11

Developments on an Affordable Robotic System for Humanitarian Demining

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1. Introduction

Humanitarian demining is a multi-faceted and broad domain. Occasionally, specific economic interests in specific areas of landmine infested countries may foster an avalanche of investments for massive demining. However, the great majority of the territory is left out of these demining activities, meaning that the problem is prolonged for decades. Affected countries, usually developing ones, lack both economic and educated human resources to tackle this prolonged humanitarian problem. This long-term battle must thus be fought with scarce and locally available resources, restricting greatly the type and amount of employable technology.

Cost, complexity, maintainability, among others, are thus key factors to be taken into account when developing technology to actually help countries facing the humanitarian demining problem. This chapter addresses this concern by proposing a technology development roadmap for the humanitarian demining domain. An outcome of the roadmap is a set of requirements for the construction of a *portable demining kit*, as a possible solution to enable what is already known as s*ustainable demining*. The rationale behind this is that by making *portable demining kits* locally available it will be possible to promptly respond to emergency situations. The number of casualties can then be drastically reduced by providing a fast assessment of the probability of a given land being contaminated with landmines. To see the daylight, the robotic demining kit should be general purpose to some degree, i.e. to be usable as a service robot for other tasks besides demining. This allows operators to practice the interaction with the system during prolonged absence of landmine-related activities. In addition, the owner (e.g. a local authority) can exploit the system to obtain additional profits. This portability is essential to guarantee that the system pays for itself, thus reducing the problems associated with its maintainability.

Three sub-types of *portable demining kit* will also be presented, along with some ongoing developments towards their implementation. These developments include novel mechanical platforms, locomotion, piloting, localisation, and perception systems. The main design guidelines are affordability, robustness, and intuitiveness, so that the system can be easily purchased, maintained, and used.

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Along with these robot-oriented developments, a multi-agent supporting software platform will also be presented. The multi-agent paradigm is well suited to enhance multi-experts and multi-robots inter-operability. In addition, the platform facilitates scalability, allowing robots and humans (i.e. agents) to be added/removed to/from a mission in a seamless way. A third feature that comes hand-in-hand with the multi-agent paradigm is modularity, something essential to foster vertical development and integration with off-line tools, such as simulation-based training applications.

This work is being carried out since 2003 by a portuguese SME, *IntRoSys S.A.*, in partnership with UNINOVA research centre of the New University of Lisbon and LabMAg research centre of the University of Lisbon. This joint collaboration emerged from the acknowledgement of a business and scientific opportunity stemming from the unavailability of sustainable robotic systems applicable to the mine action domain.

2. Technology Development Roadmap

Based on (Santana, P. et al., 2005; Santana, P. et al., 2007), this section overviews a set of recommendations for the development of technology for the mine action domain, with special focus on robotics. By carefully considering the specificities of the humanitarian demining domain, the goal of this roadmap is to guide robotic technological developments towards higher levels of acceptance confidence. Typically, the acceptance of a novel technology is dependent on its field applicability and its affordability.

Previous work has identified opportunities (UWA, 1998; GICHD, 2002) and guidelines for the development (UNMAS, 2003b) and procurement (UNMAS, 2003a) of technology applicable to the mine action domain. According to these studies, it is reasonable to assume that *close-in detection* and *area reduction* are priority domains with very significant benefits from demonstrating progress on R&D. Based on this assumption, the remainder of this section develops around these two tasks. However, as it will be shown later on, other tasks can also be easily covered by the same technical solution.

2.1 Cost and Complexity

Usually *high-tech* means high-cost and high-complexity, which are two considerable drawbacks in humanitarian demining. Typically in developing countries, deminers are people with little formal education, which requires simpler human-machine interfaces than those usually considered by technology developers. In addition, operation sites are remote and hazardous, turning a simple repair into a daunting task. This fact leads to the conclusion that the use of local equipment has the advantage of being low-cost, readily available, easily maintained or repaired, and of stimulating local economy (Smith, A., 2003). Donations are being progressively reduced, posing additional financial problems to affected developing countries (Barlow, D., 2007). Finally, it is paramount to remember that detection and clearance of landmines is part of an extensive list of humanitarian problems (e.g. food supply and medical assistance) in a post-conflict situation, meaning that funds must be shared, reducing even further the financial support to demining activities.

Robots performing such a complex task in such demanding environments only rarely can be made low-cost, easy maintainable and locally manufactured. Hence, if the goal is to exploit the current bulk of knowledge present in the mobile robotics literature to solve the demining problem as fast as possible, it is rather preferable to focus on a part of the mine action process where the inherent complexity and cost of the robotic solution are not key factors. Nevertheless, all the development should target simplicity, low cost, easy maintenance, and usage.

An example of a successful introduction of a high-cost technology to the mine action domain is the use of heavy-weight machines to trigger landmines. Although this solution, i.e. mechanical demining, does not cope with the humanitarian demining safety and accuracy requirements, damages the soils, is logistically difficult, and expensive (UWA, 2000; Habib, M. K., 2002a), its application is growing in the area reduction, terrain preparation, and post-clearance tasks (GICHD, 2004). This is because a single machine can work faster than a thousand deminers over flat fields (Habib, M. K., 2007), offsetting its disadvantages until better technologies are developed (Habib, M. K., 2002b). It is now believed that 90% of the land subject to a process of detection and clearance is not contaminated (Barlow, D., 2007). Therefore, a slight improvement in area reduction, terrain preparation and post-clearance tasks (e.g. for quality assurance) have a significant impact in the overall process' efficiency. It is thus reasonable to assume that the potential high-cost and complexity inherent to a novel technology developed for these tasks is counterbalanced by its outcomes.

In fact it is not just a question of efficiency, it is also a matter of safety. For example, vegetation cutting is considered as being one of the most boring/difficult tasks to be performed by a deminer (Cepolina, E. E. & Hemapala, M. U., 2007). Following the same line of thought, area reduction is also among the most dangerous tasks. Deminers usually perform it faster than when searching systematically for landmines (Colon, E. et al., 2007). Being of much less complexity than landmine detection, tackling these problems would produce faster effects in the mid term.

2.2 Risk Assessment

The reduced complexity of area reduction, terrain preparation, and post-clearance tasks when compared to the problem of systematic landmine detection and removal is mostly concerned with the difficulty in discriminating landmines from metal debris, natural clutters, and other objects without the need for vegetation cutting (Habib, M. K., 2007). This problem is being tackled by many research groups in sensor technology and sensor fusion techniques. But the fact is that despite all R&D efforts and improvements in multi-sensor fusion with all its advantages (e.g. false positives reduction), the detection and clearance process remains unsatisfactorily robust. In addition to these more related technological limitations, personnel in the field are conservative regarding these innovations. The general awareness of these limitations complicates the acceptance of novel technologies as alternative to metal detectors and manual prodding. This contention is reasonable due to the risky nature of the task, which makes procedural and conservative approaches preferable.

Surveying tasks have a different nature though. They are mostly probabilistic. *Impact surveys* are performed by interacting with population, governments, military forces, etc., in order to, among other goals, gather information about the most probable contaminated sites. During *technical surveys* more detailed information is obtained to make the detection and clearance process more accurately defined. A component of this phase is to define boundaries to the demining process by means of *area reduction*. To accurately define these boundaries, every patch should be thoroughly analysed. Since the goal of area reduction is exactly to avoid analysing the entire terrain, these requirements must be relaxed. Hence, *area reduction* can also be seen as a probabilistic process (i.e. risk assessment). *Post-clearance surveys* involve accreditation and monitoring of the demining organisation before and during operations (i.e. quality assurance) and inspection of cleared land before it is formally released to its owner (i.e. quality control). Once more, this process is also probabilistic. In fact, a more realistic goal than the UNMAS one of 100% clearance is the *zero-victim* target (EC, 2005). This means that land prioritisation, area reduction, and fast response to casualties are of utmost relevance.

The probabilistic and information-driven nature of these tasks suggests that any available technology providing additional data is beneficial. Thus, even though a novel product may not be able to provide a 100% sure output, as required for detecting landmines, it can be used as another knowledge source feeding the decision making process during a survey phase. Just as with complexity and cost criteria, technology developed for employment in survey phases is more likely to be accepted than for the detection and clearance phase.

2.3 Product's Life Cycle

Some market studies, e.g. (Newnham, P. & Daniels, D., 2001), concluded that the market of humanitarian demining is not active and wide. As a result, product's development usually requires direct or full funding. In addition, the technology buyers are mostly donors and not the end users. These factors endow the humanitarian demining market with complex (and sometimes hidden) dynamics, hindering the application of conventional product's life-cycle and return of investment strategies.

It is essential that developers design products capable of being transferred to other domains until they are accepted in the restricted humanitarian demining market. That is not to say that the developed technology should be general purpose. As pointed out in (Habib, M. K., 2007), technology should be developed with the special purpose of demining, otherwise it will most surely fail in coping with the hard requirements of real minefields. Although a reasonable trade-off between being general purpose to enable *transferability* and being optimised for the demining domain is surely difficult to achieve, being aware of it is already a good starting point.

2.4 Explosive Remnants of War (ERW)

Unfortunately, landmines are no longer alone in the top list of priorities in mine action programmes. Many other explosive remnants of war (ERW), such as cluster munitions, are becoming a bigger threat (Nema, M., 2007). These can be launched in air strikes covering larger and more indiscriminate areas than those affected by landmines deployment. Again, fast area reduction and risk assessment mechanisms appear as key mechanisms to help cover wider areas in a shorter period of time.

3. A “Business Model”

To cope with the presented technology development roadmap a business model has been devised (Santana, P. et al. 2005). It envisages a successful return of investment by guaranteeing a natural technology transfer to other domains, and also by covering aspects of the humanitarian demining process with recognised added-value. At a first sight, it may seem heartless to talk about business and return of investment when human life is the centre of the question. However, these are essential factors in triggering the attention of rich countries' industry to this problem. If this goal is attained it will be much easier to develop better and cheaper technology for the humanitarian demining domain.

Restating the major conclusion obtained from the roadmap, area reduction is among the most demining-related activities prone to accept advanced technology. It can also be concluded that technology transfer should be favoured as much as possible. If area reduction is considered as an instance of a *generic remote monitoring toolkit*, solutions developed for it can also be applied to the domains of civil protection, surveillance, remote environmental monitoring, law enforcement, etc., emphasising the potential for technology transfer (see Fig. 1).

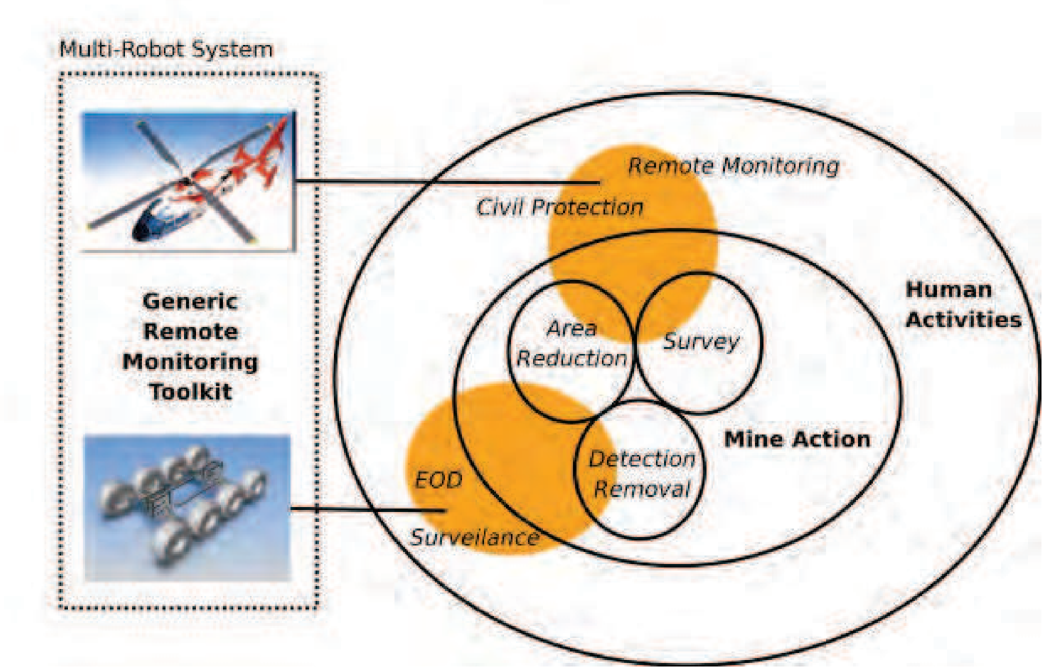


Fig. 1. The generic remote monitoring toolkit

3.1 A Portable Demining Kit

A particular component of the *generic remote monitoring toolkit*, a *portable kit* for rapid intervention in humanitarian demining emergencies, is the topic of this section. The idea is to have a low-cost, light, and simple maintenance robot fleet available in some hot spots of affected countries. Each time a landmine related accident is reported, a small team (e.g. one operator and one robot) is deployed to the affected area. Being small and light, the robot(s) can be carried in a common all-terrain vehicle, as well as being easily manipulated by the operator(s).

Once on site, the operator can perform area reduction and mapping in order to, for instance, provide information for risk assessment, delegating to others the full demining process. This can be extremely important as the field must be prioritised before being demined, and especially because locals may risk using the affected fields for agriculture or any other basic

survival activity. In fact, in many cases, populations start raising their crops in the minefields or start using mined roads as soon as a conflict finishes, which results in a high number of human casualties.
Therefore, this approach is intended to be a pragmatic way of reducing the number of casualties by providing the populations with immediate risk assessment information about the terrains they will be using. A set of design criteria for such a portable demining kit has been defined:

- **Field Applicability.** Due to the harsh, unstructured, and unpredictable nature of the application scenarios, designing a robotic system for landmine detection is a quite complex task. The following items should be taken into account when developing a mobile robot for humanitarian demining:
  - Locomotion capabilities. Landmine detection sensors are complex and usually require slow motion to perform properly. This sets up an upper limit to the robot's speed requirements. In fact, the true requirement for a demining robot is to be easily deployable (i.e. small and light), capable of traversing all-terrain, high slope, uneven, and densely vegetated terrains, while maintaining itself operational.
  - Accidental landmine triggering. The lighter the robot, the smaller the chances of triggering an undetected landmine. However, light robots are difficult to build, particularly if the goal is to make them autonomous. Autonomous robots require batteries, sensors, computational units, motors and respective drives, plus a robust mechanical platform with protective material against explosions. Therefore other strategies are required in addition to make robots as light as possible. One is the requirement for a safe lane in which the robot moves while scanning a potentially contaminated parallel lane. Another is to design the mechanical platform to be holed so that most of the explosion energy can pass through it. Making a breakable structure helps in isolating the damages.
  - Landmine detection & avoidance. Safe lanes not always exist. Picture for instance a cluttered environment or a situation where the robot must analyse an area between nearby trees. This issue can be tackled by scanning in real time the surface where the wheels/legs of the robot will move over. However, ground robots used for area reduction may not be equipped with landmine detection sensors. Rather they may be limited to lighter and cheaper chemical sensors, which can only be used to detect minefields and not particular landmines. This limitation stems from their high sensitivity to the chemical in question, but low spatial resolution. This is a big challenge that some have turned around by using unmanned aerial vehicles, such as (Eisl, M. M. & Khalili, M., 2003; Cramer, E. A., 2001). The challenge still remains though; aerial means can hardly operate in forest like environments, in which ground is not visible from above. Refer to (Santana, P. & Barata, J., 2005a) for a thorough analyses of the applicability of unmanned helicopters to the humanitarian demining domain.

- Tripwires detection. Tripwires and other mechanisms to trigger landmines are very difficult to detect, especially in areas with dense vegetation. Nevertheless, some attempts have been reported (e.g. (Babey, S.K. et al., 2000)).

- **Ease of use.** A demining mission is much more efficient if robots are used as advanced devices to help experts and operators on the ground. It is widely accepted that such robotic systems to be successfully applied in the mine action domain must have a simple human-machine interface. Moreover, it is essential for the system to disturb as little as possible the operator. The operator must be focused on the landmine detection sensors output and not on the machine that carries them. This mainly requires the system to:
  - Be (semi-)autonomous. This is essential to reduce the operator's attention in all respects of the robot' activity. Since the operator will be immersed in the landmine detection sensors output, the robot's telemetry should operate on an event driven way, i.e. information should pop-up when it is meaningful. This requires the robot to self-diagnose, or at least to self-monitor. Obstacle avoidance, adaptation to terrain's roughness, sensor and actuator degradation are also essential features. Finally, the mission (i.e. tasks and interactions between robot(s) and operator(s)) should be stereotyped and automatically managed.
  - Be implemented with interoperability capabilities. Other experts, such as specific landmine experts not present on field, should be easily accessible when required. This feature is essential to motivate the distribution of portable kits throughout affected countries. Without remote access, experts would be required to be present in the minefield, which would hamper a fast deployment of the system. Interoperability also allows many operators, and even robots, to interact in a more transparent and harmonious way, in real team work.
  - Be mimicked in a realistic simulation-based training tool. Operators should be provided with a tool through which they could train in a simulated environment. This allows operators to train nominal and extreme situations, reducing the chances of erroneous behaviour in the real minefield. Thus, the simulator needs to model, to some extent, the robot's dynamics and kinematics, terrain, robot-terrain interactions, and landmine detection sensors.

- **Modularity.** Modularity is another essential criterion for a system to operate with so many and so demanding requirements. Being modular, the system is more easily extended and customised, reducing re-engineering costs. For instance, modular software allows an easier integration in an IT infrastructure while modular hardware allows an easier integration with custom made mechanical platforms for some special needs. A good (dis)assembly procedure reduces the transportation requirements, as well as the time and cost spent in maintenance tasks. Modular software, such as the one enabled by the multi-agent paradigm allows the scaling up/down of the system in the field as the number of operators and robots varies. Finally, training can also be improved by having a modular system, as it is possible to train for a specific component without requiring access to the whole system.

- **Affordability.** To be sustainable, the system must be affordable. Three major strategies have been considered to reduce the cost of the system:
  - Sensors reuse. Instead of considering high cost laser scanners for terrain perception, high cost navigation sensors (e.g. RTK-DGPS and inertial navigation systems) for localisation purposes, stereoscopic vision can be used for both. Since the number and diversity of parts to be maintained in stock is smaller, the logistic requirements are relaxed. In addition, the cost is reduced in about one order of magnitude when compared to conventional localisation+perception systems.
  - Compliant mechanical structures. By allowing the robot to adapt passively to the environment, the sensory requirements for terrain perception are reduced, and consequently their cost. Moreover, robustness increases when part of the robot's ability to safely traverse uneven terrain is decoupled from the control system.
  - General purpose properties. The system is more easily self-sustained if it can be exploited for other purposes. In addition, the more applicability it has, the more used it is, and consequently the better operators control it.

4. Towards the Implementation of a *Portable Demining Kit*

This section presents some conceptual and technical solutions that cope with the set of previously presented requirements for a *portable demining kit.* As mentioned, three sub-types of portable demining kits are being considered. Each of them is to be applied in different situations, which by their typical sequential nature can also be called of stages. The first stage refers to minefield detection, the second one to area reduction, and finally the third one to detection and clearance. As it will be shown, the three stages do not always follow each other in a pre-established sequence.

4.1 First Stage: Minefield Detection

Someone is aware of a previous conflict exactly on a location of particular importance for the local community. In this hypothetical scenario it would be extremely beneficial if the community could request a fast minefield risk assessment. For this purpose a team of small robots (~50 cm long) with poor localisation and terrain classification capabilities carrying a chemical sensor to minefield detection could be applied. Being extremely light, the probability of triggering a landmine is rather low. Even if that happens, their low cost and small dimensions makes their substitution easy. Therefore, there is no need to accurately detect landmines in order to avoid them. The chemical sensor does not provide high spatial resolution and therefore simple localisation capabilities suffice. The output of these robots operating autonomously and fast is a low resolution map of landmine explosive (e.g. TNT) in the potential minefield.
Bearing this in mind, i.e. low cost, simple, and small disposable robots, some biologically inspired models have been developed for terrain classification and reactive control. As concluded in (Santana, P. et al., 2007), biology is a good inspiration for building sustainable

robots. Nature tends to evolve simple, efficient, and robust solutions, exactly what is required for such a team of small robots. The remainder of this section describes some of these biologically inspired models for the implementation of a small robotic team. These models have been tested in real robotic platforms, being a migration to small size robots scheduled for the mid-term.

4.1.1 Morphological Computation for Affordable All-terrain Piloting

Robots designed to operate autonomously in natural environments require a proper perception of their surroundings. Typically this problem is managed recurring to complex, expensive, and high consumption sensors, such as 3-D laser scanners and stereoscopic vision systems. These hard requirements are mostly necessary when robots have demanding dynamical and kinematic constraints, and their actions are intended to be optimal. However, a small and light robot operating in a natural environment is much less demanding in this respect. This vision lead to the development of a novel concept for *affordable embodied all-terrain locomotion* (Santana, P., 2005; Cruz, H. et al., 2005; Santana, P. et al., 2007).

The basic idea of this concept is to categorise the environment recurring to little computational power, by means of properly distributing simple sensors in key locations of the robot's body. The relative perspective these sensors have over the world makes them “tuned physical filters” to extract relevant environment's features. The output of the filters feed the control system allowing it to perform obstacle avoidance, speed control based on terrain's roughness, etc..

In order to test the method, some experiments have been carried out in a first version of the Ares robot (see Fig. 2). The Ares robot was equipped with a set of simple sensors utilising this approach so as to implement physical filters to distinguish *tall* from *low* objects, and *obstructive* from *non-obstructive* objects. Namely,

- An upper sonar set composed of eight sensors mounted on an elevated *pendular* platform allows the robot to detect *tall* objects (e.g. trees). The higher the platform is, the higher the objects must be in order to be detected by the sensors. Hence, specifying the height of the platform is like tuning a filter to reject *low* objects. Being *pendular*, the platform keeps its vertical position whatever the robot's roll angle. To reduce cost, the eight sonars can be substituted with a single one mounted on a servo.
- To detect *low* objects, a lower sonar set (a single sonar in this case) is used. Once again, this sonar set implements a physical filter to detect *low* objects.
- Two front bumpers attached to tunable springs detect *obstructive* objects (e.g. dense bushes). If a bumper is triggered, then it means that the robot touched an object that projects a force onto the robot greater than the one produced by the springs. Thus, specifying the strength of the springs is like tuning a filter to accept *non-obstructive* objects (e.g. weeds).

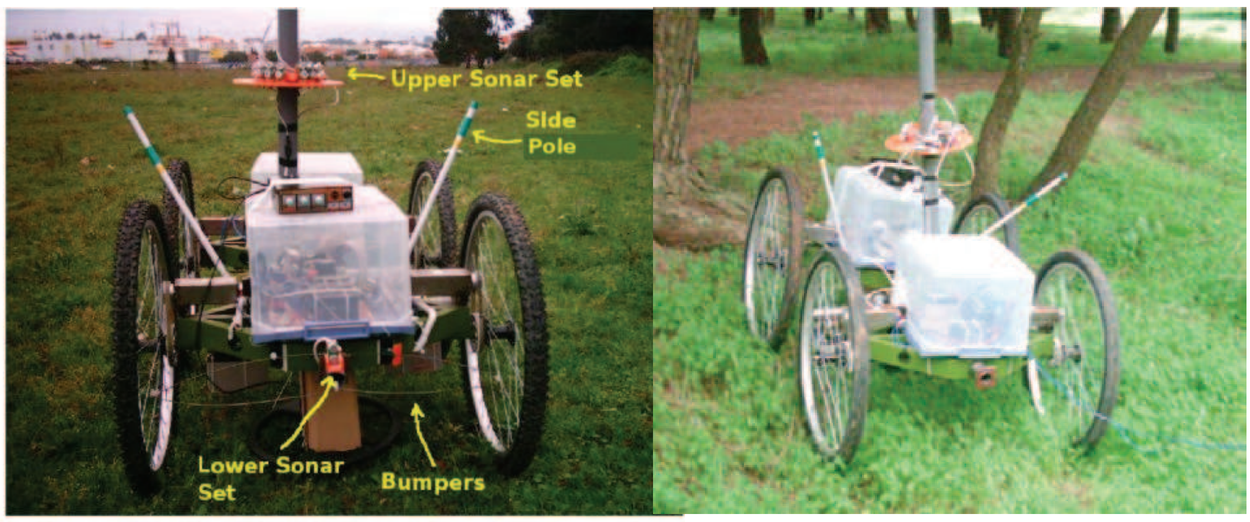


Fig. 2. The first Ares robot version

It is possible to react to all *obstacles* (i.e. *obstructive objects*) encountered by the robot using the bumpers alone. For a proper piloting of the robot, however, detecting *obstacles* before colliding with them is required. To do so, some heuristic knowledge about the environment can be used. A typical example of such knowledge is the fact that usually: weeds are *low* objects and *not obstacles* to the robot; trees are *tall* objects and *obstacles* to the robot; rocks are *low* objects and *obstacles* to the robot.

Based on these heuristics, the previously presented physical filters can be used to avoid *obstacles*. Since from the above facts it follows that *tall* objects are usually *obstacles,* each time a sensor in the upper sonar set detects something (i.e. a *tall* object) the robot should avoid it according to a given avoidance policy. However, some *low* objects are *obstacles* (see for instance the case of rocks). Therefore, each time an object is detected by the lower sonar set (i.e. a *low* object), the robot slows down its speed as it is not sure about the nature of the object. If a bumper is triggered afterwards, then the robot initiates an avoidance routine as it has detected an *obstructive* object, and consequently an *obstacle*.

This example illustrates how it is no longer possible to distinguish between software and hardware in terms of what takes control over what. Under this paradigm, the robot's body *is* part of the decision process, i.e. it is fully *embodied*. These ideas are closely related to the principles of *morphological computation* (Pfeifer, R. & Iida, F., 2005), in the sense that the body of the robot contributes greatly to the decision making process. In fact, some parameters of the robot's morphology (e.g. the height of the upper sonar set) can be used as constants in a *holistic embodied algorithm*. The absence of any central geometric representation of the environment results in low-cost and robust robots.

Despite its simplicity, this method is an interesting solution to the problem of making small and simple robots which perform well, perhaps not optimally, in complex environments. Next we present a behaviour-based control architecture developed to support control logic such as the one presented in this section.

4.1.2 The Survival Kit Architecture

Although a method to implement *embodied* all-terrain controllers was just presented, the underlying architecture was not covered therein. To close the gap this section briefly describes a behavioural architecture especially designed for disposable/affordable robots, the Survival Kit (SK) (Santana, P., 2005; Santana, P. & Correia, L., 2005; Santana, P. & Correia, L., 2006).

The SK architecture is the bottom layer of the robot control system, and it supplies the robot with safe local navigation capabilities. Thus, everything required to maintain the survival of the robot, in terms of immediate reactions, should be implemented within the SK architecture. Upper-layers are allowed to modulate the SK. Fig. 3 illustrates the main components of the SK architecture.

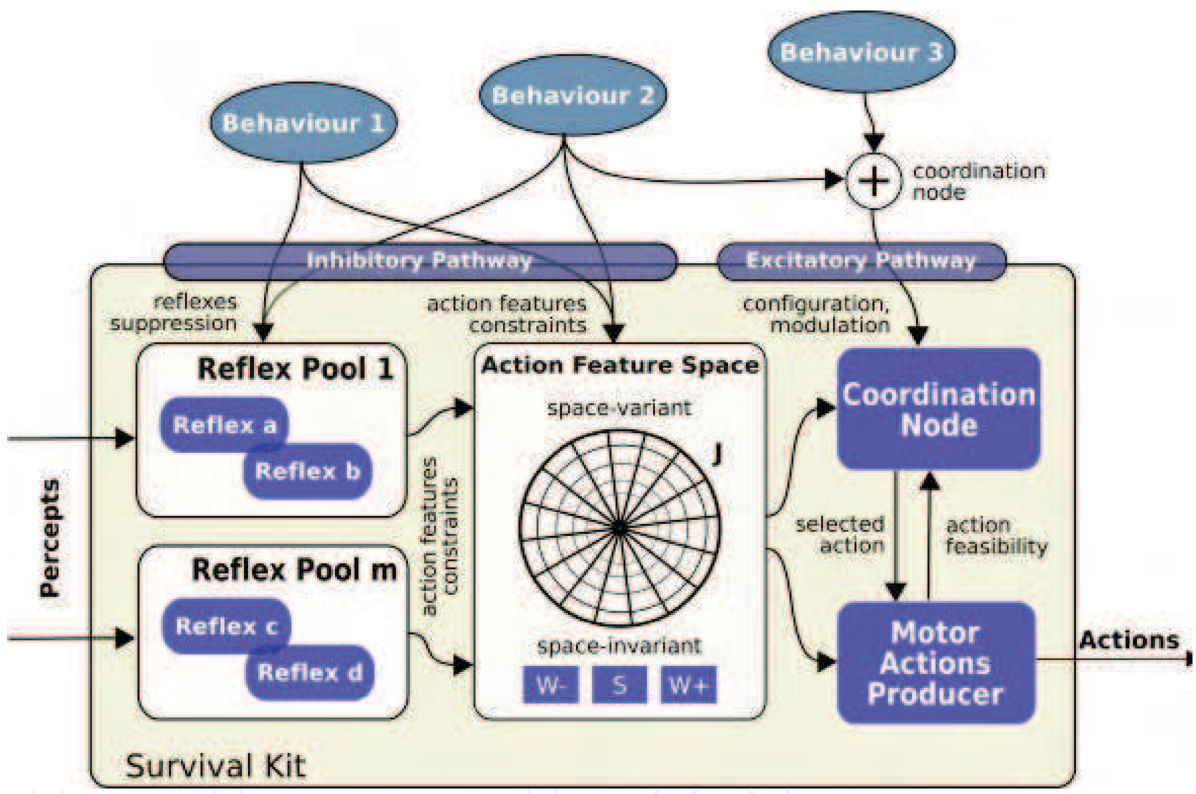


Fig. 3. The Survival Kit architecture

The core of the architecture is the *action feature space*, which indirectly describes all the robot available actions. An *action feature* is an attribute of the action, such as the *maximum allowed velocity* and the *maximum distance* the robot can travel in a given sector of the environment. This departs from the conventional *action space* (Rosenblatt, J. K., 1995; Pirjanian, P., 1998), in which actions are explicitly represented by tuples that are directly mapped to actuator commands, such as *linear and angular velocities.* The action feature space is composed of two sub-spaces: the *space-variant* and the *space-invariant*. The *space-variant action feature sub-space* is sectorial. Each sector corresponds to a region in the environment with the same shape. In each sector, associated to each action feature there are two slots, one for a constraint on the respective action feature, and another one for its temporal validity. A second action feature sub-space, the *space-invariant action feature sub-space*, is composed of action features without spatial relationship, such as *possibility of producing angular velocities*. These action features can also be temporarily constrained.

Reflexes are units responsible for constraining action features in order to implement a part of the survival policy, such as reacting to a collision. For the sake of clarity an example is given. Let us define the action feature v_{max}, as *the maximum linear velocity allowed in a given sector of the environment*, and a reflex *adapt_speed*, as the mechanism to set up the maximum speed the robot can travel in a given sector of the environment based on the terrain's roughness. This reflex can then add constraints to v_{max} so as to limit the robot's speed when the terrain's roughness increases. For instance, a constraint of $1\ ms^{-1}$ could be added to v_{max} in sector *0* for *100 ms.* In this way the reflex explicitly states what is the maximum speed the robot can have when travelling along sector *0,* if its mechanical structure is to be preserved.

A set of conditions must be met when accepting a new constraint. If a new constraint reduces the possible set of actions (e.g. if the new constraint is intended to reduce the value of v_{max} to $0.5\ ms^{-1}$), then it is immediately accepted. If the new constraint validity is greater than the current one, then the constraint validity is updated with the newer value. This approach guarantees that new constraints never relax previous ones, or their validity time. When its validity time expires a constraint is released.

Modulation comes in many forms. Upper layers can: constrain action features, suppress reflexes (e.g. docking requires to suppress reflexes sensible to bumpers), and provide a desired course of action (e.g. desired speed and direction). This plasticity is a must if the SK is to be embedded into a more complex system capable of producing complex adaptive behaviour.

The *coordination node* is the module responsible for selecting, from the actions still available, the one that better suits the modulatory signal provided by the upper layer. This is achieved by maximising an objective function that selects the best sector from the ones still available, and then builds up the commands that are immediately sent to the actuators. Among others, the objective function takes into account the free-space connectivity of the environment for a proper navigation through obstacles.

It is worth mentioning that the previously presented all-terrain piloting method is directly mapped into this architecture. Reflexes implement reactions to the *physical tuned filters* by specifying constraints, such as constraining v_{max} in the presence of *low objects.* Further details can be found in (Santana, P., 2005).

4.2 Second Stage: Minefield Area Reduction

If an explosion has already taken place, TNT and other compounds will be spread all around. In this case chemical sensors will always return a positive result, being of little use to determine if any other landmine is present in the field. Another technology, such as metal detectors or Ground Penetrating Radar (GPR), is therefore required. In addition, if after the first stage, i.e. minefield detection, the field is considered contaminated with TNT, a subsequent area reduction may be required so as to reduce as much as possible the amount of unusable land.

Hence, for the second stage, i.e. area reduction, robots should be able to transport other non-chemical sensors, such as GPR and metal detectors. These sensors are bulkier and require more energy to operate. Therefore the robot must be more powerful and consequently heavier. As a result the chances of triggering a landmine when stepping on it increase up to dangerous levels. Detecting the landmine in order to avoid it is then a must. This chapter being focused on the robotic platforms, this latter topic will not be covered.

4.2.1 The Ares Robot

The already presented Ares robot has been improved in a second version (Santana, P. et al., 2007) (see Fig. 4 and Fig. 5) for the second stage. Rather than developing a robot for planar and smooth outdoor environments, focus has been given to a platform able to traverse high slope uneven terrain. This way the robot can be used in cluttered areas where deminers usually have more difficulties in operating.
Fig. 4 illustrates the robot's mechanical structure, in which it is possible to see its four independently steered wheels in four different locomotion modes:

- **Double Ackerman mode.** This refers to a car-like locomotion method, but in this case the rear wheels also turn according to the double Ackerman geometry (Fig. 4 top-left). The Ackerman geometry must be continuously maintained. In this mode the robot is capable of producing a turning radius down to 80cm without lateral slippage.
- **Omnidirectional mode.** In this mode the four wheels are aligned to produce linear trajectories without rotation (Fig. 4 bottom-left).
- **Lateral mode.** This is a special instance of the previous mode, in which the four wheels are aligned and perpendicular to the main axis of the robot, allowing the robot to move sideways (Fig. 4 bottom-right).
- **Turning-Point mode.** In this mode the robot is able to rotate around its own geometrical centre without lateral slippage (Fig. 4 top-right).

This characteristic of high mobility enables low friction quasi-holonomic motions. In addition to its importance in the case of demining tasks, in which locomotion with lateral slippage is undesirable as it can trigger landmines by disturbing the ground, high manoeuvrability is also essential to make the robot get into highly cluttered environments.
The robot is implemented with low-cost, easily available components, like bicycle wheels. Besides being low cost and widely available, bicycle wheels also have the advantage of providing the robot with a considerable height from the ground (~40 cm). The upper bounds of the volume occupied by the robot are 1.51 m x 1.36 m x 1.50 m. The actual volume varies according to the selected locomotion mode. Both front and rear axes can freely and independently rotate around a longitudinal spinal axis (see Fig. 4 bottom-left). By having this passive joint, the robot is capable of being compliant with respect to uneven terrain.
The size of the wheels and the compliant body are extremely important features in reducing the sensorial and computational requirements of the robot, as they reduce the need for explicit handling of most natural obstacles (e.g. small rocks) present in the minefield. Less sensors and less computer power results in less energy consumption, less complexity, less cost, and consequently a more affordable and sustainable platform for mine action. By adapting the tyres to the nature of the terrain, it will be possible to cope with most environments where the system is to be applied. Fig. 5 illustrates the Ares robot performing in an all-terrain environment.

Fig. 4. The second Ares version mechanical platform (see text for details)

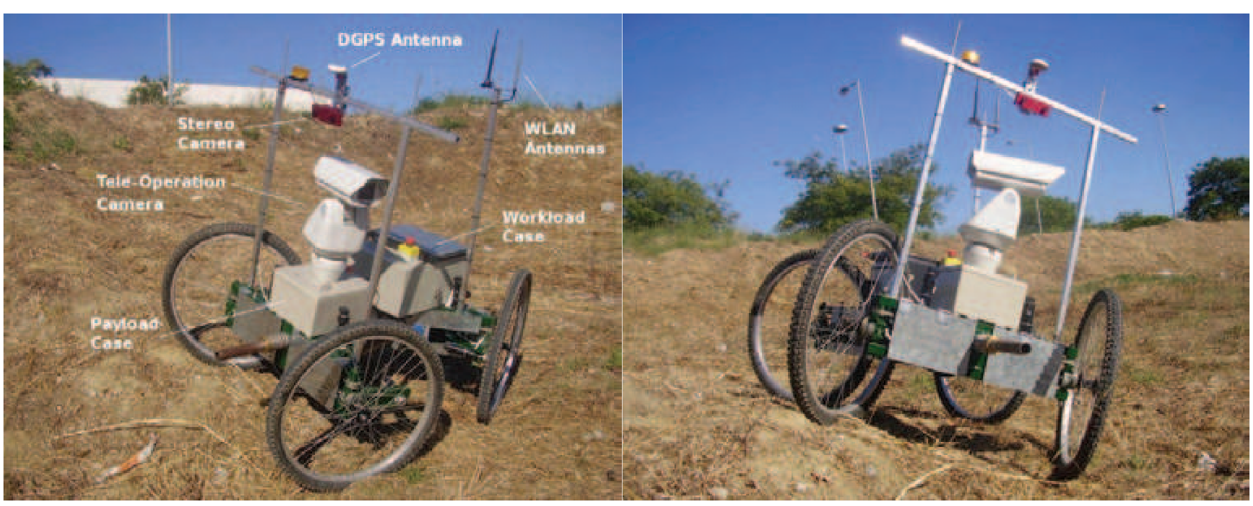


Fig. 5. The Ares robot in all-terrain

4.2.2 The Ares Robot's Locomotion Control System

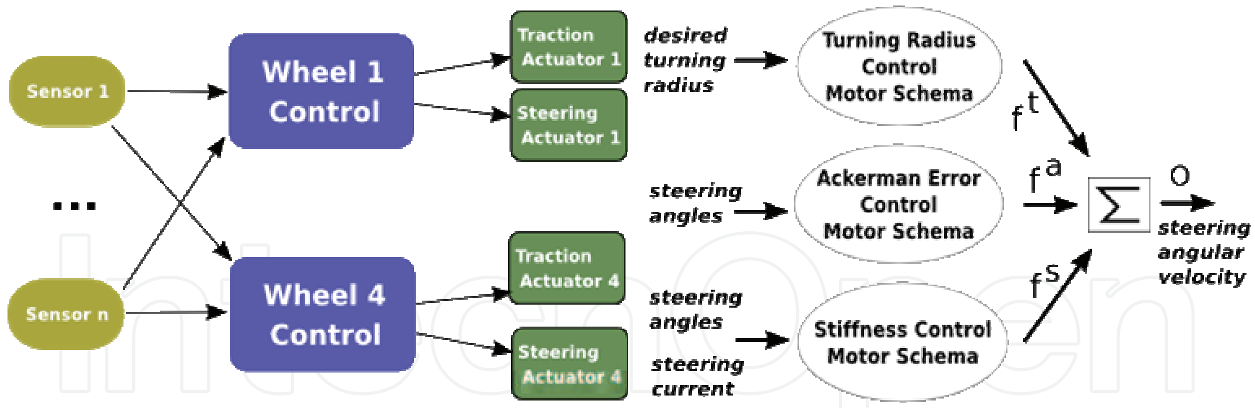
Among the most demanding challenges faced by a robot operating in a complex natural environment is the maintenance of a good performance in transient and extreme situations. This means that, more important than searching for optimal nominal behaviour, it is preferable to design the system to be endowed with graceful degradation. High slopes, loose terrains, fallen branches, etc., usually cause non-nominal states, such as significant lateral slippage and imminent turning over risk. To cope with these, a behaviour-based approach for the locomotion control system has been followed.

In these situations, to be more useful than behaviour-based solutions, model-based approaches require a complete model of the robot's dynamics, kinematics, and robot-terrain interactions. Such a model would be too complex to be used in real time. Rather, reflexive model-free approaches are fast at the expense of a more exhaustive trial and error design phase.

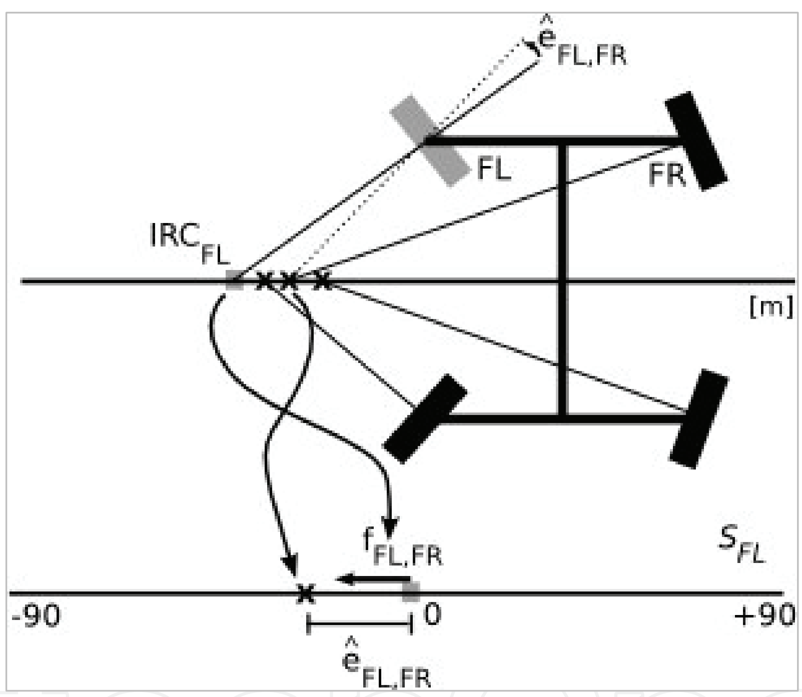
Fig. 6 illustrates part of an intuitive and biologically inspired approach to solve the locomotion control problem for the Ares robot (Santana, P. et al., 2006). The Ares robot, which is a Four-Wheel-Steering Robot (FWSR) encompasses several joints needing effective coordination. Failing to maintain a proper coordination results in wheel slippage, which usually induces mechanical stress, extra energy consumption, and ground disturbance.

Each wheel is seen as an independent entity with its own controller (see Fig. 6a). Each wheel controller is composed of a set of behaviours (see Fig. 6b), each responsible for a partial goal of the wheel, such as maintaining coordination with other wheels, responding to unexpected events (e.g. wheel blocking), or to maintain a target steering angle. A way of specifying each behaviour is by computing a resulting force vector that will be applied to the actuator according to a set of sensory inputs. In this case the behaviour is called motor-schema (Arkin, R. C., 1989).

Each motor-schema creates its own 1-D *potential field space*, designed to produce the desired behaviour. A point in the potential field space corresponds to an angular distance to be travelled by the steering actuator. According to sensory information, goals, etc., a motor-schema populates its potential field space with potential fields that can either attract or repel the steering actuator. The superposition of all potential fields over position zero in the potential field space, produces a "force" which will generate a proportional steering angular speed. As an example, the particular case of the Ackerman error control motor schema is analysed below (see Fig. 6c). First, the motor-schema determines the Ackerman error that the steering actuator *FL* (front-left) has relative to all other actuators. For instance, relative to *FR* (front right), the error is given by $\hat{e}_{FL,FR}$. This value refers to the number of degrees *FL* has to turn so as to guarantee that there is no Ackerman error between both steering actuators, i.e. $IRC_{FL}=IRC_{FR}$.



a) Locomotion control architecture b) Wheel controller



c) Ackerman Error Control behaviour

Fig. 6. Partial view of the behaviour-based locomotion control system

Then, an attractive potential field is added to the potential field space in the position defined by $\hat{e}_{FL,FR}$. This potential field induces an attractive force onto the steering actuator, in order to reduce the Ackerman error relative to *FR* (i.e. $\hat{e}_{FL,FR}=0$). The attraction to one of the steering actuators is then weighed against the attraction to the other steering actuators, following the procedure described above. Since all other wheel controllers are implemented likewise, steering actuators will cooperate implicitly.
Weights are defined empirically. However, their explicit semantic allows the designer to perfectly distinguish how each of them contributes to the intended displayed behaviour.

This is essential to promote fast and easy adaptations in the operations site. Motor-schemas are just a possible way of specifying behaviours. To better handle all types of exceptions, other methods for behaviour specification and coordination are being considered. Refer to (Pirjanian, P. , 1999; Arkin, R. C., 1998) for two thorough surveys on the field of behaviour-based robotics.

4.2.3 The Ares Robot's Perceptual and Localisation System

As mentioned earlier, sensor reuse is essential to reduce costs. With this in mind stereoscopic vision has been selected as the primary sensor to both localisation and environment perception. A 9 cm baseline Videre Design STOC is being used for both purposes. This device already comes calibrated and with enough computational power to provide range information up to 50 Hz. The device is mounted on the front of the robot at a height of 1.30 m (see Fig. 5).
An algorithm based on (Manduchi, R. et al., 2005) has been developed and can be briefly described as follows. A surface ramp is considered part of an obstacle if its slope is larger than a certain value, and if it spans a vertical interval larger than a given threshold. Closer obstacle points are then considered as part of the same object. This approach allows the determination of obstacles in slopped terrain without explicit ground plane extraction, which is a demanding computational task. With this information it is then possible to obtain data about obstacles, such as their approximate size and shape, and consequently reject those that are too small or too sparse. Fig. 7 illustrates the capabilities of such a system, motivating the use of stereo vision as the primary sensor in natural environments. In addition to obstacle detection, the very same sensor can be used for terrain classification and also for visual inspection of ERW.

Fig. 7. A typical result of obstacle detection with the stereo head

As aforementioned, stereo vision is also employed to enhance the localisation system. Two localisation accuracy levels have been defined for the humanitarian demining problem:

- **Accurate relative localisation.** Sensors' output (e.g. landmine and obstacle detectors) must be accurately fused to enable a proper operation of classification, identification, and mapping algorithms. This requires sequential sensory readings to be fused together with an accuracy in the order of one centimetre. Conventional localisation techniques based on relative motion estimation (e.g. dead-reckoning) can provide such accuracy.

- **Global convergence.** Even with one centimetre accuracy in relative motion estimation, the global localisation error grows unbounded when the estimation is integrated over time. Thus, although maintaining a good enough accuracy for landmine classification and identification is attainable with relative motion estimation techniques, geo-referencing each detected landmine requires a global localisation method. Painting the ground when a landmine is detected is an efficient mechanism to allow deminers to detect landmines by visual inspection, even without a proper geo-referencing. Hence, a low resolution (~1 m) global localisation suffices for the humanitarian demining domain.

These conclusions are essential for reducing costs. See for instance that a global localisation in the order of one centimetre accuracy can be achieved with high cost DGPS-RTK systems, which often fail nearby trees and buildings. In these cases it is necessary to estimate the robot's localisation by integrating relative motion and attitude changes. This procedure is commonly known as *dead reckoning*. For this purpose, typically high cost inertial navigation systems (INS) are employed. By relaxing global localisation requirements to one meter accuracy, the cost of a DGPS can be lowered by one order of magnitude. A Novatel EGM-333 has been selected for this. To fulfil the relative localisation role of expensive inertial systems, three low-cost systems are being used:

- A low cost Honeywell HMR 3000 compass is used to provide accurate robot's attitude information. Being based on accelerometer information to determine the pitch and roll of the robot, it is sensible to spurious accelerations.
- Wheel based odometry can be used in smooth terrains, and if carefully considered, can also provide valuable information in uneven terrains (Ojeda, L. et al., 2006).
- *Stereo based visual odometry* estimates the robot's displacement and attitude changes based on the relative motion of visual features perceived by the stereo head. This mechanism can be used in conjunction with the compass and wheel odometry mechanisms to provide accurate relative localisation in smooth, uneven, and sloped terrains.

We have developed an implementation of the stereo based visual odometry technique based on the work of (Agrawal, M. & Konolige, K., 2006). The method is composed of three main computational stages:

- **Feature selection.** The first step is to select landmarks from a 2D image for which the 3D position can be accurately measured.
- **Feature tracking.** In the second step landmarks from the current iteration are matched (i.e. tracked) against the landmarks from the previous iteration.
- **Motion estimation**. With the 3D position of a set of landmark pairs, the motion of the camera, and consequently of the robot, that better describes the relative position change of the landmarks is computed.

Fig. 8 illustrates the results of a typical run of the visual odometry algorithm filtered with compass information (for posture global convergence). The robot was tele-operated in Ackerman mode to perform a loop, i.e. to start and finish the run in the same location, with an average speed of 0.5 ms^{-1}. No special care has been taken in order to adapt the robot's speed to the terrain, which resulted in considerable oscillations felt by the stereo-head. Nevertheless, the positioning error, computed as the Euclidian distance between 'S' and 'E' (i.e. the starting and finishing positions of the robot in the map, respectively), was ~2.6 m, which in a ~50 m run results in an error of ~5%.

Fig. 8. A typical result of the visual-based dead-reckoning system. The estimated path on the left is superposed, with perspective correction, on a view of the terrain on the right. The superposing is illustrative only. The arrows represent the direction of motion, and the robot is on the starting position, represented by 'S' on the estimated path

4.3 Third Stage: Accurate Landmine Detection and Removal

The previously presented Ares robot may become a useful tool for area reduction, helping people to assess the risk when using land. However, it may be essential to clean some specific contaminated area, such as a narrow passage leading to an agriculture field. For this purpose, a machine able to perceive and manipulate the terrain in an accurate and stable way is paramount. Therefore, a robot such as Ares, whose main scanning capability is provided by its own motion, does not cope with these requirements. In addition, being light, the Ares robot is not adequate to transport a robotic arm for ground manipulation. Fig. 9 illustrates a 3D model of the Poseidon robot (Cruz, H. et al., 2005), a well adapted machine for accurate ground analyses and manipulation.
Although the Poseidon robot is still in design phase, its unique features deserve some especial attention. It will be made of aluminium and it has a squared shape with a 3 m^2 effective scanning area. In this area, a 3 DOF scanner will be handling any sort of landmine detection sensor or ground manipulation tool. The stabilization of the frame is ensured by the use of telescopic legs. A power screw and an electric motor actuate this device. These are attached to the structure through a spring which smooths the walking process. The walking movement of the structure is accomplished by means of a 2 DOF mechanism. A complete step can reach up to 3 m. This configuration only allows acting upon a DOF at a time, as illustrated in Fig. 9.

Since, the weight is an important asset, and the structure has large dimensions, the use of aluminium and polymeric material has been selected to reduce the structure weight. For the lateral beams a double "I" shape 190 mm wide, 80 mm high, 3200 mm long and 14 mm thick was chosen. Low cost and wide availability were the main concerns regarding the selection of this shape. These beams support the top scanner and the locomotion sliding structures. However, with such dimensions the beam is heavy, at about 18 kg/m. After a stress study, it was realized that drilling oval holes along the section could reduce the weight without a loss of rigidity. With this re-design, about 25% of its weight has been lost. An asymmetric "I" shape has been selected for the locomotion sliding beams. The use of aluminium provides a lightweight solution and reduces the electromagnetic influence on metal detectors.

The 3 DOF scanner is also built in aluminium whereas the sliding mechanism is made of polymeric material. The use of a polymeric material reduces the maintenance operation (because it does not require lubrication) and allows operation in dust conditions without further protective devices, which simplifies the design process. The sensors fitting zone is designed case by case to ensure a perfect assembly between the sensors and the scanner. The 3 DOF permits a perfect compliance between sensors and ground. Being able to move sensors and actuators in a 3 m x 3 m area without moving the legs makes it the ideal tool for accurate sensor fusion and ground manipulation. Despite being big, the robot will be easily disassembled so that it can occupy little space in an all-terrain vehicle.

Fig. 9. The 3D model of the Poseidon robot

This robot is an upgraded version of a 1 m² pneumatic frame-like robot (see Fig. 10). Being pneumatic, its control is much less precise than that of its electric counterpart, reducing its ability to cope with uneven terrain. In addition, the logistics associated with compressed air for the pneumatic system is much more complex than the one for the electric version.

Fig. 10. The pneumatic version of the Poseidon robot

5. Human-Robot Teaming

A demining campaign is better achieved when multiple robots are employed, and in particular when these are low cost and light. However this requires them to be simple and therefore unable to fulfil the mission alone. A multi-robot approach is essential for the previously presented *first stage portable demining kit*, in which several small and simple robots scan wide areas searching for minefields. Consequently, as robots get damaged they must be replaced whenever possible. This requires the system to be highly flexible with scalability properties. It is also known that robotic systems performing complex tasks still require human intervention, or at least supervision. Since expert supervision may only be viable by remote interactions, the system should be *transparent* and *accessible* from any point in the internet.

All these requirements for inter-operability, modularity and scalability, make the use of the multi-agent paradigm a natural solution to the computational backbone of the architecture (Santana, P. & Barata, J., 2005b). Bearing this in mind, the Distributed Software Architecture for Autonomous Robots (DSAAR) (Santana, P. et al., 2006b; Santos, V. et al., 2007) has been devised. In DSAAR, robots and any other resource, are composed of two main layers: (1) the *social ability layer* and (2) the *individual control layer* (see Fig. 11).

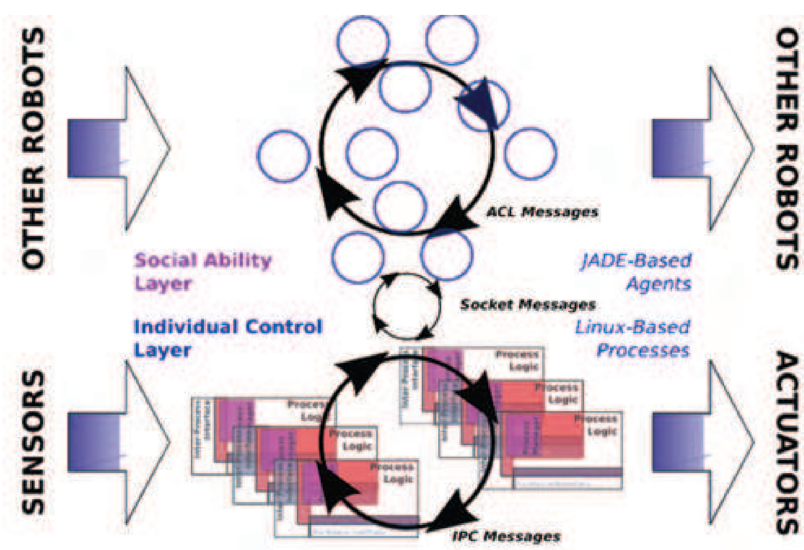


Fig. 11. A robot control system under DSAAR

A set of Jade[1] agents (blue circles in Fig. 11) is responsible for implementing the robot's *social skills*. Hence, these Java agents interface with other agents representing other robots in order to act cooperatively. They also interact with *mission support agents* so that operators can interact with the system. All agents in the system communicate with FIPA-ACL[2] (FIPA compliant Agent Communication Language) messages, according to an ontology specified in Protégé[3].

Ontologies are not just vocabularies, they may represent complex relationships between concepts. A general ontology serves as backbone for the whole system. Then, concepts

1 http://jade.tilab.com/
2 http://www.fipa.org/
3 http://protege.stanford.edu/

maintained in the general ontology are used to build up new concepts, these specialised and therefore useful for specific purposes. An example is the case of the concepts used in tele-operation agent-based communications. Being stripped down versions of more complex concepts, these communication oriented concepts can help in reducing the bandwidth requirements. Nevertheless, all being concepts in the system related to each other through a general ontology, it is possible to maintain a common language throughout the system.
In the bottom of Fig. 11 it is possible to depict a set of entities responsible for the control of the robot's autonomous behaviour. These entities are implemented as Linux processes following an appropriate control model. The previously presented Survival Kit architecture and locomotion control method are implemented at this level.

5.2 Mission Support Agents

To allow an intuitive interaction between operator(s) and robot(s), a set of agent-based tools has been developed. These tools are supported by *mission support agents* which interact with the *social ability agents* present in each resource (e.g. robot). The following text briefly describes two of them, viz. tele-operation and 2D map tools.
The tele-operation tool (Santos, V. et al., 2007) (see Fig. 12) allows the user to control the robot, a camera or both by using a generic USB gamepad. Via the gamepad, the operator can select the robot's locomotion mode, lock either the direction axis or the speed axis while controlling the robot, inspecting the pitch, twist, heading, wheel angle, wheel speed, battery status, and localisation information. All this information is supplied by the robot's *image agent* through ACL messages.
Also fed by the robot's *image agent, t*he 2D map tool (Santos, V. et al., 2007) (see Fig. 12) provides the user with a map along with all its common functionalities, such as zoom in, zoom out and map navigation.

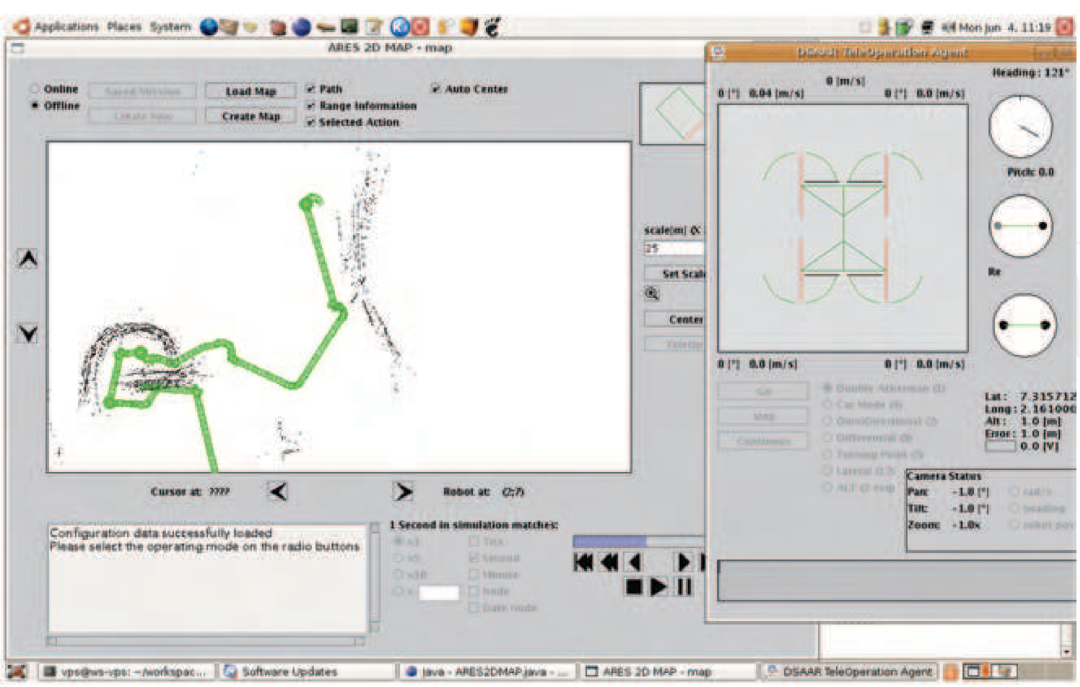


Fig. 12.The 2D map (on the left) and the tele-operation (on the right) tools

The tool provides information in both *off-line* and *on-line* modes. In the former case, the tool can be used to navigate in a previous mission object created with log files produced by the robot. Therefore, it is possible to know what has been done by the robot in a previous mission up to a millisecond resolution. Obstacles and robot localisation/path can be inspected directly in the tool, whereas detailed information about past wheel angles, currents, etc., are provided to the user through the tele-operation tool. The 2D map sends messages to the tele-operation tool as the robot's *image agent*, allowing the operator, in this way, to perceive past and present information through the same interface.
The on-line mode allows the user to see what is actually happening in the the current mission. The obstacles are just low resolution representations of the real world, and are simply superposed in the map as they are detected. Refined occupancy maps are produced on-board the robot, and then provided as bitmaps to populate the 2D map tool's background. This way the communication bandwidth is kept under reasonable levels.

6. Conclusions

This chapter presented some guidelines to build a *portable demining kit*, which is intended to be a fast deployable and affordable robotic system to aid in emergency situations. Since the logistics of a *portable demining kit* are less demanding when compared to a regular demining campaign, local mine action centres, provided with such a tool, will be able to be more responsive to emergency situations, reducing the chances of further victims.
It has been shown that to be successful, these kits must also be self-sustainable. This ranges from requiring simple maintenance, to the fact that they should be usable in other domains. If that is the case, then the owners, local governments for example, can exploit the devices for other purposes.
Several aspects of a sustainable robot capable of coping with the requirements of the mine action domain have been covered. The most important one is related to cost. The robot should be as cheap as possible. For that purpose a solution whose main sensor is stereo imaging has been proposed. This is used for localisation and perception. The localisation system is about one order of magnitude cheaper than conventional localisation systems.
Other essential topics are modularity and interoperability. These two basic engineering principles are paramount in making the system scalable. Scalability refers to the ability to allow elements of the system to be added and removed without inflicting dramatic effects on the system's performance. These elements can be robots and operators. Remote experts should be enabled to be integrated to the system as complications emerge. Modularity and interoperability is handled under the multi-agent paradigm. Furthermore, scalability must also be seen under the light of re-engineering. Add-ons, adaptations, and vertical developments are fostered having a system complying to the multi-agent paradigm.
The major cornerstone for the future work is the testing of the system in an actual demining scenario.

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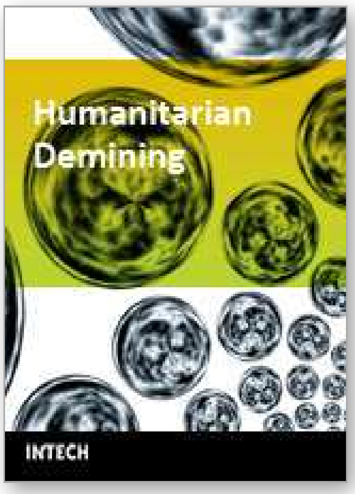

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United Nation Department of Human Affairs (UNDHA) assesses that there are more than 100 million mines that are scattered across the world and pose significant hazards in more than 68 countries. The international Committee of the Red Cross (ICRC) estimates 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).