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A Modular Concept of the Robotic Vehicle for Demining Operations

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Abstract. Paper analyses some most important characteristics that should be taken into consideration in building the robotic demining vehicle. Based on previous experiences from the development of demining technology the modular concept of the multipurpose vehicle and some its main functional parts are discussed. Such robotic vehicle can be used as general porter of various detection systems, tools for cleaning terrain as well as neutralization equipment. Further development towards partially autonomous system and some principal tasks of positioning in dangerous terrain are analyzed. The real construction of the vehicle equipped by the flailing mechanisms for mechanical activation of explosions is briefly presented.

Keywords: robotic vehicle, humanitarian demining, mine detection/destruction, remote control

1. Introduction

Landmines, especially anti-personnel, are more-less psychological weapons. The advantages that give 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.

The key problem of demining lies, and will be solved, if mines are reliably detected and exactly localized. Then the neutralization procedure could be directly addressed to the place of their occurrence. These both steps could be made by automatic ways. This is a big challenge for robotic research. Overviews of many existing research projects, techniques and equipment have been developed for performing particular tasks are listed in several databases as well as in conference proceedings as for instance: www.gichd.ch, www.eudem.vub.ac.be, www.hdic.jmu.edu, www.state.gov/t/pm/rls/rpt/, www.demining.brtrc.com/r_d, etc.

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 most crucial task in the whole process. Because of automatic demining process is based on operation of special robotic vehicles research is oriented to the development mobile agents able to operate in/above the dangerous and partially unknown terrain as porters of detection systems and neutralization tools (Ide, 2004). Unfortunately, despite this effort, purely mechanical ways of destruction are still most widely applied techniques of automatic demining (Habib, 2002; Licko, 1997; Lindman, 2003; Stilling, 2003). A modular approach to the design development and one concept of robotic demining vehicle is presented below.

2. Study and Some Considerations Before Design

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.

Both these tasks are directly related to the problem and solving 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.

2.1. Main Rules and Design Considerations

Then, before the design and building a robotic system to be in use on the minefields there are some main rules have to be respected yet in conceptual design. 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.).
- The cost and availability of detection as well as neutralization technologies is a very important factor that could limit their mass use in 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 technologies will not totally replace standard hand searching/neutralization methods but they will be applied beside them. 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.

2.2. Design Criteria and Performance

Solving a robotic system for demining, there are four kinds of criteria should be considered, as follows.

Operational criteria

- Working efficiency/neutralization capability
- Reliability of cleaning
- Self-recovery capabilities
- Working time to charge/repair
- Diagnostics and maintenance
- Way of the operation/control and level of autonomy

Technical parameters

- Performance characteristics of the mobility system (speed, slopes, payloads, masses, maneuvering capabilities, etc.)
- Characteristics of detection systems, neutralization and cleaning tools
- Control and communication systems
- Mines and protection against explosions
- etc.

Applicability

- Working conditions (environment, terrain, mines, etc.)
- Transport to minefields
- Repairs /Availability of spare parts
- Technical level/skills of operators
- Integration with respect to other technologies
- Acceptable (friendly) by local people/operators

Cost and economy

- Total cost of the system (including services)
- Working costs (USD/hour, USD/m^2,..)

3. Experiences from the Development and Using Demining Machines

Lot of research work has resulted in design of several demining technologies as well as development of new machines and especially detection systems. But despite several sophisticated solutions and systems, except flailing technology, they did not find such acceptance in practical use as was expected previously. There are for instance: removing mines by special tools, thermal or laser destruction or others. One reason is that the majority of these techniques need precise localization of targets—mines. The other problem is that after years of their deployment the terrain is frequently covered by vegetation or other mechanical objects. This fact naturally results in hard decision which technique will be used in particular cases.

After more then fifteen years of development, production and using flailing vehicles in many regions lot of experiences as regards to their further development have been gained. First vehicles produced since 1993 were verified in real conditions and are actually used by demining companies and military peace forces for cleaning the post battle minefields in several countries. The flailing activation technology was verified in real conditions and it is actually one of the most widely used ways of mechanical demining (www.gichd.ch; Stilling, 2003; Lindman, 2003). For instance: using two flailing vehicles, in Fig. 1, (Havlik and Licko, 1998) the area about 126000 m^2 with mixed mines has been cleaned in Eastern Slavonia within summer-winter period. The flailing destruction technology proved its efficiency and mechanical robustness by its using in complicated road terrain where, beside several hundreds antipersonnel mines, 305 anti-tank mines have been destroyed.

As confirmed experience the remotely operated flailing vehicles exhibit some important advantages. There are:

- Fast speed of demining operation. Comparing to classical hand demining procedures the system based on mechanical flailing technology is about 10 times faster.
- Low cost and high efficiency of the system especially when infected terrain is covered by grass or small vegetation
- Comparing to conventional techniques the "remote" operation and control of demining process exhibits lower psychological pressure for service persons.
- Universal technical solution of the system based on multipurpose soil machines as small loaders. The loader and maneuvering unit can be combined with several additional accessories can be used for demining process. Such concept guarantees availability of spare parts, verified reliability and good maintenance.
- Relatively low weight, fast and low cost transport to the place of use is highly required.

Figure 1. The remotely operated flailing vehicle.

4. Research and Modular Concept of the Vehicle

4.1. Studies and Requirements

Main functions of the vehicle can be characterized as follows: 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 that any agent working in risky environment except principal functions should exhibit three following features: self-recovery capability, minimal risk assessment and maximal reliability in all actions. The crucial importance in demining plays self-recovery performance.

As follows from the study and experiences the vehicle includes some "general purpose" parts to perform common functions as well as some specific "task oriented" equipment performing special activities. The modular concept is then based on separation of these functional parts. Such approach could minimize cost of a general purpose system and the whole system, as well.

The general purpose parts represent the mobility system—vehicle and the on-board manipulation equipment.

The mobility system represents a remotely controlled vehicle moving on wheels, belts or legs. Particular applications differ by requirements on speed, weight, mechanical protection against environment and explosions of mines. As regards to control and

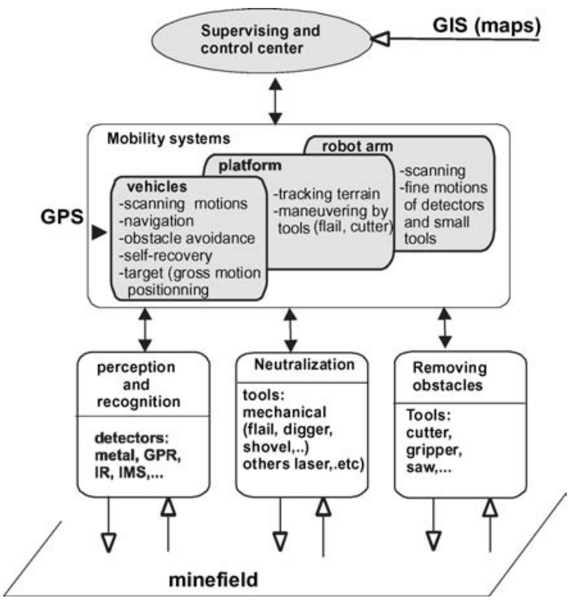

Figure 2. Parts of the ground robotic vehicle for demining.

communication systems, including sensors/detectors related to motion and maneuvering capabilities main functional parts of these systems can be practically unified. The on-board manipulation equipments represent the heavy load manipulator/platform and a robot arm with several task oriented tools.

Considering possibility to use the ground vehicle for performing all principal tasks a most general solution, according to Fig. 2, should include following functional parts:

- The vehicle and mobility system
- The heavy manipulator
- The platform as porter of detection systems
- The long reach robotic arm
- A set of tools for removing obstacles/vegetation
- Neutralization/destruction tools
- Control and communication systems.

Then the unified concept that enables to combine several functional equipments is depicted in Fig. 3, (Havlik, 2002, 2003, 2004).

4.2. Main Parts and Characteristics

Let us briefly specify some functional specifications and parameters for these principal parts.

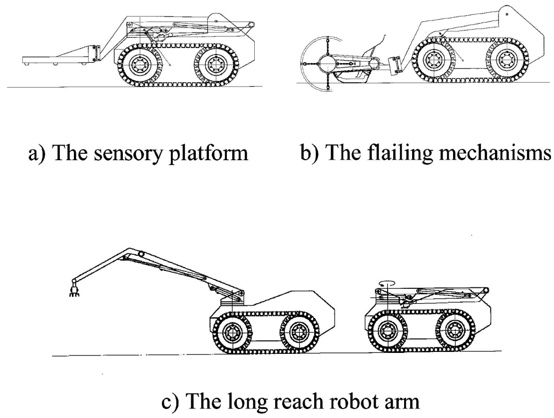

Figure 3. Conceptual studies of the vehicle.

4.2.1. The Vehicle. The vehicle and its mobility system should provide desired good maneuvering capability in various terrains. Following this requirement the solution that enables to combine wheels and belts was adopted. Some main mechanical characteristics and design parameters are listed in Table 1 (Licko, 2002).

Table 1.

Dimensions	4 × 2 × 2.5 m
Mass	Max. 4 500 kg
Operation speed	During demining : 0–5 km/hour during transport: 0–15 km/hour
Transport capacity	up to 1000 kg on the end of manipulator/on platform
Pressure on terrain	0.5 bar—belt version 4.5 bar—wheel version
Maneuverability	Max slope—30°
	Transversal angle—10°
Rotation	Around internal wheels/belt (one side stops)
	Around vertical axis (wheels/belts turn in opposite direction)
Bottom above the terrain	250 mm
Brake distance to stop	From 5 km/hour: max. 1.3 m
Driving unit	Diesel engine; power–approx. 60–80 kW, driving pump as the general source of hydraulic energy for all systems, including mobility. Maneuvering/motions by slip controlled hydraulic motors in wheels

4.2.2. The Heavy Manipulator and Sensory Platform. The 2 d.o.f. manipulator with 1000 kg payload capacity enables to fix various tools as well as special demining equipment: saws or cutters of vegetation, removing shovels, etc. The platform, as depicted in Fig. 3(a), with 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. As to sensing principles, there are for instance: metal detection, infrared sensing/imaging (IR), ultrasound, Ground Penetrating Radar (GPR)/Mm-wave radar/ultra-wideband radar, X-ray spectroscopy, active acoustic and seismic, magnetic field sensing, neutron activation analysis, charged particle detection/IMS (Ion Mobility Spectroscopy), nuclear quadrupole resonance, chemical, biosensors. As obvious, using no single sensor and sensing principle can guarantee 100% reliability of mine detection. For this reason it is need to scan the terrain in front of the vehicle by several detection systems fixed on the platform.

In case of the vehicle for destruction of mines the platform is replaced by flailing activation mechanisms, as described later.

4.2.3. The Robotic Arm. The on-board robot arm, as depicted in Fig. 3(c), performs some specific tasks especially in situations as follows:

- Targets are not exactly localized and additional searching/detection by hand held detectors should be made.
- Targets are hidden by vegetation/stones, or, targets are in inaccessible positions for flail. In these cases special demining procedures and tools have to be applied.

The 6 d.o.f. remotely controlled robot hand with the reach 3 m has payload capacity about 20 kg. 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 using other neutralization procedure seems to be not reliable, or could be too dangerous.

4.2.4. 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 many different end of arm and remotely operated tools with sensory feedback are being developed. There are: sand suckers, cutters, shovels, special grippers, diggers and probes, etc.

4.2.5. Neutralization/Destruction Tool. When compare existing techniques of neutralization, i.e., removing or destruction, 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 if coordinates of targets are not exactly known and terrain is covered by vegetation. For this reason it was adopted as primary technique to be integrated on the vehicle.

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 Fig. 4. 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 will be struck more then five times by the minimal force/energy 4000 N.

4.2.6. Control and Communication. 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 of particular vehicles.

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

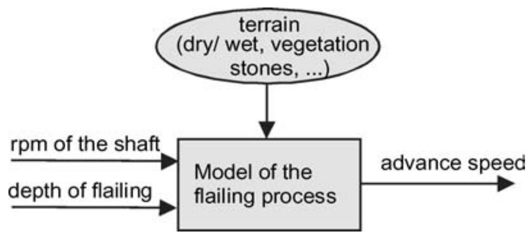

Figure 4. Model of the flailing process.

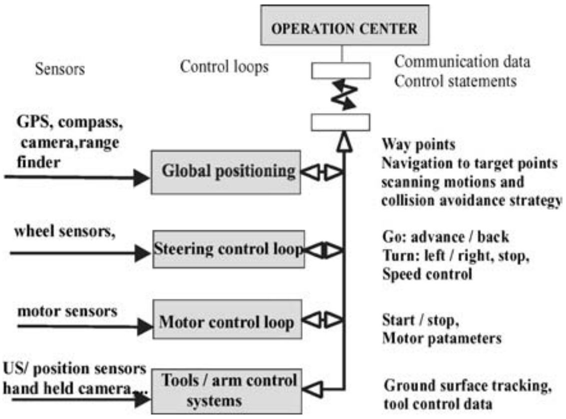

Figure 5. Components of the vehicle control system.

- *Automatic/programmable control* mode through communication with operation center. This mode supposes normal operation of all systems as included scheme in Fig. 5. Communication system for automatic modes transmit control and sensory data: waypoints/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.

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 Fig. 6.

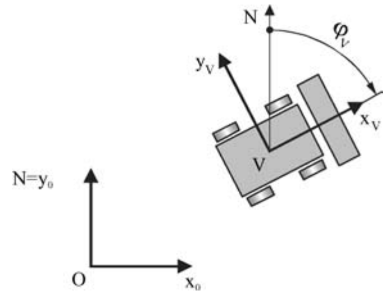

Figure 6. Position and orientation of the vehicle.

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} expresses 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 Fig. 7.

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

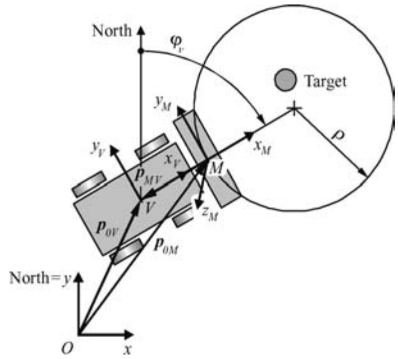

Figure 7. Approach to the target.

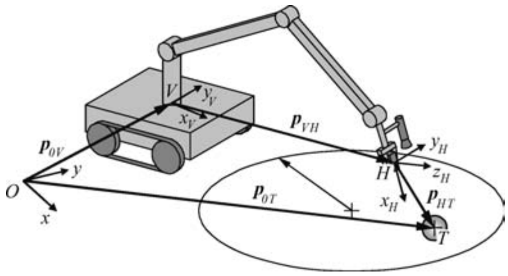

Figure 8. Precise localization of the target by detectors in robot hand.

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 Fig. 8).

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}.

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

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

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

$$\boldsymbol{p}_{VH} = [x_H, y_H, z_H, 0]^T,$$
$$\boldsymbol{A}_{VH} = \begin{bmatrix} \boldsymbol{R}_{VH} & \boldsymbol{p}_{VH} \\ 0 & 1 \end{bmatrix}$$

and R_{VH} is the 3×3 rotation matrix of the H reference system into V system and p_{VH} is the positional vector of the H system with respect to V.

Then, considering introduced reference systems it is obviously

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

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

$$A_{0V} = \begin{bmatrix} \sin\,\varphi_V & -\cos\,\varphi_V & 0 & x_v \\ \cos\,\varphi_V & \sin\,\varphi_V & 0 & y_v \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where x_v, y_v, and φ_v are three measured variables that determine position and orientation of the vehicle.

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

Figure 9. The vehicle.

possibility is using another vehicle, which helps to remove the first one from that dangerous place.

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.

5. The Flailing Vehicle and Experiences

An example where considerations and principal requirements, discussed above, were applied, is the new design of the light-weight demining vehicle (Licko, 2002). The remotely operated machine, as shown in Figs. 9 and 10 equipped by the flailing activation mechanism. The modular concept enables that the vehicle can be easily transformed as porter of various detection systems or other attachments (see project ANGEL). For preliminary maneuvering experiments the vehicle was originally equipped by the single camera fixed on the 2 axes platform.

Figure 10. The flailing mechanisms.

Tests. Characteristics of the vehicle were tested under "real minefield conditions" (Report, 2003). Some important results from these tests are summarized in Table 2. In each experiment 50 pieces of AP PMA2 blast mines were deployed. The depth of cleaning/flailing was adjusted within 20–25 cm.

Further parameter which characterizes maneuverability and the "productivity" of a particular demining technology is the cleaned area per time. As obvious, this strongly depends on ground conditions and operator experience. For this reason the grounds were divided within three categories as specified in Table 3. For each category of terrain the daily cleaned area was calculated. Principal assumption is that the machine is controlled by the skilled operator.

Experiences. Results from experiments and more then ten years application of similar machines can be summarized into statements as follows:

– Application of purely mechanical destruction techniques can not guarantee 100% reliability of cleaning terrain from mines and the flailing technique, as

Table 2.

Exp.	Terrain	Depth of deployment (cm)	Clearing speed (m/h)	Mechanically neutralized (%)
1	sand	0	202	96
2	–/–	10	139	100
3	–/–	20	174	98
4	Gravel	0	228	90
5	–/–	10	202	98
6	topsoil	10	168	96
7	ridges	15	151	86

Table 3.

Category A:	
Terrain	Flat or gentle slopes
Ground	Dry soil, sand
Vegetation	Dry (max. 5 cm thick stems), not higher than 1 m, no trees, no piles,
Obstacles	Only "moderate" obstacles
Daily cleaned area	About 8250 m^2
Category B:	
Terrain	Flat, max. slope 10°
Ground	Partially wet
Vegetation	Green/wet, (max. 5 cm stems), not higher than 1,5 m, distance between trees 5 m,
Obstacles	"difficult"
Daily cleaned	About 5250 m^2
Category C:	
Terrain	Uneven, slopes more then 10°
Ground	Wet, muddy, marsh
Vegetation	Wet, bushes higher then 1.5 m, distance between trees about 5 m,
Obstacles	"Very difficult"
Daily cleaned	2550 m^2

well. Despite this fact the vehicle with flailing mechanisms is an effective tool especially in all cases when positions of mines are not exactly known, if the terrain is covered by vegetation, or, if there is another suspicion or some uncertainty. To satisfy maximal reliability the post verification of the cleaning process can be realized using vehicles equipped by mine detection systems.

– Using remotely operated vehicles minimizes psychological pressure and improves safety of persons. The useful help for operator is, if some functions are performed automatically, for instance flailing process with respect to advance speed, or, straight line control routines.
– The efficiency of the whole demining process will be improved if mines are previously detected and localized. Then, the destruction vehicle could be directly navigated to these positions where mines are expected.

6. Conclusion

Considering large polluted areas and drawbacks of actual demining technologies main contributions by using robotic vehicle 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.

The paper presents a modular concept and describes the robotic vehicle equipped by the flailing activation mechanisms. This concept enables to design and built unmanned vehicles for detection and localization of mines as well as for their neutralization. It is considered that vehicles will be programmable controlled from the operation center. The operator will work with digital maps and GPS sensory data and all relevant information will be recorded. All activities in dangerous terrains, as minefields, require applying specific approaches to searching, precise localization of single targets and neutralization process as well. Operation of unmanned vehicles in such terrains requires that they have some level of autonomy to solve especially critical situations. This is the task for research in the future.

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Within years 1991 and 1992 he has been appointed as invited professor at Swiss Federal Institute of Technology (EPFL-DMT/IMT) in Lausanne, Switzerland. Currently he is head of the research department at the Institute of Informatics of the Slovak Academy of Sciences in Banska Bystrica, Slovakia.

His research activities diverge from solving problems of advanced robotics, control to applications. His main contributions are oriented to the following topics:

- Mechatronic design and flexible structures
- Sensors and sensory equipment
- Applications of advanced robotics: precise assembly and welding, service operations
- Robotic tools for demining.

He is author more then 100 scientific papers in books, international scientific journals and conference proceedings. He was leading several research projects oriented to development advanced sensing and robotic systems for manufacturing (arc welding, assembly) or for humanitarian demining.

He is /was member of several professional organizations and committees under IARP, IMECO, IFAC or IFToMM.