} \tag{2}$$

Express now the actual position of the platform in global world coordinates for any combination of three controlled lengths of cables. Solving the above relations we have a unique solution for the Cartesian position $\boldsymbol{p'}_N$, when a combination of cable lengths q_A, q_B, q_C is given.

$$\begin{aligned} x'_N &= \frac{1}{2.\overline{AB}}(q_A^2 + \overline{AB}^2 - q_B^2) \\ y'_N &= -\frac{1}{tga}x'_N + \frac{1}{sina}\cdot\overline{AF} \\ z'_N &= (-)\sqrt{q_A^2 - x_N'^2 - y_N'^2} \end{aligned} \tag{3}$$

where according to Fig.6

$$\overline{AB}^2 = (x_A - x_B)^2 + (y_A - y_B)^2 + (z_A - z_B)^2$$
$$\overline{AC}^2 = (x_A - x_C)^2 + (y_A - y_C)^2 + (z_A - z_C)^2$$
$$\overline{BC}^2 = (x_B - x_C)^2 + (y_B - y_C)^2 + (z_B - z_C)^2$$
$$\overline{AF} = \frac{1}{2.\overline{AC}}(q_A^2 + \overline{AC}^2 - q_C^2)$$
$$\alpha = arccos(\frac{\overline{AB}^2 + \overline{AC}^2 - \overline{BC}^2}{2.\overline{AB}.\overline{AC}})$$

Direct task of kinematics

The position and motion of the platform is specified by three control parameters arranged into vector $\boldsymbol{q} = [q_A, q_B, q_C]^T$. The task is to express the motion in the global references. As derived above we calculate the actual global position is given by transformation (1).
Applying the time differentiation we have for velocities

$$\dot{\boldsymbol{p}} = \boldsymbol{J}_0 . \dot{\boldsymbol{q}} \tag{4}$$

and because of the Jacobi matrices $\boldsymbol{J}_A$ and $\boldsymbol{J}_0$ for incremental motion/velocity in local and global reference frames are related $\boldsymbol{J}_0 = \boldsymbol{S}.\boldsymbol{J}_A$ one get

$$\dot{\boldsymbol{p}} = \boldsymbol{S}.\boldsymbol{J}_A . \dot{\boldsymbol{q}} \tag{5}$$

Inverse task

For a given global position $\boldsymbol{p}$ we are looking for control parameters in the vector $\boldsymbol{q}$. Considering (2, 4) one can directly write for cable velocity and acceleration

$$\begin{gathered} \dot{\boldsymbol{q}} = \boldsymbol{J}_0^{-1}.\dot{\boldsymbol{p}} \\ \ddot{\boldsymbol{q}} = \boldsymbol{J}_0^{-1}(\ddot{\boldsymbol{p}} - \boldsymbol{J}_0\dot{\boldsymbol{q}}) \end{gathered} \tag{6}$$

where inverted Jacobi matrix is in form

$$\boldsymbol{J}_0^{-1} = \begin{bmatrix} 1/q_A & 0 & 0 \\ 0 & 1/q_B & 0 \\ 0 & 0 & 1/q_C \end{bmatrix} * \begin{bmatrix} x_N - x_A & y_N - y_A & z_N - z_A \\ x_N - x_B & y_N - y_B & z_N - z_B \\ x_N - x_C & y_N - y_C & z_N - z_C \end{bmatrix} \tag{7}$$

Force analysis

Denote by Q_A, Q_B, Q_C cable forces in tension and define the vector $\boldsymbol{Q} = [Q_A, Q_B, Q_C]^T$. Considering a possible external force $\boldsymbol{P} = [P_x, P_y, P_z]^T$ the load on the platform will be $\boldsymbol{F} = \boldsymbol{G} + \boldsymbol{P}$. Applying principle of virtual works one can write

$$\boldsymbol{Q}^T.\Delta\boldsymbol{q} = \boldsymbol{F}^T.\Delta\boldsymbol{p} \tag{8}$$

Solving this relation the forces in cables and external load are related

$$\boldsymbol{Q} = \boldsymbol{J}_0^T.\boldsymbol{F} \tag{9}$$

As follows from decomposition of an external load the values of three cable forces will increase with increasing *z*-coordinate of the platform position.
Naturally, in order to avoid an overload condition and to protect the system all cable forces should be supervised on maximal their values. These maximal cable forces give the upper boundary surface that limits the workspace. An example of the workspace analysis for a real geometry is given below. The upper limit surface of the operation workspace is given by boundary conditions

$$Q_i \leq Q_{lim} \tag{10}$$

Dynamics

The system dynamics in Cartesian space is described by equations

$$m\,\ddot{\boldsymbol{p}} + \boldsymbol{G} + \boldsymbol{P} = \boldsymbol{J}^{-T}.\boldsymbol{Q} \tag{11}$$

As follows from principle each cable force should be non-negative ($Q_i > 0$). This fact states the limit condition for maximal acceleration of the desired trajectory of the moving platform. Thus from (10, 11) it should be satisfied

$$\ddot{\boldsymbol{p}} \geq \boldsymbol{g} \tag{12}$$

where $\boldsymbol{g} = [0\ \ 0\ \ -g]^T$

Control

In general, the dynamics of the system with rigid cables is described in cable coordinates as follows

$$\boldsymbol{M(q)}\,\ddot{\boldsymbol{q}} + \boldsymbol{C(q,\ \dot{q})}\dot{\boldsymbol{q}} + \boldsymbol{D(q)q} \ = \boldsymbol{Q} \tag{13}$$

where ***M, C, D*** are (3x3) matrices that represent terms for inertia (**D**), Coriolis, centrifugal and friction forces **(C)** and gravity forces (**D*)*.**
Rewriting equation (11) into this form the system has to be controlled will be

$$m\,.\boldsymbol{J}^{\,T}.\boldsymbol{J}\ \ ^{1}(\ddot{\boldsymbol{p}}\quad \dot{\boldsymbol{J}}\dot{\boldsymbol{q}}) + \boldsymbol{J}^{\,T}(\boldsymbol{G}\ +\ \boldsymbol{P})\ =\ \boldsymbol{Q} \tag{14}$$

where

$$u = \ddot{p} = A.K_v(\dot{p} - \dot{p}_d) + K_p(p - p_d) - \ddot{p}_d \tag{15}$$

is the control vector, K_v, K_p are positive definite matrices and index d denotes desired values. Rem.: The choice of these matrices in some optimal sense is not the objective of this paper.

5.3 Calibration procedure

As soon as all three winch mechanisms with end pulleys have been installed on place we do not know the coordinates of the fixation points vectors $p_i = [x_i, y_i, z_i]^T$, i = A, B, C ; need for kinematic and force transformations. There is an initial problem: we have to execute calibration i.e. to actualize the parameters in relations for motion and force transformations for a real arrangement of the whole system. Principal requirement is to perform this calibration without any additional equipment.
In order to find the unknown coordinates of the A, B, C points the following calibration procedure is proposed in four steps:

a) Let us stake out three points M, N, and P on the ground x-y plane. These points create a triangle with known geometry. Although, in principle, this triangle could be chosen quite arbitrarily, it is more advantageous will be to construct it equilateral, as depicted in Fig.7.

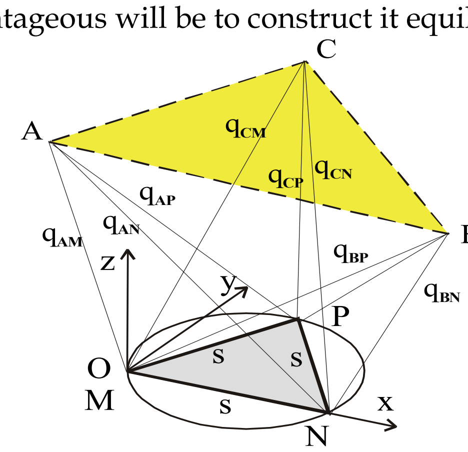


Fig. 7. Geometry for calibration

b) Using individual command of particular servos we perform positioning of the platform sequentially into points M, N and P. Denote by symbols: q_{AM}, q_{BM}, q_{CM}, q_{AN}, q_{BN},, q_{CN} and q_{AP}, q_{BP}, q_{CP} all measured lengths of cables that correspond to particular positions according to Fig.7.

c) Solving three tetrahedrons MNPA; MNPB and MNPC, the coordinates x,y,z of A,B,C points are calculated.

Consider now the equilateral triangle MNP; (MN = NP = PM = s; $s = R\sqrt{3}$). The position vectors and coordinates of these points are

$$\begin{aligned} \boldsymbol{p}_{N1} &= \begin{bmatrix} \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \end{bmatrix}^T \\ \boldsymbol{p}_{N2} &= \begin{bmatrix} R\sqrt{\boldsymbol{3}} & \boldsymbol{0} & \boldsymbol{0} \end{bmatrix}^T \\ \boldsymbol{p}_{N3} &= \begin{bmatrix} \tfrac{1}{2} R\sqrt{\boldsymbol{3}} & \tfrac{3}{2} R\sqrt{\boldsymbol{3}} & \boldsymbol{0} \end{bmatrix}^T \end{aligned} \tag{16}$$

Then, after substitution into (3) solutions for i = A,B,C will be

$$\begin{aligned} x_i &= \frac{1}{2R.\sqrt{3}}\left[q_{i1}^2 + (R.\sqrt{3})^2 \quad q_{i2}^2\right] \\ y_i &= \frac{1}{6R}\left[q_{i1}^2 + q_{i2}^2 \quad 2q_{i3}^2 + (R.\sqrt{3})^2\right] \\ z_i &= \sqrt{q_{i1}^2 \quad x_i^2 \quad y_i^2} \end{aligned} \tag{17}$$

d) Actualize the transformation matrix S_{0A} in (1) that relates actual configuration of fixation points A,B,C with respect to a given ground reference system O(x,y,z). Let us denote the elements of this transformation matrix

$$S_{0A} = \begin{vmatrix} s_{11} & s_{12} & s_{13} \\ s_{21} & s_{22} & s_{23} \\ s_{31} & s_{32} & s_{33} \end{vmatrix} \tag{18}$$

In order to calculate particular elements that express rotation of two reference systems one can write

$$s_{11} = \cos a_1 = \frac{x_B - x_A}{|AB|}; \qquad s_{21} = \cos\beta_1 = \frac{y_B - y_A}{|AB|}; \qquad s_{31} = \cos\gamma_1 = \frac{z_B - z_A}{|AB|}$$

$$|AB| = \sqrt{(x_B - x_A)^2 + (y_B - y_A)^2 + (z_B - z_A)^2} \tag{24}$$

and

$$s_{13} = \cos a_3 = \frac{n_x}{|\boldsymbol{n}|}; \qquad s_{23} = \cos\beta_3 = \frac{n_y}{|\boldsymbol{n}|}; \qquad s_{33} = \cos\gamma_3 = \frac{n_z}{|\boldsymbol{n}|}$$

$$\boldsymbol{n} = \overrightarrow{\boldsymbol{AB}} \times \overrightarrow{\boldsymbol{AC}} \tag{25}$$

where $\boldsymbol{n}$ is the vector perpendicular to the plane given by triangle ABC. It is calculated as the cross product of multiplication of two vectors $\overrightarrow{AB}$ and $\overrightarrow{AC}$ and $|\boldsymbol{n}|$ is its absolute value.

$$s_{21} = \cos a_2 = \frac{r_x}{|\boldsymbol{r}|}; \qquad s_{22} = \cos\beta_2 = \frac{r_y}{|\boldsymbol{r}|}; \qquad s_{23} = \cos\gamma_2 = \frac{r_z}{|\boldsymbol{r}|}$$

$$\boldsymbol{r} = \boldsymbol{n} \times \overrightarrow{\boldsymbol{AB}} \tag{26}$$

Similarly $\boldsymbol{r}$ is the vector that complements the orthogonal reference frame $\overrightarrow{\boldsymbol{AB}}$, $\boldsymbol{n}$, $\boldsymbol{r}$.

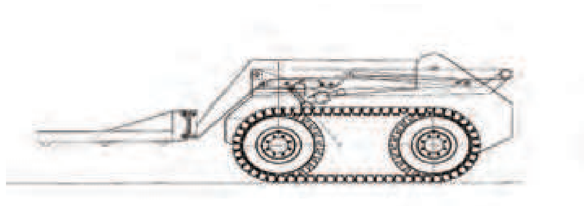
Each new installation of this mechanical system requires adaptation of all transformations with respect to real configuration. The procedure includes mathematical model of the system that consists of following basic programs:

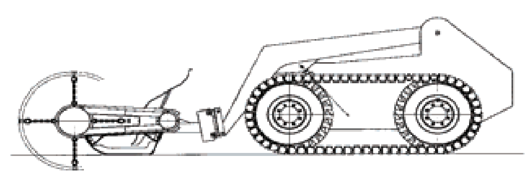
- Calibration according to the described procedure.
- Solving the direct and inverse tasks of kinematics
- Calculation of Jacobi matrices
- Force analysis for quasi static and dynamic cases.

6. Land Robotic Vehicles

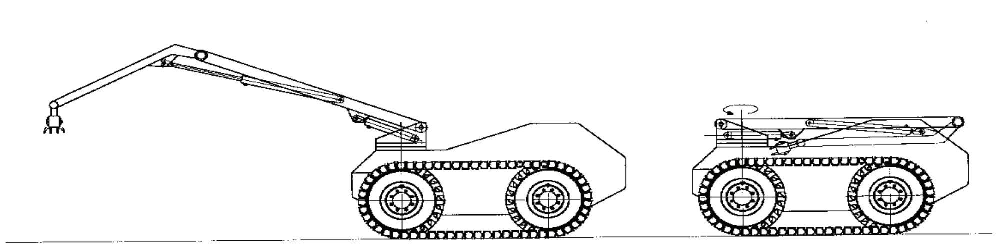
6.1 A Modular Concept

The vehicle for demining process can be characterized as follows: It is a remotely / programmable controlled general porter of several detection systems able to perform searching dangerous terrain, localize and neutralize mines. It exhibits excellent mobility and maneuvering capabilities in various terrains. It should be noted that destination of the vehicle to work in dangerous environment requires some specific systems and protection equipment. Then the unified concept of robotic vehicles that enables to combine several functional equipments can be adopted, as depicted in Fig. 8. (Havlik, 2002, 2003, 2005).





a) The vehicle with sensory platform b) The vehicle with flailing activation mechanism



c) The long reach robot arm

Fig. 8. Possible concepts of robotic vehicles

6.2 Functional parts

Taking into account possible situations that could arise in demining process a most general solution of the ground vehicle could include following functional parts:

– ***The vehicle and its mobility system.*** The vehicle and its mobility system should provide desired good maneuvering capability in various terrains. Following this requirement that enables to combine wheels and belts seems to be the best solution.

– ***The heavy manipulator.*** The 2 or 3 d.o.f. manipulator enables to fix various soil tools as well as special demining equipment: flailing mechanisms, saws or cutters of vegetation, removing shovels, etc. The sensory platform, as depicted in Fig. 3a, exhibit possibility to install a set of appropriate detection systems can be fixed on the end flange. It is equipped by distance sensor what enables tracking terrain at a given vertical distance as well as collision protection range detectors.

– ***The long reach robotic arm*** The on-board robot arm, as depicted in Fig. 3c, performs some specific tasks especially in situations as follows:
  - Targets are not exactly localized and further – more precise searching / detection procedures using hand held detectors should be made.
  - Targets are hidden by vegetation / stones, or, targets are in inaccessible positions for removing or other way of neutralization. In these cases special demining procedures and tools have to be applied.

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

- ***Mine detection system and on-board sensory equipment.*** The vehicle, as a complex robotic system, works in partially unknown, or, not exactly structured environment. To perform main demining tasks it should be equipped by large variety of sensors and detection systems that, beside functionally of particular mechanisms, will satisfy reliability and safety of the whole process. Categories of sensors and detection systems with respect to functions and mechanisms brings next table.

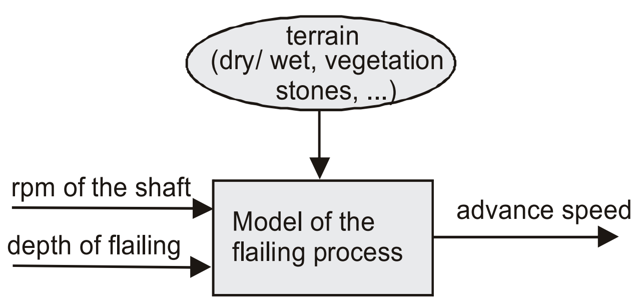
Task	Places and Outputs	Sensors / detection systems
Mine detection and recognition systems	Operation center (localization of targets) Vehicle (security control) Marking system	Metal detectors, ground penetration radar (GPR), IR camera, Gamma detector, vapor detectors, etc.
Navigation (gross motion control)	Operation center Vehicle (control system)	GPS, compass, camera, range finder,
Fine operations by on board tools (fine motion control)	Robot arm, manipulator Grippers, marking system, tools for preparing activation of mines, etc.	Hand held camera, tactile / force sensors, position and proximity sensors, … Hand held detectors for explosives
Monitoring / reliable functioning	Engine, power sources, communication, etc.	Temperature, pressure, tension (V) / current (A), switches, …

Table 3. Categories of sensors

– ***Tools for removing obstacles / vegetation and preparing terrain.*** For removing obstacles many different remotely operated tools with sensory feedback should be developed. There are: cutters, shovels, special grippers, sand suckers, probes, etc.
– ***Neutralization / mine-destruction tools.*** Referring to possible techniques of neutralization, i.e., removing or destruction, the set of exchangeable tools in a magazine is considered. When compare existing techniques from the safety point of view, the flailing technique seems to be a single way which relatively safe, fast and reliable. It can be used especially in cases when coordinates of targets are not exactly known and terrain is covered by vegetation. The verified configuration: the vehicle with flailing activating mechanism on the heavy manipulator is depicted in Fig. 8.

In principle, explosions of mines are activated by the beating force of hammers on the ends of rotating chains. On order to satisfy reliability of the cleaning procedure this force should be keep above some given limit and every point of the terrain should be bit several times. Naturally, the rotation speed (rpm) of the flailing shaft and advance speed of the vehicle are mutually related and depend on several factors, as shown in Figure 8 (left). This dependence was experimentally tested and the simple mathematical model was built. The output of this model, partially integrated into control system, is desired value of advance speed during operation.

Practically, the control system for the flail should guarantee that every local place of the terrain that corresponds to diameter of mines to be struck more then five times by a minimal force / energy.



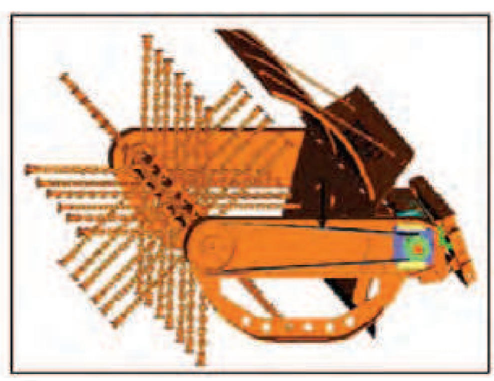


Fig. 8. Model of the flailing process and the flailing mechanisms

– ***Covers for protection the vehicle in cases of explosions.*** Any explosion (activated or accidental) can seriously damage equipments, or destroy the whole vehicle. For this reason it should exhibit adequate mass and armored protection covers. One of ways that minimizes effect of explosion during flailing is using the formed cover in front of the vehicle which changes direction of the pressure wave.

– ***Navigation, control and communication systems.*** The communication system transmits large amount of sensory and control data between the vehicle and the control station. For this reason maximal reliability of transmission should be guaranteed. As discussed above it is not expected that the system could work automatically. Nevertheless, searching and neutralization procedures made by mobile robotic vehicles should exhibit some level of autonomy. This fact naturally requires some unified approach to navigation and control. The general scheme of the control system in Fig. 9 shows some main components arranged in four control loops: global positioning, steering control loop, motor control loop and loops for control of various on board equipments (robot arm, manipulator, tools).

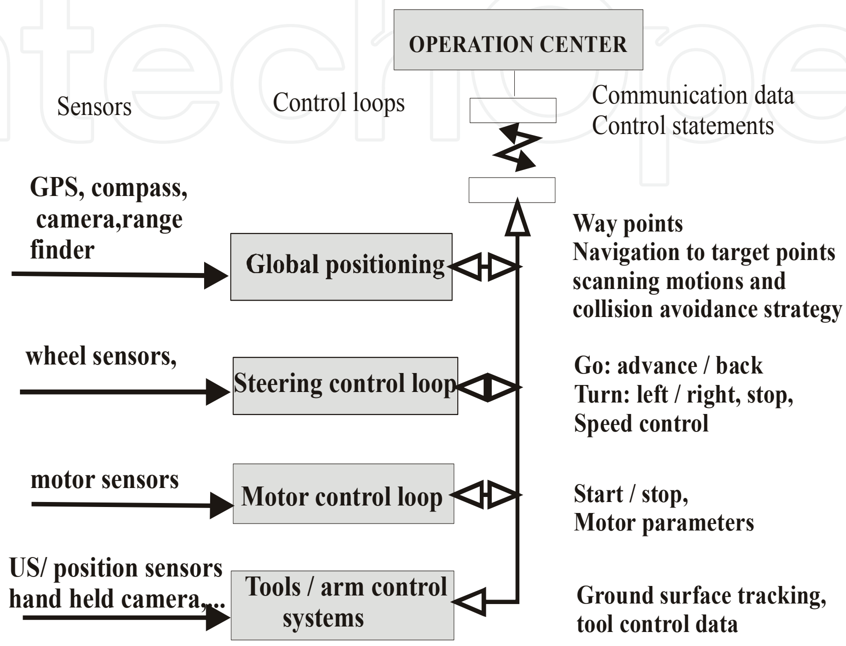


Fig. 9. Components of the vehicle control system

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

- ***Automatic / programmable control*** mode through communication with operation center. This mode supposes normal operation of all systems as included scheme in Figure 5. Communication system for automatic modes transmit control and sensory data: way-points / trajectory, control statements for vehicle and motor, images from camera (remote vision), vehicle and motor states, warning error situations, etc.
- ***Manual control*** using joystick / control panel / keyboard that allows maneuvering the vehicle without operation center. Manual control is used in cases as follows: removing the vehicle from the minefield and recovery if any situation due to failure of any other system (programs, communication, etc.), loading / unloading the vehicles during transport, testing. This control mode directly operates steering and motor control loops. Communication is limited and corresponds to main statements for limited maneuvering motions.

6.3 Principal Control Routines

In general, any demining procedure consists of many specific tasks and some general control routines that can be performed automatically. Within general routines there are especially 3 positioning tasks:

Task 1. Position and orientation of the vehicle.

Altitude and longitude of the vehicle is directly measured by on board GPS unit. The accuracy and resolution of measurements should correspond to accuracy of digital maps where all targets are recorded. As to orientation angle (azimuth φ) can be directly measured by digital compass. Then, three variables (x_V, y_V, φ_V) are controlled coordinates of the vehicle as can be seen in Figure 10.

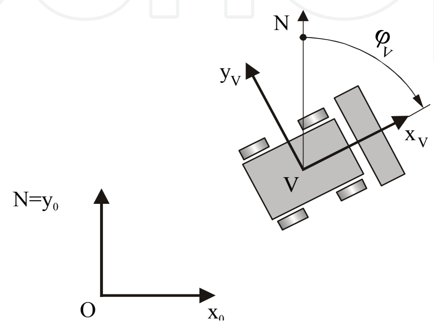


Fig. 10. Position and orientation of the vehicle

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

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

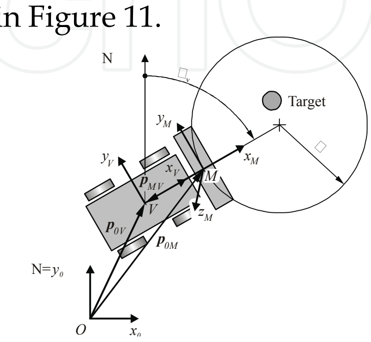


Fig. 11. Approach to the target

Task 3. Precise localization of target positions. (Inverse task)
The vehicle is in a position and the target is detected by some of detection systems. The exact position of the target should be stated and recorded. Practically the vehicle stops in some sensing position and performs searching dangerous terrain according to a given searching strategy, which corresponds to detection system just used for searching. (see Figure 12.)
There are, in principle, two possibilities:

- Detectors are on the sensory platform in front of the vehicle
- Detectors are in the robot hand.

The task is then to ascertain positions of targets using transformations that relate to particular detection system. Fusing sensory information it is possible to repeat detection procedure by using different sensing technologies including camera in the hand. Performing this task the vehicle is then maneuvered to this goal position specified by three variables x_V, y_V, φ_{ap}.

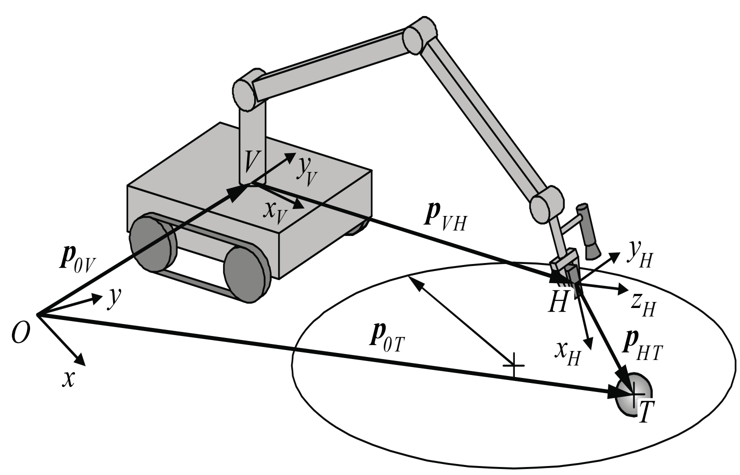


Fig. 12. Precise localization of the target by detectors in robot hand

Let us describe now the procedure for calculation of position of targets in all principal tasks. Considering reference coordinate systems, as specified above global position of the target detected by the sensor can be expressed using transformation

$$\boldsymbol{p}_{0T} = \boldsymbol{A}_{0H} \cdot \boldsymbol{p}_{HT} \tag{18}$$

where symbols $\boldsymbol{p}$ denote positional vectors related to particular reference systems and $\boldsymbol{A}$ represent transformation matrices between these systems. Thus, for instance

$$\boldsymbol{p}_{VH} = [x_H, y_H, z_H, 0]^T \tag{19}$$

$$\boldsymbol{A}_{VH} = \begin{bmatrix} \boldsymbol{R}_{VH} & \boldsymbol{p}_{VH} \\ \boldsymbol{0} & 1 \end{bmatrix} \tag{20}$$

and $\boldsymbol{R}_{VH}$ is the 3x3 rotation matrix of the H reference system into V system and $\boldsymbol{p}_{VH}$ is the positional vector of the H system with respect to V.

Then, considering introduced reference systems it is obviously

$$\boldsymbol{A}_{\boldsymbol{0}H} = \boldsymbol{A}_{\boldsymbol{0V}} \cdot \boldsymbol{A}_{VM} \cdot \boldsymbol{A}_{MH} \tag{21}$$

Because of positions of targets are given by two coordinates in global – world references particular transformation matrices can be simplified as follows

$$\boldsymbol{A}_{\boldsymbol{0V}} = \begin{bmatrix} \sin\varphi_V & -\cos\varphi_V & 0 & x_v \\ \cos\varphi_V & \sin\varphi_V & 0 & y_v \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{22}$$

where x_v, y_v, and φ_v are three measured variables that determine position and orientation of the vehicle.
Rem. Accurate calculation of target position requires that the inclination angle of the vehicle be considered. Although the actual inclination of the vehicle can be measured by a two-axis inclinometer following maximal simplicity of sensory equipment it is reasonable to neglect errors due to inclination. Anyway, when consider maximal allowable inclination angles in terrain this error will be within the range of the accuracy of GPS measurements.

Further more sophisticated control routines can be programmed. Then, the level of autonomy, provided to the vehicle will naturally relate to additional sensory equipment.
There are for instance:

- Obstacle avoidance algorithms. In general, as obstacles can be considered all unexpected objects that prevent to continue in desired activities; motion for the vehicle, or robot / manipulator. Some typical obstacles are: stones, trenches, trees, positions of mines, etc. If any obstacle is detected, the motion should stop and situation will be evaluated. Automatic avoidance will be primary solved for some class of obstacles.
- Scanning motion strategies. Automatic performing scanning motions will help to reduce number of actions that the operator should carefully control.
- Self-recovery strategies. This is an important and specific feature directly related to particular tasks. Its main purpose is to prevent / to avoid loses or self-destruction of the vehicle. The self-recovery starts especially in unwanted situations as follows: any failure of technique due to explosion (communication, engine, control system, sensory system, etc…), fault decision made by the operator, or, there are no / not enough information for further action and the vehicle it could be destroyed. It is very risky for service persons to interact directly in place. The primary task is to remove it from the dangerous terrain without any risk for persons. There are, basically, two simplest ways how to solve such situation. The first one is using a cable and to pull it out. The other possibility is using another vehicle, which helps to remove the first one from that dangerous place.

7. Conclusion

Some conceptual considerations in designing robotic systems for detection, localization neutralization of mines, especially anti-personnel are presented. As discussed any robotic system for performing dangerous works under harsh working conditions should satisfy

several criteria and performance requirements. Crucial importance is given to security and reliability.
In general, it is considered that demining operations are performed by unmanned vehicles with special on-board equipment and the whole process is monitored from the operation center. The operation center is working with digital maps and GPS sensory data that enables to localize any objects and to control mobile vehicles in global or locally stated coordinates. It is expected that robotic vehicles are provided by some degree of autonomy in performing particular actions. Dangerous terrain and avoiding unexpected explosions of mines result in applying the specific approach to searching with precise localization of targets and neutralization. Both operations closely correspond to sensory equipment for detection as well as destruction technology.

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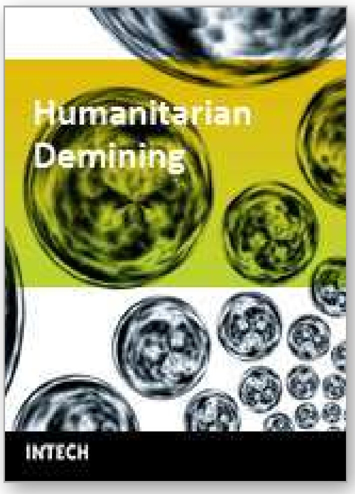

Humanitarian Demining

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United Nation Department of Human Affairs (UNDHA) assesses that there are more than 100 million mines that are scattered across the world and pose significant hazards in more than 68 countries. The international Committee of the Red Cross (ICRC) estimates that the casualty rate from landmines currently exceeds 26,000 persons every year. It is estimated that more than 800 persons are killed and 1,200 maimed each month by landmines around the world. Humanitarian demining demands that all the landmines (especially AP mines) and ERW affecting the places where ordinary people live must be cleared, and their safety in areas that have been cleared must be guaranteed. Innovative solutions and technologies are required and hence this book is coming out to address and deal with the problems, difficulties, priorities, development of sensing and demining technologies and the technological and research challenges. This book reports on the state of the art research and development findings and results. The content of the book has been structured into three technical research sections with total of 16 chapters written by well recognized researchers in the field worldwide. The main topics of these three technical research sections are: Humanitarian Demining: the Technology and the Research Challenges (Chapters 1 and 2), Sensors and Detection Techniques for Humanitarian Demining (Chapters 3 to 8), and Robotics and Flexible Mechanisms for Humanitarian Demining respectively (Chapters 9 to 16).

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