A MULTI-ROBOT SYSTEM FOR LANDMINE DETECTION

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Abstract

This paper describes the development of a multi-robot system for Area Reduction in Humanitarian Demining. In spite of the specific requirements imposed to the work being carried out by the Humanitarian Demining domain, the results being achieved can also be used in other domains such as surveillance and remote monitoring. A multi-agent based architecture is responsible for coordinating a progressive stochastic analysis of the terrain. The all-terrain navigation used by the mobile robots is attained by a novel embodied reactive obstacle avoidance method. A Control Mission software has been developed to plan, configure and supervise the operations. Highly compliant legged and wheeled platforms have been developed accomplishing low-cost all-terrain robots. Digital signal processing algorithms have been applied for landmine detection using the payload sensors.

1. Introduction

Despite the general awareness on the amount of landmines laid down around the globe, end-user’s needs for new technologies must be properly assessed in order to avoid the waste of financial funds, which could be better applied in other vital parts of the process, such as manual demining. Hence, R&D in Humanitarian Demining should be focused on sustainable demining that means it must take into account the socio-economic impact of its results. Bringing formerly mined land back to their landlords involves much more than landmines removal activities (demining). This is the reason why this global process is known as Mine Action rather than Humanitarian Demining.

With this in mind, close-in detection and area reduction are considered as priority domains with very significant benefits for demonstrating progress on R&D [23]. Area reduction is defined as the process that reduces the amount of land that will be afterwards extensively analysed by close-in detection.

In this line, IntRoSys - S.A. created a roadmap [22] where area reduction is pointed out as the activity where the application of high-tech, namely mobile robotics, has more chances of faster success. This results from the fact that area reduction is an inherently probabilistic task, which has been more receptive to the higher costs and more complex technological solutions than in close-in detection. Moreover, considering area reduction as a subtype of a Generic Remote Monitoring Toolkit, the research results being achieved in this domain can easily be applied in other related domains (see figure 1), which becomes a major advantage since the Humanitarian Demining market is inefficient, small, and shrinking [10], from a firm point of view.

This paper describes a project being carried out by the Portuguese SME company IntRoSys¹. This project targets the development of a multi-robot system for Humanitarian Demining with an emphasis in Area Reduction.

In section 2 the current use of technologies to support Humanitarian Demining is briefly reviewed. After that the architecture of the system is introduced in section 3. Afterwards the control solution is described in section 4. Next the mechanical solution is described in section 5, and in section 6 the sensors carried by the robotic platforms are presented. Finally, the conclusions are summarised in section 7.

2. Technology Review in Humanitarian Demining

Humanitarian Demining has been often cited as a potential application for many research fields (e.g. multirobot systems, digital signal processing, machine learning, control systems, multi-agent systems, etc.). However, end-users real needs are seldom taken into account. The AMI-02 project intends to close the gap between end-users and the research community by developing sustainable technology.

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Ground wheeled vehicles has been the most used type of locomotion in demining. See for instance the low-cost, small and simple Pemex robot [16]; in the other extreme of the complexity spectrum we may find high-cost, heavy and complex all-terrain robots (e.g. the MR2 robot [11]). Legged robots have also been studied; for instance, the 4-legs Titan-IX [13] and the 6-legs and 2-arms heavy and bulky robot [17], which can also move on the wheels located in its torso. Inaccessible areas where conventional robots are of little use have been tackled with biologically inspired robots that produce peristaltic, rotating and crawler movements [5].

Unmanned helicopters are starting to be applied in the humanitarian demining domain. The ARC Project [8] uses an unmanned helicopter to gather multi-spectral and IR data. The U.S. Department of Defence has a humanitarian demining R&D programme where a Synthetic Aperture Radar (SAR) is mounted on an unmanned helicopter [4]. The Remote Sensing Laboratory (RSLab) at Russia, has been using helicopters to acquire visible spectrum images [12]. A set of German military projects in airborne detection, mobile landmine detection and clearance have also been carried out in the last few years [15].

It is known that real problems are difficult to solve with a single robot. Moreover, in humanitarian demining, the chance of exploding a robot is always present, which turns simpler and dispensable robots a much better and preferred solution. In addition, if the robotic team is heterogeneous, each robot can be better fit into a specific part of the task, or a specific part of the field. There are already some applications of multi-robot systems in Humanitarian Demining (e.g. [14]).

A fundamental part of Humanitarian Demining is sensor development and usage. IntRoSys is focused on sensor usage, which covers the aspects of sensor choice, integration and installation into the mobile platform, and fusion. Some work comparing different sensor fusion methods applied to landmine detection has been already developed [6]. The most used sensors for landmine detection have been infra-red cameras, ground penetrating radars, and metal detectors. The most used fusion techniques are naive Bayes’ approaches, Dempster Shafer theory, fuzzy probabilities, rule-based methods and voting techniques.

3. Architecture

This section describes the conceptual view of the project. The parts which have been already implemented are explicitly referred to in sections 4, 5 and 6.

3.1. Multi-Agent System Support

Figure 2 depicts the multi-agent system architecture, which is split into three layers: (1) the human agents layer that provides interfaces with the end-user, experts and operator; (2) the software agents layer that configures, maintains, and exploits the robots by interacting with the upper layer; (3) the physical layer, where robots lay.

An overview of other potential applications of multi-agent systems applied to Humanitarian Demining can be found in [19].

Let us briefly describe the software agents layer. The team image agent mirrors the physical robot in the server, allowing a human agent to interact with the robot via an abstract representation. The strategic agent is responsible for configuring the robot team to better accomplish the goals. Production agents fetch payload data (i.e. via landmine detection sensors) and transform it into information and knowledge, which is used by the end-user to assess the existence of minefields and other related information. The blackboard concept is a possible solution for the implementation of the production agents and respective products database.

3.2. Operations Preparation

Figure 3 depicts the operation of a strategic agent when configuring a team. First, a set of multi-spectral images and/or ranging data are acquired from an aerial platform (e.g. an unmanned helicopter). The acquired images are composed in a mosaic which is used to assess opportunities (i.e. potential landmine locations) and navigability of the terrain. These operations are performed
by a knowledge-based system, which with probabilistic, heuristic, and explicit knowledge interpret the data to detect features (e.g., tree, fence). Such features are then associated to end-user concepts (e.g., potential risk).

Opportunities and navigability assessments are fused to analyse which team configuration strategy should be applied. The CoBASA architecture [2] will be the backbone of this procedure. The CoBASA architecture is an agent-based architecture, in which cooperation is regulated by contracts and which was initially developed for a flexible approach to dynamic shop floor re-engineering. Its ability to handle resources configuration makes it an interesting approach to the problem of robotic team configuration.

Other interesting techniques to augment reasoning capabilities of the strategic agent are non-monotonic reasoning and fuzzy logic. These techniques allow reasoning under uncertain and incomplete information. Moreover, they are straight forms of representing common sense reasoning, such as minefield personnel domain knowledge.

4. The Control System

This section describes the control system. The architecture described in the previous section is not yet fully implemented, which is expected only at the end of the project. However, those parts related to the control solution that have been already implemented are going to be addressed in this section.

4.1. Mission Control

Figure 5 illustrates the server front-end, which is implemented in Java so it can be ported to any platform. Currently, it is running on a Linux based laptop. This software allows the user to both design and supervise a mission. In addition, if required, the user can also teleoperate the robots (see figure 6 for a snapshot of the teleoperation front end). A mission is defined as a graph. Each graph’s node can be assigned to one of a set of available behaviours (e.g., zig-zag, wait, wall-following, wander, etc.). Each graph’s arc has attached a motivation to reach the node. Such motivation is expressed in terms of desired navigation speed, maximum time allowed to reach the destination, etc. Therefore, the user defines a mission by configuring nodes and arcs, which later on can be downloaded by FTP to the robot. Based on the downloaded mission the robot (i.e. avoiding obstacles) can now perform the plan autonomously. Continuous communications between the server and robot are maintained using TCP-IP sockets.

4.2. The Robot Control System Hardware

Usually, development teams invest considerable effort in developing generic black-box controllers, which hopefully can be fitted into every robot. Despite the interest on
such a modular approach, it fails in developing robots for this specific task, where cost and simplicity are the major requirement. Therefore, different control systems shall be considered, such as: a micro controller based control system for low cost robots, a hard-real-time control system for aerial vehicles control and a soft-real-time control system for ground vehicles.

The current control system is running on Linux (Debian distribution) and it was implemented in C and C++. The hardware platform is a PC-104 with RS-232 ports and AIO cards. The first approach has been based on low-cost components, such as: sonars (for obstacle avoidance), compass, and DGPS (for navigation). In order to reduce costs, vision and/or ranging sensors outside the minefield will be used to track the robots operating within the minefield. Such solution avoids the explosion of the high-cost positioning system while keeping accurate positioning.

4.3. Reactive Navigation

Reactive navigation has been the main project’s focus in terms of control systems. The reactive system, called Survival Kit (refer to [21] for a detailed description) provides safe navigation using a minimal system. This allows the implementation of such architecture in low-cost and low-power computational units, such as micro-controllers. Moreover, the architecture does not need self-localisation mechanisms to operate properly. This feature reduces the solution cost. This is particularly true in all-terrain navigation, where odometry is infeasible, by requiring expensive sensors (e.g. inertial and/or high-resolution DGPS-RTK).

An interesting feature of this algorithm is that it can provide optimised path navigation, an unusual feature in reactive navigation systems. Reactive approaches to avoid dead-ends have also been taken into account, such as wall-following methods. The algorithm itself handles U-obstacles if the obstacle is within the sensors range. If the obstacle is bigger, the robot gets into it but then wall-following solves the problem.

The algorithm also takes into account robot’s dynamics and kinematics in a simplistic manner. Special attention was taken in handling vehicles of variable configuration, such as one of the robots we are currently working with. A momentum component creates an implicit local map of the surroundings, which is described in terms of the interactions between the robot and the environment, reducing responsiveness to noisy sensors.

The Player/Stage simulator [9] has been used as the simulation environment. See figure 7 for a simulation run of the algorithm in the Player/Stage simulator.

4.4. Embodied All-Terrain Navigability Assessment

The work on rough terrain navigation has been typically tackled with high-cost solutions. See for instance [3] where stereoscopic-vision based range data is used to detect obstacles. The system that will be presented below intends to solve the all-terrain navigation problem in a low-cost fashion. Some experimental runs of the physical robot have been performed, showing the feasibility of the solution.
One of project’s earlier prototypes is present in figure 8. This prototype allowed the exploration of a novel method for all-terrain navigation. The solution has potential for other domains, such as exploratory of unknown and unstructured all-terrain environments by dispensable (i.e. low-cost) robots. A set of distributed reflexes result in the all-terrain navigation behaviour, which is in fact an emergent property, since neither the global behaviour is written anywhere nor there is a global and geometric representation of the environment. Let us now discuss each of the reflexes that compose the all-terrain navigation behaviour.

The core of the method is its heuristic knowledge about the terrain (e.g. bushes height, rocks, etc.), which could be extended to probabilistic knowledge, as long as there is enough data on the terrain characteristics (e.g. bushes average height). This knowledge is used at design time phase, mainly for the definition of the height where the upper sonars set is mounted, which could be described as: if the upper sonars detect any object, then it must be an obstacle. This is true because of the heuristic/probabilist knowledge that most tall - translated to height in the sonars frame of reference - objects are obstacles (e.g. trees), whereas low obstacles are soft obstacles (e.g. grass, small bushes). Notice that these rules work for most of the environments.

Therefore, if an object is perceived by the upper sonars, which are supported by a pendular platform keeping them with zero-tilt, the robot avoids it, whereas if the object is only perceived by the lower sonars, which are disposed between robot’s front wheels, the robot simply slows down so it can pass over the object safely. The remaining low objects that are in fact obstacles, force the bumpers, which are located nearby the lower sonars, to trigger an avoidance behaviour. Above a certain tilt angle, the upper sonars detect the front wheels, requiring the robot to turn in the opposite direction and consequently to restore a safe tilt angle.

As can be depicted in figure 8, the vehicle was able to navigate surrounded of tall grass. All these reflexes are implemented within the aforementioned Survival Kit. The power and simplicity of the method comes from the fact that it is highly embodied and looks for emergence.

4.5. Unmanned Aerial Vehicles

The relevance of technology transfer, from Humanitarian Demining to other domains, has been the drive to approach other solutions other than ground vehicles, such as unmanned helicopters. The problem of unmanned helicopters control has been intensively studied in the last few years, mostly around aggressive manoeuvring (see [18] for a survey). For demining, low-bandwidth controllers are enough, which discards the need for high-cost attitude/position sensors. What we envision as very important, it is on-line adaptation to handle degradation of both sensors and actuators, as well as, sensors displacement. Currently, we are entering on this field. One first milestone is a comprehensive state-of-the-art focused on the problem of unmanned helicopters low-level control, which will be published shortly. The interested reader may find in [20] a study on the application of unmanned helicopters to Humanitarian Demining.

5. The Mechanical Systems

This section describes the current status of our mobile platforms from the mechanical point of view (refer to [7] for a detailed description). Some different types of locomotion have been tested, each one with its advantages and disadvantages. The strength of a multi-robot system, is to have heterogeneous robots cooperating for a common goal: to analyse the soil and identify landmines.

5.1. Legged Robots

Legged robots usually mimic insects; they usually have more than four legs for better stability and are small to be able to naturally open way through the vegetation. Although they are usually slower than wheeled robots, they have higher mobility, less weight and better skills to detect landmines and tripwires [1].

A first approach to the legged robots solution was to implement the 8-legs robot present in figure 9. The core of the system is its x,y,z bed, which is used to manipulate the payload sensors. This design allows mapping of the soil, by fusing different sensor modalities accurately.

The solution herein presented is pneumatic, which is not handy to use in remote locations; moreover, the robot is heavy. To overcome these problems, an electrical version is being redesigned to replace the pneumatic one. Electrical versions, despite their logistic advantage, allow fine positioning of the legs, which is important to guarantee stability in uneven terrain.

5.2. Wheeled Robots

Wheels and tracks are the locomotion methods more widely used. However, it is difficult to choose from the
two the one which is the best. On the one hand, tracks allow better mobility than wheels, but they are less energy efficient due to extensive slippage during direction changing. On the other hand, a careful design of the wheels kinetics structure can result in higher mobility [1].

Software development and testing has been used in a simple three-wheels robot (see figure 10) specifically designed for testing purposes. The *Ares* robot has been developed to be low-cost, simple, and easily repairable and maintained, making it suitable for the *area reduction* task. Due to its low cost the planned sensorial payload to be loaded on this robot is a vapour sensor that *smells* TNT.

Figure 8 shows the robot operating. It is possible to see its ability to negotiate uneven terrains. Its compliance to the terrain is an important asset for all-terrain navigation, even if this quality is usually disregarded by the research community. The robot is be light enough to move over landmines without triggering them.

A new version of the *Ares* robot is being worked out, which will allow (quasi-)omnidirectional motion and pitch/roll compensation (zero-tilt maintenance) for the upper sonars platform. The current version is limited to roll compensation.

### 5.3. Aerial Robots

As aforementioned, unmanned aerial vehicles are the next step. Mechanical systems assume extreme importance in the augmentation of the helicopter stability and payload accommodation. In fact, helicopters are naturally unstable, requiring good control laws to maintain them stable. The integration of some mechanical parts to facilitate its control is extremely desired.

Being an high vibration environment helicopters induce noise in the sensors, hindering correct signal processing. Therefore, a correct accommodation of sensors to filter vibrations will be pursued. Active stabilisation mechanisms will also be subject of research; nevertheless, passive mechanisms are preferred due to their simplicity.

### 6. The Sensorial Payload System

This section describes the sensorial payload system development, which accommodates the embedding of all landmine detection sensors. Some signal processing have been used to detect landmine signatures, mainly Fourier transforms. With those signatures, fusion among different sensors (e.g. metal detectors and GPR) and decision mechanisms are being studied. *Production agents* use these signal processing algorithms in order to produce the final product, the detection and identification of minefields.

The main sensors that are being tested are Ground Penetrating Radar (GPR), vapour sensors and metal detectors. Metal detectors are the most common sensors applied to Humanitarian Demining. However, since they detect every small metal fragment, the false positive alarms rate is significantly high. To reduce it, GPR can be applied to detect which alarms do really are about large metal objects. Furthermore, plastic landmines are hardly detectable by metal detectors, whereas are easily visible for GPR. Vapour sensors are extremely useful for area reduction; however, they are normally limited to TNT particles, which is not always the case in a real minefield.

Figure 11 illustrates how two metal objects underneath the soil are seen by a GPR. A human eye would easily depict that there are two buried objects at a distance indicated by where the parabolas are (one parabolic is 2m away from the reference point while the other is at 11m).

#### 6.1. Fourier Analysis

To automatically detect the existence of a landmine in a GPR image, Fourier transforms have been applied. Figure 12 shows that the objects in 2m and 11m positions irradiate more energy then the surrounding environment. The energy values (the y-axis) have been calculated based on the square of the original signal Fourier components. It has been shown that noise/signal ration is good, allowing easy identification, and so, the algorithm is a *good observer*. Further details are to be published shortly.
work will be done on the application of Wavelets transforms, which fit better with the pulsing nature of a GPR signal.

7. Conclusions

This paper describes part of the work being carried out by the Portuguese SME IntRoSys within the project AMI-02, which is being supported by the Portuguese Ministry of Defence and whose main target is the development of a heterogeneous Multi-Robot System for Humanitarian Demining. The multiagent based architecture to support the demining process was outlined and its main parts described. After that the robots main control aspects and their main mechanical features were described. Finally, the sensors to be loaded on each robot were briefly outlined.

The main conclusions about this work are:

- Low-cost solutions are required to meet end-users needs in a sustainable demining framework;
- Heterogeneous mobile robots is an advantageous characteristic since it reduces complexity through specialisation;
- Merging reactive navigation, external positioning tracking and a stochastic approach for terrain coverage, is low-risk and subsequently a low-cost solution;
- The high-cost robot localisation task can be solved by external robot tracking;
- The main sensors to be available in our robotic team are metal detectors, GPR, and vapour sensors. Sensor fusion will be the glue to merge these sensors’ data.

The approach being followed in this project is not constrained to the Humanitarian Demining domain. Other domains, such as surveillance and remote monitoring, can benefit from the work being carried out.

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References


