GUARDIANS

REPORTS ON
1) SIMULATOR ENVIRONMENT FOR ANALYZING NON-COMMUNICATIVE AND COMMUNICATIVE SWARMING
2) SWARMING ON REAL ROBOTS

DELIVERABLE 3.9 AND 3.10 (COMBINED DELIVERABLE)

VERSION FINAL

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CogSys
Cognitive Systems

1 Introduction

The Guardians (Group of Unmanned Assistant Robots Deployed In Aggregative Navigation by Scent) project is an FP6, EU funded, project developing a swarm of autonomous robots.

The GUARDIANS project has faced several challenges, the main one was how to apply a group of relatively simple robots without centralised control to a real-life scenario, such as the industrial warehouse in the emergency of the fire.

During the life-span of the projects the tasks of the GUARDIANS robots have been identified more precisely and roughly felt in two, partially overlapping, categories.

The *first category of tasks* are related to directly assisting fire-fighters, such as guiding a fire fighter, accompanying them and indicating them possible obstacles and locations of danger.

The *second category* comprises tasks which we refer as to the supportive tasks and can be fulfilled without a human squad-leader, such as deployment on the site, positioning as beacons and maintaining communication.

In relation to the five GUARDIANS scenarios, in Scenario 1 ‘Robots accompanying a firefighter’ and Scenario 5 ‘GUARDIAN robot as a labourer’ for the firefighter mostly the first category of tasks have been demonstrated, whereas Scenario 2 ’Communication demonstration’, Scenario 3 ‘Robots’ swarm dispersion. Building triangulation, positioning on the site, constructing a topological representation of the site’ and Scenario 4 ’Gas source localization’ demonstrated the second category of tasks. For detailed description of Scenarios see Deliverables 5.2 and 7.2.

Some tasks of both categories are overlapped, such as searching and navigating the environment; the main difference in this respect is that in the first category the robots act within immediate vicinity of the human, and therefore their sensor range may covers only a relatively small area of the environment, whereas in the second category of tasks the robots can disperse in the site and therefore the perception of the environment is more global.

In order to fulfil the tasks the robot should cooperate. Team or Collective robotics are divided in two major streams: *accidental or non-intentional cooperation* and *intentional cooperation*. Conventionally, the Swarm robotics paradigm is used for non-intentional cooperation; cooperation just happens and emerges from the group behaviour without being made explicit. Intentional cooperation can be described as combining particular behaviours aiming at an explicit goal. Robots interacting with people can comprise both aspects, whereas people, in general, interact intentionally with robots.

The GUARDIANS main goal was to demonstrate the strength of the group of robots in comparison to a single robot. However, the robot’s team capacities should be not just a simple summation of capacities of a single robot. The robots team should act as a whole and produce more complex behaviors as a collective. Therefore, several basic behaviours were identified in each category, and not surprisingly some ideas, terminology and development from Swarm robotics field have been used whenever appropriate.

Swarm robotics research is distinguished by the following criteria [1]: a swarm consists of (i) a large number, of (ii) homogenous, (iii) autonomous, (iv) relatively incapable or inefficient robots with (v) local sensing and communication capabilities.

The GUARDIANS group of robots does not comply directly to this definition. First of all, the group consists of non-homogenous robots, and human agents can be also part of the group. Secondly the number of robots in the group may be not very large in particular if robots accompany a fire fighter.

However, some characteristics of a swarm are present as well. The GUARDIANS group does not have a predetermined size, and due to huge dimensions of a warehouse a large number of robots may be required to fulfil tasks in the second category (criterion (i)). Communication with the outside might not be possible and the human being will be busy ensuring his own safety, thus autonomy (criterion (iii)) is a requirement; A single robot cannot do much in a large warehouse (criterion (iv)) and as communication cannot be guaranteed the robot cannot but rely on local information (criterion (v)).

Swarm robotics is also often divided into so-called communicative-less and communicative robotics. The former case, in general, means that 'communication' is assumed to be implicit, i.e. robots react to each other without explicitly exchanging messages, whereas in communicative swarm robots can exchange information.

The first category of behaviours required from a group of robots to assist the fire fighter can be split into two subcategories, roughly corresponding to non-intentional and international cooperation. The first subcategory focuses on basic navigation behaviours of multi-robot or human-robot teams, which have to be achieved without central and on-line control. These behaviours can be also achieved without explicit communication and therefore can be still applicable when communication links are severed. The generated global behaviour is relatively independent of the number of robots in the team, that makes the team also robust to failures of individual robots.

These behaviours have been demonstrated in Scenario 1.

The second subcategory is tasks directly related to interaction between a robot team and a fire fighter. This subcategory has been demonstrated in Scenario 1 and 5.

In both categories both non-intentional and intentional cooperation are applied.

In the second category of tasks the strength of the robot collective has been even more emphasised.

The GUARDIANS robot team is self-organising and can be seen as a hybrid of a (heterogeneous) swarm, a mobile ad-hoc network and an (evolving) topological map of the environment. For example, The Map Building process is not a separate activity, but an inherent by-product of the GUARDIANS self-organising system. The second category of Tasks were demonstrated in Scenario 2 and 3. Scenario 4.

In this deliverable we summarise the results related to Scenario 1, 2 and 5. This deliverable is also strongly related to Del. 3.5 3.7, 3.8 and 6.2.2 and 6.2.3, We do not repeat in this deliverable the results presented in the aforementioned deliverables.

1.1 Swarming algorithms testing in Simulation Environment

Most of developed algorithms have been first tested in Simulation Environments. The software for simulation used were: Player/Stage [2], Netlogo [3]. Netlogo, is a cross-platform multi-agent programmable modelling environment was used mostly for testing and visualising complex behaviours, as it allows to work with many agents simultaneously. The use of the Player/Stage programming environment was two-fold: 1) for testing algorithms; and 2)for testing corresponding interfaces. The Player robot server is a robot control interface, and Player allows direct application of algorithms to real robots.

The detailed description of Swarming algorithms in simulation environments is presented in the first attached document. (L.Alboul, J.Penders, J. Saez-Pons and Leo Nomdedeu, Heterogenous multi-agent system behavior patterns for robotics application, to appear in the handbook ‘Emerging Robotics and Sensor Technologies for Humanitarian Demining and Risky Interventions’, 2010).

At SHU, several students have worked on developing multi-robots behaviours in the frames of the Guardians project. They worked mostly with Player/Stage. They are:

Chui Ching Yee, Grid-based Map Building and Navigation Algorithms for Mobile Robots, 2007-2008, Carlos Bataller Narbó, Behavioural Control for Autonomous Robots and Map Building, 2007-2008, Chathura Wijaya Sri Dolahamuna, ‘Wall Following Behaviours for Mobile Robots’, 2007-2008, Manuel Espinosa Prieto, ‘Multi Robot 2D Tracking BY Colour Image’, 2008-2009, Miquel Cerezo Gandia, ‘Multi-Robot Team’s Behavioural Algorithms for Map Building and Path Finder’, José María Blasco Igual, ‘Multi-Robot Group Formation Control Algorithms’, 2008-2009. Their theses are available for inspection.

1.2 Swarming on Real Robots

Most of the algorithms developed regarding multi-robot interaction and cooperation have been tested on real robots. As we used Player/Stage, the applications of the algorithms were more or less straightforward. In case of small robots where ARM-Linux is installed, cross-compilation was required. The latter is related to Scenario 3 and described in details in Del. 6.2.2 and 6.2.3. The application of swarming algorithms on real robots in Scenario 1 and 5 is described in detail in the second and third attached documents. (Joan Saez-Pons, Lyuba Alboul, Jacques Penders and Leo Nomdedeu, ‘Multi-robot team formation control in the GUARDIANS project’, to appear in the Journal of Industrial Robot, 2010, and A. Naghsh, J. Saez-Pons, J. Penders J. Gancet, E. Motard, L. Nomdedeu, J. Sales, E. Cervera, R. Marin, P. Sanz, R. Sebastia, Sebastia, ‘Remote and in-situ multirobot interaction for firefighters interventions under smoke conditions’, submitted).

References

[1] E. Sahin. Swarm robotics: From sources of inspiration to domains of application. In *Swarm Robotics: SAB 2004 International Workshop, Santa Monica, CA, USA, July 17, 2004, Revised Selected Papers*, pages 10–20. Lecture Notes in Computer Science, Springer Verlag, 2005.

[2] http://playerstage.cvs.sourceforge.net/viewvc/playerstage/papers/

[3] http://ccl.northwestern.edu/netlogo/

HETEROGENOUS MULTI-AGENT SYSTEM BEHAVIOUR PATTERNS FOR ROBOTICS APPLICATION

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1. Aim of Chapter

The aim of this chapter is to present several basic behaviours required for a group of heterogeneous agents (robots and humans) in rescue and search operations. The listed behaviours are especially needed in the GUARDIANS project; however they can be used in many robotics applications where a group of robots is deployed. The behaviours are linked to specific tasks to be fulfilled; and can be achieved without explicit communication and centralised control, by using only information from the local sensors. Besides the theoretical framework, examples of implementations of proposed behaviours on ERA-Mobi robots are given as well. The chapter concludes with discussions of possible practical 'set-ups' for achieving the proposed behaviours in real-life environments.

2. Introduction

The Guardians[1] (Group of Unmanned Assistant Robots Deployed In Aggregative Navigation by Scent) project is an FP6, EU funded project, developing a mixed human-multi-robot system to assist fire-fighters in search and rescue operations in an industrial warehouse in the event or danger of fire (Penders, Alboul, Roast and Cervera 2007). The main component of the system is a team of

[1] GUARDIANS runs from 2007 to 2010, and involves the following partners: Sheffield Hallam University (coordinator), Robotic Intelligence Lab, Jaume-I University, Spain; Heinz Nixdorf Institute, University of Paderborn, Germany; Institute of Systems and Robotics, University of Coimbra, Portugal; Space Application Services, Belgium; K-Team Switzerland; Dept. of Electrical and Electronics Engineering, TOBB University of Economics and Technology, Turkey; Robotnik Automation, Spain; and South Yorkshire Fire and Rescue Service, UK.

heterogeneous autonomous robots capable to interact with humans and able to produce certain self-organising behaviour patterns. The latter means that some techniques of swarm robotics are applicable.

The GUARDIANS multi-robot team consists of mini-robots and middle sized robots. That means that the robots are not suitable for performing heavy physical tasks, but nevertheless, can be very useful in many fire fighting situations, as was confirmed after consulting with South Yorkshire Fire and Rescue Service, UK, referred further to as SYFIRE. SYFIRE is a member of the GUARDIANS consortium and the GUARDIANS project progresses with close collaboration with fire fighters.

SYFIRE proposed a warehouse as the principal GUARDIANS application scenario, by indicating that industrial warehouses in the emergency of fire are a major concern to them. Searching for victims may be extremely dangerous due to the enormous dimensions of the warehouses and the expected low visibility when smoke develops. Large warehouses are divided into sections separated by (several hours) fire resistant walls. The typical section dimensions are about 100×200m2. In the event of a fire, the fire may be confined to a certain area of the warehouse; however smoke might cover the whole section. SYFIRE pointed out that apart from the smoke, the warehouse is, in general, in a normal and neat state, and the ground is easily passable. For a robot team this implies that there are no exceptional requirements concerning robots motion and even wheeled mini robots are suitable.

The development of smoke represents a great challenge for firefighters as it reduces visibility dramatically and human beings easily get disoriented and may even get lost. Rendered without sight fire-fighters can only rely on their touch and hearing senses. However, the sense of touch is restricted by their clothing gear and the sense of hearing is reduced by the noisy breathing apparatus, with which fire fighters are equipped to provide fresh air. Besides the dimension, low visibility and reduced perception of fire fighters, an important constraint on successful operation is the time constraint. The amount of oxygen in the breathing apparatus suffices for about 20 minutes. The average speed with which experienced fire-fighters progress in the event of dense smoke (informally measured during the 'tasting exercise session' at the SYFIRE training centre), is about 12m per minute. Given the crawling speed, fire fighters can proceed about 240m with a full tank. Taking into account that they have approximately 20 minutes of air between getting in and getting out, the maximum advance they can make is only 120m which is less than the largest dimension of the modern warehouses. Another issue related to the time constraint is such phenomenon as *flashover* that can occur also very quickly.

Note that in UK the fire fighting procedures requires a two-stage operation: first, one team lays out and fixes a guideline along a wall and then leaves, and then subsequent teams aiming towards the scene of operations enter and advance following the guideline. This is done in order to decrease the situations when fire fighters can be lost, but this reduces the available time even further. Besides the aforementioned problems, an important requirement is continuous and uninterrupted communication links between the crew inside and managing crews outside. In a warehouse however, the racks form a dense lattice of metal joints, which might be packed with tins, cans or other metal based packaging. Within such a metal cave, the transmission and reception of radio signals is problematic.

In such situations a team of GUARDIANS robots can be very useful to perform the following tasks: searching and exploring the warehouse and gathering information; maintaining the communication link to the outside base station and supporting the fire-fighters to move around and if required leading them through the site.

Mini-robots in the GUARDIANS robot team are represented mostly by Khepera III (developed by the partner K-TEAM), and middle-sized robots are ERA-Mobi robots, commonly referred to as Erratics robots (Videre Design). These robots are to be applied in some, possibly large, quantity. The larger robot called Guardian, developed by the partner Robotnik Automation, represents an exception (see Figure 1). This robot can be a member of a team, but also can perform certain tasks where a more powerful robot may be needed, such as carrying tools for fire fighters.

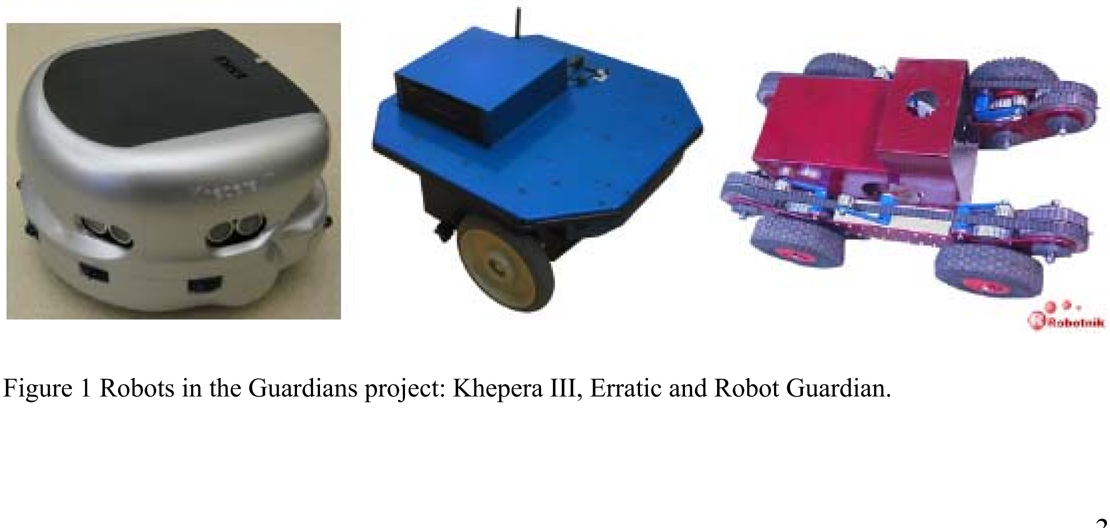


Figure 1 Robots in the Guardians project: Khepera III, Erratic and Robot Guardian.

We focus on basic navigation behaviours of multi-robot or human-robot teams, which have to be achieved without central and on-line control. These behaviours can be also achieved without explicit communication and therefore can be still applicable when communication links are severed. The produced global behaviour is relatively independent of the number of robots in the team. This makes the team robust to failures of individual robots and flexible with respect to its size.

The basic behaviours that we cover are robot-robot and robot-fire-fighter avoidance/attraction as well as robot-obstacle avoidance, and formation generation and keeping. For developing these behaviours we use the social potential field framework, which was introduced by Reif and Wang (Reif and Wang 1999). In our approach robots, humans and obstacles are considered as classes of special agents and for each pair of 'agents' different potential functions are applied. As a result, we can generate a global behaviour that leads to forming certain formation patterns of the group of robots or mixed robot-human teams. Some theoretical considerations on patterns' convergence and stability are also given.

Our algorithms have been implemented using Player/Stage software (Player) that allows their direct application to real robots, and JADE (Jade) (Java Agent Development Environment) that takes care of the agent's life-cycle and other agent-related issues. For testing our theoretical considerations, in particular the convergence of the behaviours we use the programming environment NetLogo (Netlogo) which allows working with a large amount of agents. Simulation results comply with theoretical considerations and show that the algorithms are robust and capable to deal with teams of different sizes and failure of individual agents, both robots and humans. We also tested our approach on the Erratic mobile platforms; and the results of implementations confirm with the results of simulation.

At the end of the chapter we briefly discuss the possible 'set-ups' of the GUARDIANS and similar robotic systems in real-life environments; in particular we indicate approaches to one of the challenging 'real-life' problems, which is robot-robot and/or robot-human detection.

The work described in this chapter is partially based on previous work by (Saez-Pons, Alboul, Penders, and Veysel 2008; Alboul, Saez-Pons, Penders and Nomdedeu 2008) and further expands the ideas presented there.

3. RELATED WORK

Formation control and coordination of heterogeneous multi-agent teams (both multi-robot and mixed robot-human) has become an important and challenging research field due to the increasing use of multiple autonomous agents and swarms in various robotics applications. The research concentrates not only on techniques to achieve a desired formation given a set of parameters and limiting functions but also on the ability to modify a specific formation depending on circumstances. The team of agents should be able not only to self-configure but also to recover and reconfigure itself in the case of the loss or addition of a new member. The formation therefore should be flexible.

Various approaches have been used, however artificial potential functions (fields) methods have been taken a prominent part, due to their advantage of low computational complexity, easiness of implementation and combination of repulsion/attraction which are characteristics of all social behaviours. Artificial potential fields approaches to autonomous robot navigation were introduced more than twenty years ago (Krogh 1984; Khatib 1986) and since then have been widely used in robotic scientific community. They provide a concise and effective framework for expressing various interaction patterns. Therefore, while in the early days the methods have been used mostly for a single robot motion planning; in due course these methods became more and more popular for modelling various collective behaviours and distributive control of a group of robots. Potential functions have been used, for example, in multi-robot navigation for obstacle avoidance (Krogh 1984; Penders, Alboul and Braspenning 1994), robot aggregation (Gazi and Passino 2004a; Gazi and Passino 2004b), and robot formation keeping (Song and Kumar 2002; Schneider and Wildermuth 2005).

We concentrate on two behaviours of a mixed human-multi-robot team that are crucial for the GUARDIANS project: formation generation and formation keeping. In order to achieve these behaviours, we use as the basis the social potential field method (*SPF*) introduced by Reif and Wang (Reif and Wang 1999). By using force laws they were able to express such 'social' behaviours as clustering, patrolling, escorting etc. Bruemmer et al. also utilize the *SPF* approach as a means to coordinate group behaviours and promote the emergence of swarm intelligence that mimic the one seen in a colony of ants or swarm of bees (Bruemmer, Dudenhoeffer and McKay 2002).

The methods based on the potential field principle suffer, however, several drawbacks; the most serious one is the possibility of the convergence to a local minimum. A detailed analysis of shortcomings of the potential field principle is given in (Koren and Borenstein 1991). There are some attempts to avoid local minima; a recent one is presented in the paper by P. Fazenda and P. Lima (Fazenda and Lima 2007). However, in order to achieve elimination of certain local minima the authors make use of strong assumptions such as the condition for a robot of having knowledge of the current configuration of the whole formation, which drastically increases the complexity of the method and makes problematic its application to real-life situations.

In our approach, a general assumption is that the robots do not have common knowledge of the environment and do not have any memory of previous positions. Nevertheless, under some not very strong conditions imposed on the robot space configurations, the robots can achieve the desired behaviours and avoid certain local minima.

We would like also to mention the works of N. Leonard and her co-workers (Ogren, Fiorelli and Leonard 2004) and works of V. Gazi and Passino (Gazi and Passino 2004b), in which ideas similar to ours are expressed. However, our approach differs from the aforementioned work in several aspects. We do not assume any centralized computation and/or communication. There are no artificial virtual reference points, as in the works of N. Leonard et al. A human can be considered as a virtual leader in some respect, but he/she does not move with a constant velocity. The agent group is scalable and flexible, in the sense that the 'loss' or 'addition' of an agent either does not influence the desired behaviour or produce another, alternative, behaviour. In this respect our work has overlapping points with the work of L. Barnes and co-authors (Barnes et al. 2007). We do not determine in advance certain basic motions as translation, rotation, or expansion; however they may occur as a result of the application of potential functions on a group of robots. We also do predefine neither shapes of formations, nor the final robots positions, oppositely to the work by Gazi and Passino (Gazi and Passino 2004b). While moving, 'our' robots still preserve formation, but the shape of the formation can be deformed in the presence of obstacles and then re-established, which is similar to the results presented in (Schneider and Wildermuth 2005) .

We also provide some comments on the convergence and stability of our method. In the literature stability analyses are rarely given. They are in general provided only for certain configurations, and often reduced to performance measurements (Balch and Hybinette 2000). When given, it often involves bulky computations (Song and Kumar 2002; Ogren, Fiorelli and Leonard 2004). Our analysis on stability and convergence is based on geometric considerations, following the principles exposed in several works of the second and third authors (Penders, Alboul and Braspenning 1994; Penders, Alboul and Rodrigues 2004). While this analysis is not precise, in the sense that it may not distinguish a single solution from a class of similar solutions, but it gives a good overview of possible types of configurations and their stability.

4. System Description

4.1 Agent Classes and Their Characteristics

Depending on the circumstances we can consider several classes of agents. The classes may be the following:

1) A class of robots r_i, $i=1, 2, \ldots, n$
2) A class of humans (fire-fighters) h_j, $j=1, 2, \ldots, m$
3) A class of obstacles o_k, $k=1, 2, \ldots, l$

A class of robots, which may be *heterogeneous,* can be split in several sub-classes of *homogenous* robots and robots may be either holonomic or non-holonomic. A class of humans, in general, can be split into subclasses as well, but in the GUARDIANS scenario we consider only one class of human agents (consisting of fire-fighters); and the number of humans m is assumed to be smaller than the number of robots. In a real-life situation of fire-fighting, humans in general act in groups of two: one person takes the role of the leader and the second is the follower. In general, they are never separated, they are connected by a rope, and the follower tries to keep his hand on the shoulder of the leader. Therefore, without much loss of generality, we can assume that the class of humans consists of only one agent, and to a certain extent this agent plays the role of a leader and the robot team takes the role of a follower. The task of the robot team is not confined to following the human; the robots should assist him/her to navigate safely through the site. This means that the robots should avoid obstacles as well as prevent the human to collide with them. Therefore a reasonable requirement is that the robots should be able to organize themselves in a formation around the fire fighter and maintain this formation while moving. In a more general setting, a human can become a follower and be led by a robot or a team of robots. However, in this paper we assume that a human acts independently of the robots. The classes of humans and robots can be also fused, thus forming one class of heterogeneous agents. This can be useful in such formations in which the *leader* and *follower* roles can be switched in due course.

Figure 2 Fire-fighter with assisting robots.

In this paper we assume that our system contains only one class of homogenous robots and that the robots are *holonomic*. This is not much loss of generality, as it was shown that for a certain class of non-holonomic wheeled vehicles with differential drive, control forces can be applied on an of-wheel axis point, kinematics of which can be made holonomic by using a suitable transformation (Lawton and Beard 2003). We also assume the robots act totally *independently* and *asynchronously* from each other and do neither rely on centralized commands, nor on any common notion of time. They are capable to sense (observe) the environment, but they are *oblivious*, meaning that they do not remember any previous observation nor computation performed in precedent steps, contrary to the assumptions made in (Fazenda and Lima 2007). The robots are also assumed to be *anonymous*. The latter means that they do not have any sort of identifiers which can allow them to discriminate an individual robot among other robots. However, the robots can distinguish robots from obstacles and human. In computational simulations this is done by indicating the class of an agent, for example, by assigning a specific flag to the agents of the same class. Some considerations how it can be done in real-life applications are given at the end of this chapter.

4.2. Visibility Domains

Each robot is equipped with sensors to get information about the environment. How far a robot 'senses' the environment, it depends on the sensing range. The sensing range of each robot may vary from zero to infinity. In what follows we will refer to the sensing range of a robot as its *visibility domain*. In the present paper the *field-of-view* of each robot is supposed to be 360 degrees, resulting in a *circular* visibility domain; which in real life means that each robot is equipped with at least one omnidirectional sensor. We can determine for the visibility domain its radius R_{Visib}, which can vary from zero (a 'blind robot') till infinity. The *infinity domain* actually means that its radius takes a sufficiently large value R_{infty} that allows a robot to observe the whole surroundings where it operates. For example, the visibility domain of the radius of *n* units can be considered infinite if the diameter of the minimum bounding circle which contains the site is smaller than *n* units.

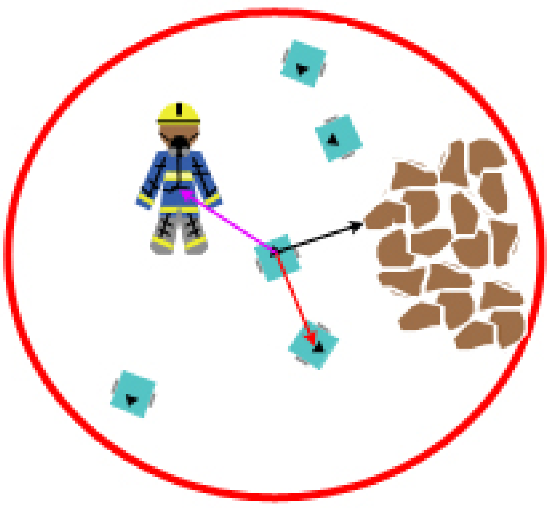


Figure 3 Visibility domain of a robot.

However the infinite visibility domain does not mean that a robot should react to any agent or object within the domain. A realistic assumption is that a robot reacts to other robots or obstacles only if they are situated at a certain distance within their visibility domain, so that the *reaction distance* d_{react} satisfies $d_{react} \leq R_{visib}$. Suppose, in the visibility domain of the robot r_i there are two obstacles O_1 and O_2, and one is hidden behind the other. In computer simulations a robot can 'sense' both obstacles, and a repulsion force can be computed by taking into consideration both of them, whereas in practice a robot will observe only one obstacle, closest to it, and therefore it is sufficient to apply robot-obstacle repulsion only to the first obstacle. Another reason for introducing the reaction distance is to produce more stable and realistic navigation patterns, such as avoiding unnecessary oscillations (Koren and Borenstein 1991). An example of such behaviour is navigation of a robot along an obstacle or a wall. We can also generalize the notion of visibility domain by introducing several visibility domains of a robot. A robot can posses an infinite visibility domain with respect to the human. It can sense the fire fighter in any location of the site if the fire fighter, for example, transmits a radio signal or ultrasonic signal, but senses other robots and obstacles within a limited visibility domain.

There is no explicit communication among robots except reactions of the robots to the environment based on their observations (sometimes referred to as *implicit communication* (Parker 2000)). The robot senses other agents in their visibility domains, is capable to estimate corresponding distances to them and act accordingly. A human does not communicate to robots. The human has two basic behaviours: he is either at rest or moving.

When the human does not move, the robots gather around the human, forming a certain formation. As soon as the human is in motion, the robots start to move as well, attracted by the human while avoiding other robots and possible obstacles.

4.3. Formations

Formation control of a group of agents has received a fair amount of attention in the literature; however the term 'formation' is not uniquely defined. In general, one can distinguish several classes of formations, which roughly can be split into the following categories:

- group of agents forms a particular geometric shape (Baldasare, Nolfi and Parisi 2003; Eisenstat, 1981; Lemay et al. 2004);
- positions of agents that satisfy a pre-defined function (Egerstedt and Hu 2001);
- the distances between the adjacent positions of agents are amid certain predefined values (Gazi 2005).

In our case, formations can be defined as groups of agents establishing and maintaining a certain configuration. The configuration does not have a predetermined shape but the agents in the group do not spread too much from each other. Our human-robot formation has to be adapted (stretched, deformed) when obstacles are in close vicinity since the fire fighter has to be protected and escorted all times. In this respect, a formation of agents in the GUARDIANS project can be seen as a coalition: the agents act as a unit, but not necessary maintain a rigid geometrical shape. Considering a group of agents as a graph (network) where each agent represents a node, and agents are interconnected via their visibility domains, we can define formation as follows: over time the robots might form one or more groups (sub-graphs), so that there exists a path in each subgraph that passes from any node to any other node, with the property that the distance d_{ri} of any individual node (robot) r_i to the agent closest to it within this path (either a robot or a human) does not exceed the certain value d_{max}. d_{max} can be defined to be smaller or equal either to the (smallest) radius of the visibility domains or reaction domains of agents. This definition is similar to the definition of the formation given in (Tanner, Pappas and Kumar 2004).

From the mathematical point of view, the aforementioned condition means that each sub-graph represents a connected graph. If no robots are lost, the agents form only one sub-graph (coinciding with their graph).

Neither initial positions, nor final positions of agents are predefined. To some extent, this definition complies with the definition proposed in (Lemay et al. 2004), where the group determines autonomously the most appropriated assignment of positions in the formation.

5. Formalism

Agents of different classes perform different behaviours. Regarding three classes of agents, neither humans, nor obstacles are supposed to react to robots. The motion of a human will be of course influenced by obstacles, but currently it is assumed that the human can easily find the way through the obstacles. In a more general framework robots may lead the human through obstacles, by indicating them a direction to follow. In this case we could consider only two classes of agents: the class of mixed agents consisting of robots and humans, and the class of obstacles. The framework will not have to be changed if we swap the leading human with a leading robot. The obstacles are considered static.

The robots are influenced by all three (or two) classes of agents. We consider M autonomous mobile robots denoted by r_m, where $m=1, 2, \ldots, M$, S obstacles denoted by O_s, where $s=1, 2, \ldots, S$ and a human H situated in a two dimensional plane R^2. Xr_m, X_{Os}, and X_H are the positions of r_m, O_s and H, respectively.

The artificial potential functions generating the basic behaviours such as robot-robot, robot-fire-fighter avoidance/attraction and robot-obstacle avoidance are described below.

5.1 Robot-Human Potential

The robots have to avoid collision with the human and at the same time they have to be able to approach and keep the human within their sensor range. We define the potential function P_{Human} between the robot r_m and the Human H as

$$P_{Human}(d_{r_m}^H) = \frac{1}{(k_{hrr}(d_{r_m}^H - w_{hrr}))^2} + \frac{1}{(k_{hra}(d_{r_m}^H - w_{hra}))^2} \tag{1}$$

where k_{hrr}, k_{hra}, w_{hrr} and w_{hra} are scaling parameters, and $d_{rm}{}^H$ is the distance between the robot r_m and the human H.

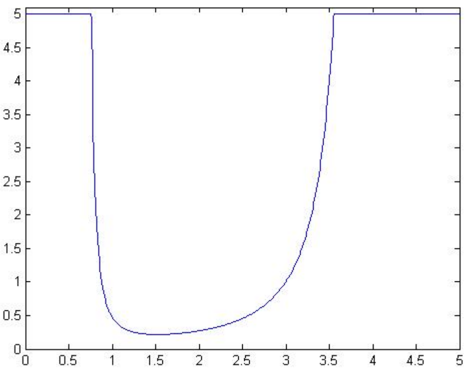


Figure 4 Robot-human potential function.

The potential function P_{Human} between the robot r_m and the human H is composed by a repulsive term that prevents the robot from colliding with the human and an attractive term that keeps the human within its visibility domain. An example of the graph of the robot-human potential function P_{Human} is given in Figure 4. In this example we have a robot r_1 and a human H in a two dimensional space R^2 and d_{r1}^H is the distance between r_1 and H. As it is shown in Figure 4 when r_1 is too close to H, $P_{Human}(d_{r1}^H)$ pushes r_1 away from H keeping the robot from colliding with the human. When r_1 is too far, $P_{Human}(d_{r1}^H)$ pushes r_1 closer to H maintaining the human within its sensor range.

5.2. Robot-Robot Potential

The potential function P_{Robot} between the robot r_m and the robot r_i is defined as

$$P_{Robot}(d_{r_m}^{r_i}) = \frac{1}{(k_{rr}(d_{r_m}^{r_i} - w_{rr}))^2}$$

(2)

where k_{rr} and w_{rr} are scaling parameters, and d_{rm}^{ri} is the distance between the robot r_m and the robot ri. Obviously, $d_{rm}^{ri} = d_{ri}^{rm}$.

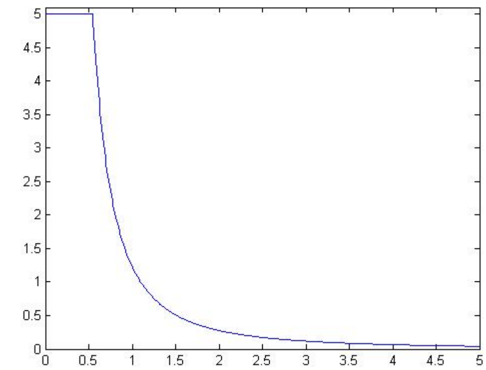


Figure 5 Robot-robot potential function.

Figure 5 is an example of the robot-robot potential function P_{Robot}. In this example we have two robots,r_1 and r_2 situated in a two dimensional plane R^2 and d $_{r1}{}^{r2}$ is the distance between r_1 and r_2. In the presence of a human we assume that robots avoid each other, by exerting on each other the repulsive force of magnitude $IR_{(m,i)}$, determined by the negative gradient of $P_{rr}(r_{mi})$:

$$\overrightarrow{IR}_{(m,i)} = -\nabla P_{Robot}(r_{mi})$$

(3)

In the absence of a human in the visibility domain of a robot, the force acting on the robot produced by other robots in its visibility domain will become a combination of attraction and repulsion similar to the potential function between a robot and the human.

$$P_{Robot}(d_{r_m}^{r_i}) = \frac{1}{(k_{rr}(d_{r_m}^{r_i} - w_{rr}))^2} + \frac{1}{(k_{ra}(d_{r_m}^{r_i} - w_{ra}))^2}$$

(4)

where k_{rr}, k_{ra}, w_{rr} and w_{ra} are scaling parameters, and $d_{rm}{}^{ri}$ is the distance between the robot r_m and the robot r_i.

5.3. Robot-Obstacle Potential

In a real world, there may be several static or dynamic obstacles in the environment. We define the potential function $P_{Obstacle}$ between the robot r_m and the obstacle O_s as

$$P_{Obstacle}(d_{r_m}^{O_s}) = \frac{1}{(k_{ro}(d_{r_m}^{O_s} - w_{ro}))^2} \tag{4}$$

where k_{ro}, and w_{ro} are scaling parameters, and d_{rm}^{Os} is the distance between the robot r_m and the obstacle O_s. The robot obstacle potential function $P_{Obstacle}$ has the same form as the robot-robot potential function in Figure 5.

5.4. Parameters

The parameters of all the employed potential functions are shown in Fig. 6. This selection reflects the specifications and characteristics of the considered system. For example, the robot's size determines the value of the contact distance, i.e. for the robot-obstacle potential function w_{ro} represents the distance at which the edges of the robot and the obstacle may come into physical contact ($w_{ro}=0.49$). The analogous selection criteria applies to the robot-obstacle (w_{rr} , w_{ra}) and robot-human (w_{hrr}, w_{hra}) contact distances. The parameter k_{ro} in the robot-obstacle potential function determines at which distance the repulsive potential starts pushing the robot away from the obstacle. Choosing k_{ro}=5 means that the robot will not start avoiding the obstacles until approximately $d_{Os}^{Rm} =1.5$ meters. The latter represents the reaction distance, described in 4.2. The similar selection criteria have been applied for the parameters of the remaining potential functions.

Potential Function	Parameter Value	
Robot-Obstacle	$k_{or} = 5.00$,	$w_{or} = 0.49$
Robot-Robot	$k_{rr} = 2.00$,	$w_{rr} = 0.98$
	$k_{ra} = 2.00$,	$w_{ra} = 4.00$
Robot-Human	$k_{hrr} = 5.00$,	$w_{hrr} = 0.82$
	$k_{hra} = 2.00$,	$w_{hra} = 4.00$

Figure 6 Values of the parameters used in the potential functions employed for simulation required robots behaviours.

5.5. Social Potential Field

The social potential function P_{Social} of r_m is defined as the sum of the aforementioned potential fields:

$$\begin{aligned} P_{Social}(X_{r_m}) &= P_R^O(\mathrm{X}_{r_m}) + P_{r_i}^{r_j}(\mathrm{X}_{r_m}) + P_r^H(\mathrm{X}_{r_m}) \\ &= \sum_{s=1}^{S} P_{Obstacle}(d_{r_m}^{O_s}) + \sum_{j=1, j\neq i}^{M} P_{Robot}(d_{r_m}^{r_i}) + P_{Human}(d_{r_m}^{H}) \end{aligned} \tag{5}$$

The artificial force that 'acts' on the robot r_m is then defined accordingly:

$$\vec{F}_{Arti}(X_{r_m}) = \vec{F}_{Arti\_Obstacle}(\mathrm{X}_{r_m}) + \vec{F}_{Arti\_Robot}(\mathrm{X}_{r_m}) + \vec{F}_{Arti\_Human}(\mathrm{X}_{r_m}) \tag{6}$$

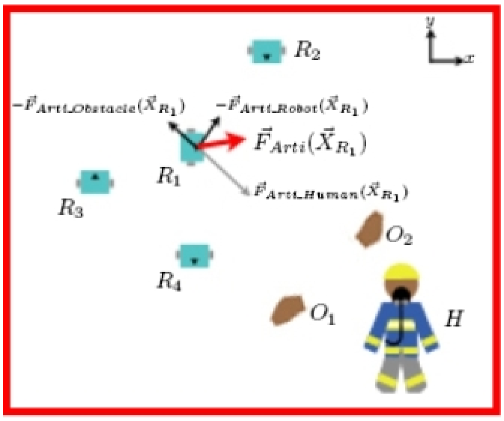


Figure 7 Forces acting on a robot.

Note that the artificial forces are not physical forces bearing on the robots. Artificial forces are virtual forces which are designed to control the motion of each robot. The robots ‘calculates’ these force itself by measuring distances to the agents in its visibility domain, using the given parameters. The forces acting on a robot are depicted in Figure 7.

6. Behaviour Patterns and Remarks on Stability

Application of the described potential functions generates certain formation patterns that correspond to local minima in the potential fields. We consider two set-ups: *formation generation* when the human is at rest or absent and *formation maintenance* when the human is moving. In the first set-up the agents' configurations converge to certain typical pattern forms, which are, in general, dependent on the visibility domains of the robots and the number of robots. In the second set-up these patterns will be either deformed, or the configuration can be split into several typical patterns with lesser numbers of robots. In what follows we briefly describe the typical patterns with some remarks on their stability. As an illustration tool, we use the computing software NetLogo.

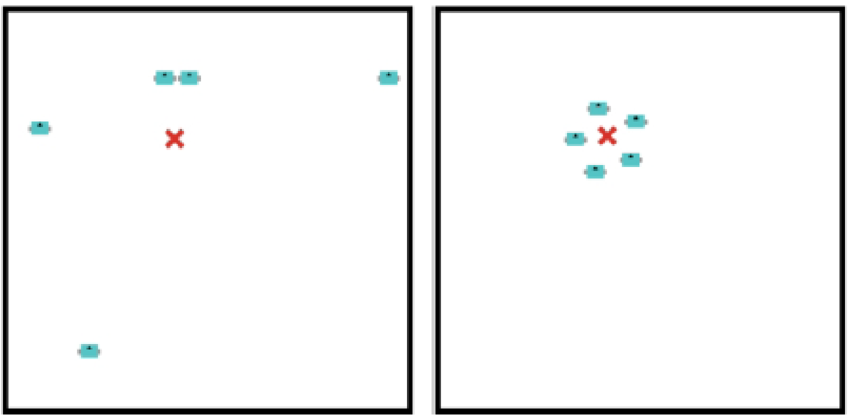
6.1 Formation generation

First we assume that there are several robots $r_1, ..., r_n$, one human H at rest, and no obstacles. The robots are situated somewhere in the site.

6.1.1 Robots with infinite visibility domains

At present we assume that robots' reaction distances coincide with the radii of visibility domains. The robots are considered to be holonomic; therefore, without loss of generality, they can be represented as points in the plane. Their positions are indicated as X_{ri}, $i = 1, ..., n$, where n is the number of robots. The internal forces that each pair of robots exerts on each other are equal by magnitude but opposite by direction. The centre of gravity CG of the group of robots, which position is computed as $\mathbf{X}_{CG} = \Sigma_{i=1}^{n} \mathbf{X}r_i /n$, represents an invariant point with respect to internal forces, which follows from the Newton third law.

Situation 1.1 If the robots are the only agents the centre of gravity of their group will keep the same position while internal forces will bring the group of robots into equilibrium. This is illustrated in Figure 8, the centre of gravity CG of the robots' group is depicted with the cross.



(a) (b)

Figure 8 Behaviour pattern of a group of robots without a human and obstacles: (a) Initial configuration, (b) Final configuration.

Situation 2.1 In the presence of other agents such as the human and obstacles, the forces that act between the human and the robots are external for the centre of gravity and the centre of gravity will be moved to the position where the sum of these external forces are equal to zero. In the absence of obstacles this point will be in the location of the human. After the centre of gravity reaches this position, the situation will be similar to the Situation 1.1 and the robots will end in the equilibrium position. The shape achieved by robots will depend on the number of robots (see Figure 9 and Figure 10), which differs from the work (Gazi and Passino 2004a), where a predefined shape for a given number of robots is considered.

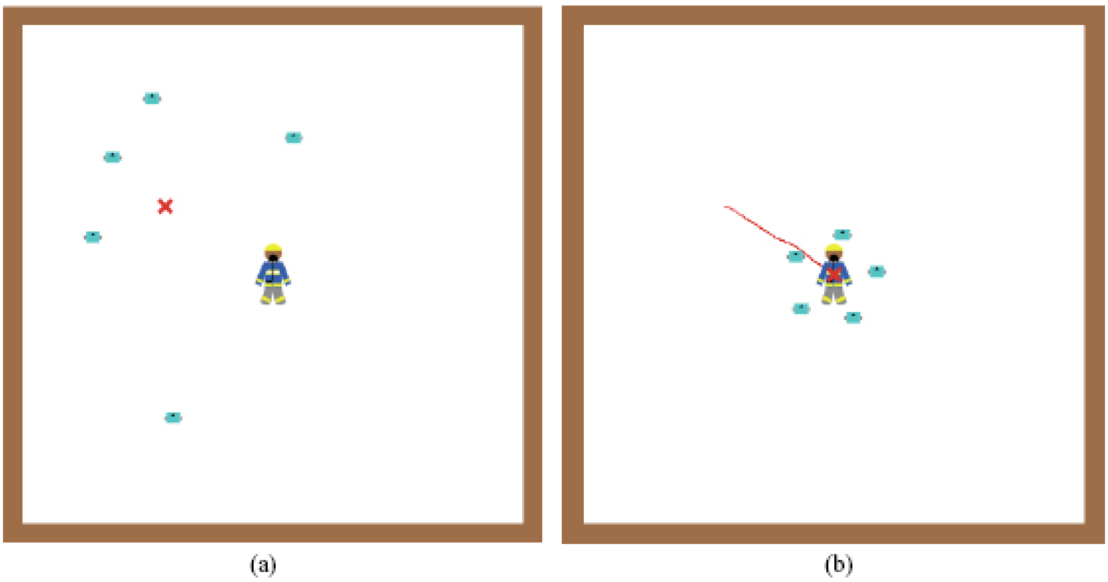


Figure 9 First example of a behaviour pattern of a mixed human-robot group: (a) Initial configuration, (b) Final configuration.

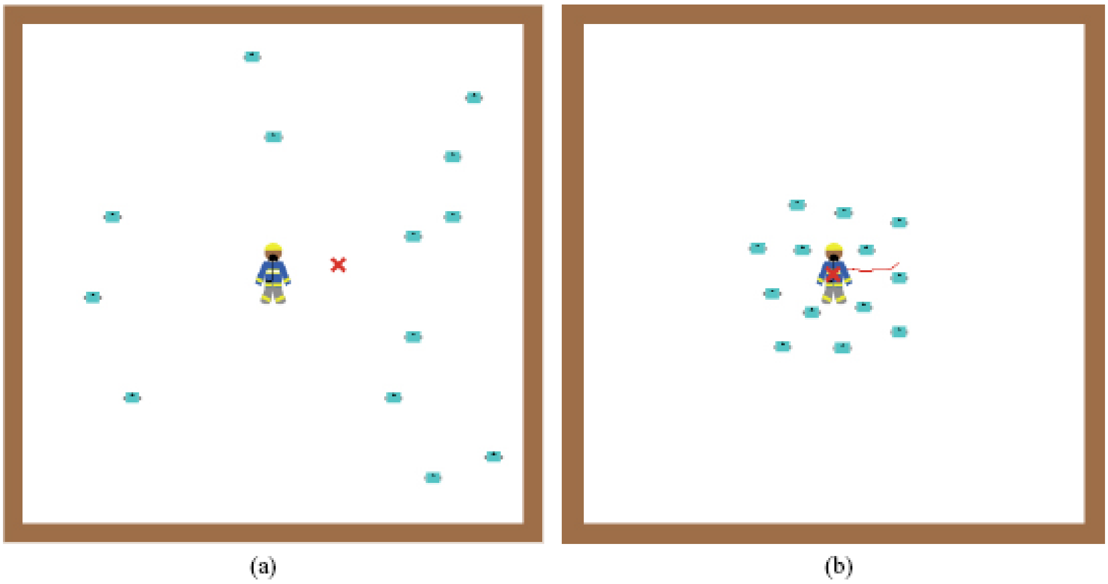


Figure 10 Second example of a behaviour pattern of a mixed human-robot group: (a) Initial configuration, (b) Final configuration.

Considering the human agent as an *Attractor*, we can pose several questions. First of all, in the absence of obstacles, how the number of robots influences the final equilibrium configuration? As we can see, when the number of robots is sufficiently small, the robots form a regular polygon. However, when the number of robots is large, the configuration does not represent a regular polygon. The cause of this is that the initial configuration of the robots is not symmetric. However, even if the robots start in a symmetric configuration, the symmetry of robots configurations while they approach the equilibrium formation is preserved until a certain point of time, when symmetry disappears, and the resulting equilibrium formation is similar to formations achieved when robots do not start in a symmetric configuration (see Figure 11 and Figure 12 for an illustration).

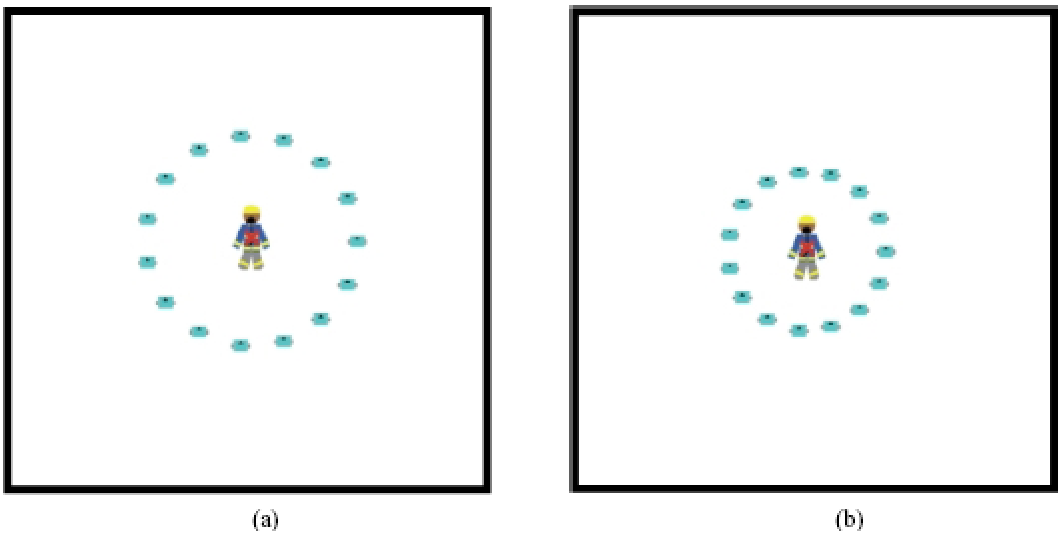


Figure 11 Behaviour pattern of a mixed group: (a) Initial symmetric configuration, (b) Intermediate symmetric configuration.

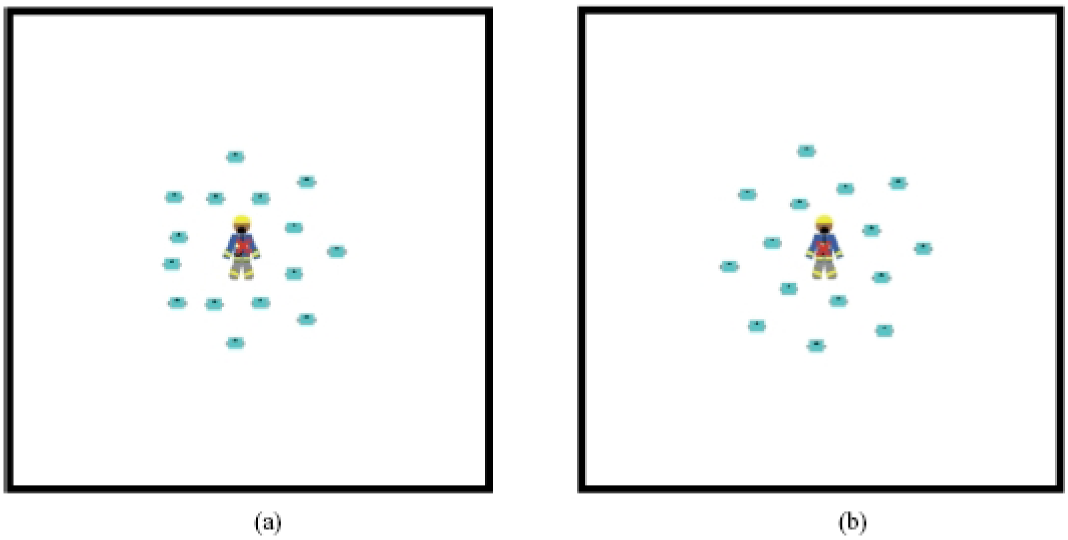


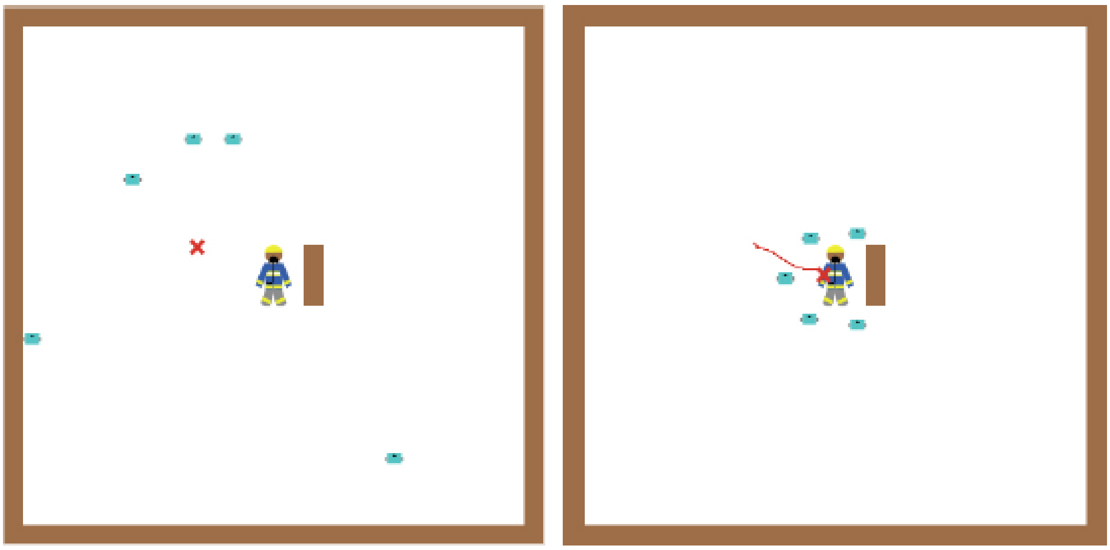
Figure 12 Behaviour pattern of a mixed human-robot group: (a) Symmetry is lost, (b) Final asymmetric configuration.

The disappearance of symmetry can be explained by the fact that time is actually discrete: an agent which might move continuously in time, changes its direction only at certain time points. As robots can move asynchronously, the virtual forces acting on robots may not be always equal by the magnitude, which results in the loss of symmetry.

However we can say, that the robots in the absence of obstacles will organise themselves in a cluster around a fire-fighter. This is due to the properties of attractive/repulsive potentials described earlier (for each robot there is a position where the virtual force acting on it vanishes).

In the presence of an obstacle the robots will form a cluster which will be moving away from the obstacle. Theoretically speaking, if we assume that robots are situated in an environment without boundary (infinite environment) in which only one obstacle is present and no ATTRACTOR, in the case of infinite visibility domains the robots will move away from the obstacle infinitely in time. In the case of more obstacles the final position of the robot group may vary: they can come to rest trapped between two obstacles or move away from both obstacles depending on the initial positions of robots.

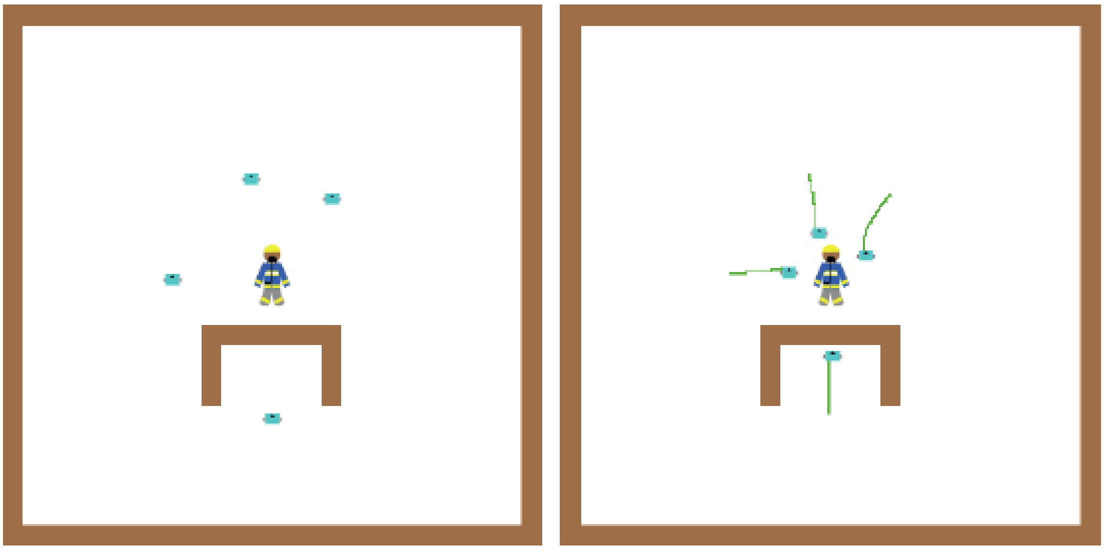
In the presence of obstacles and the human the centre of gravity will be shifted, and at its position the vector sum of forces exerted on the robots by the obstacles and the attraction forces to the human will be equal to zero (see Figure 13).



(a) (b)

Figure 13 Behaviour pattern of a mixed human-robot group in the presence of an obstacle.

Also as robots possess infinite visibility domains a typical local minimum will occur (Figure 14).



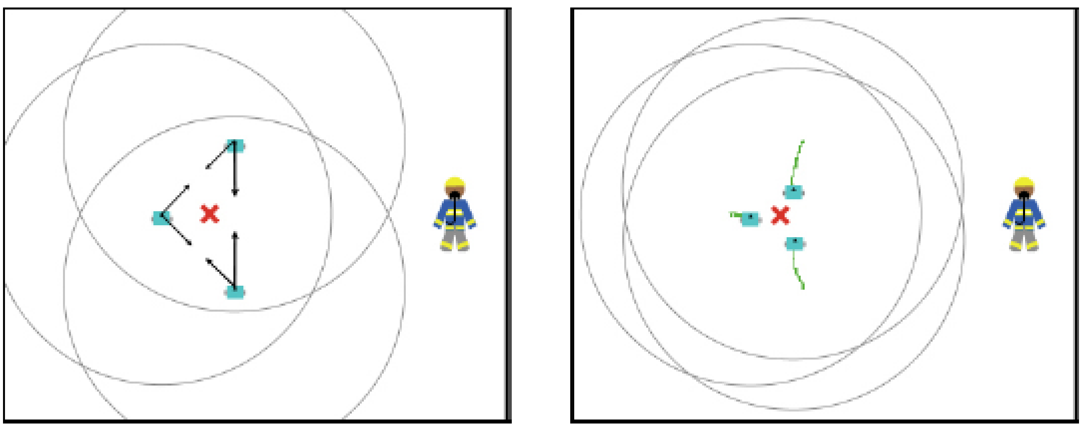
(a) (b)

Figure 14 Local minimum.

6.1.2 Robots with limited visibility domains

The 'set-up' with limited visibility domains of robots is more realistic. On the one hand, there is a possibility that some robots may be 'lost', but on the other hand it can reduce occurrences of local minima.

Situation 2.1 Robots do not 'see' the human, but sense each other. We will get a local minimum where a group will execute a clustering behaviours pattern (Figure 15). The robots' behaviour is similar to the behaviour depicted in Situation 1.1.



(a) (b)

Figure 15 Clustering of robots with limited visibility domains.

If all robots sense the human in their visibility domains, then the robots will gather around the human, the same as in Situation 1.2.

Situation 2.2 This situation occurs when some of n robots (denoted with r_j^H, $j = 1, ..., l$) sense the human, whereas each of the other robots (denoted with r_k^r, $k = n-l$) senses at least one robot from the first group. In this case the robots of the first group will exert only repulsion forces on each other, whereas their centre of gravity CG^H will move in the direction of the human by the attraction force exerted by the human. The robots of the second group will exert on each other either repulsion or attraction forces, depending on the mutual distances, whereas their centre of gravity CG^H will be subjected to the sum of attraction forces exerted by the robots of the first group. However this force is not monotonically changing and it may become equal to zero if the robots of the first group disappear from the visibility domains of the robots of the second group. In this case the robots of the second group may not reach the human and will organise themselves in a cluster as in Situation 2.1. Therefore we have the following Proposition.

Proposition 6.1 The robots with limited visibility domains will gather around the human, if at any time step the attraction force acting on the gravity CG^r does not vanish.

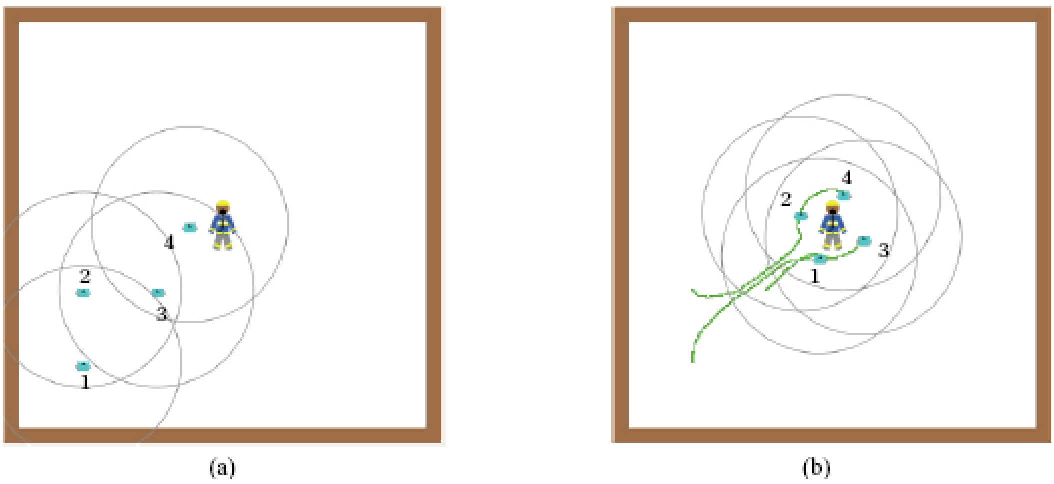


Figure 16. A chain of robots with limited visibility domains.

The above proposition is a sufficient condition. It means that there should exist a chain of robots so that at each time step the group will be a connected graph. The vertices of this graph will be the robots, whereas edges occur only if the robots that represent their end-vertices belong to the visibility domains of each other. A similar type of graphs, called *connectivity graphs*, was considered in (Muhammad and Egerstedt 2003).

The described situation is depicted in Figure 16. The robot 1 senses the robot 2, which in turn senses the robot 3. The robot 3 senses the robot 4 which senses the fire-fighter. The robots achieve an equilibrium situation around the fire-fighter.

When Proposition 6.1 holds then some of local minima can be eliminated. In Figure 17 the robots escape the trap of *C*-concavity and gather around the fire-fighter without knowing the positions of all other robots oppositely to the assumption in (Fazenda and Lima 2007).

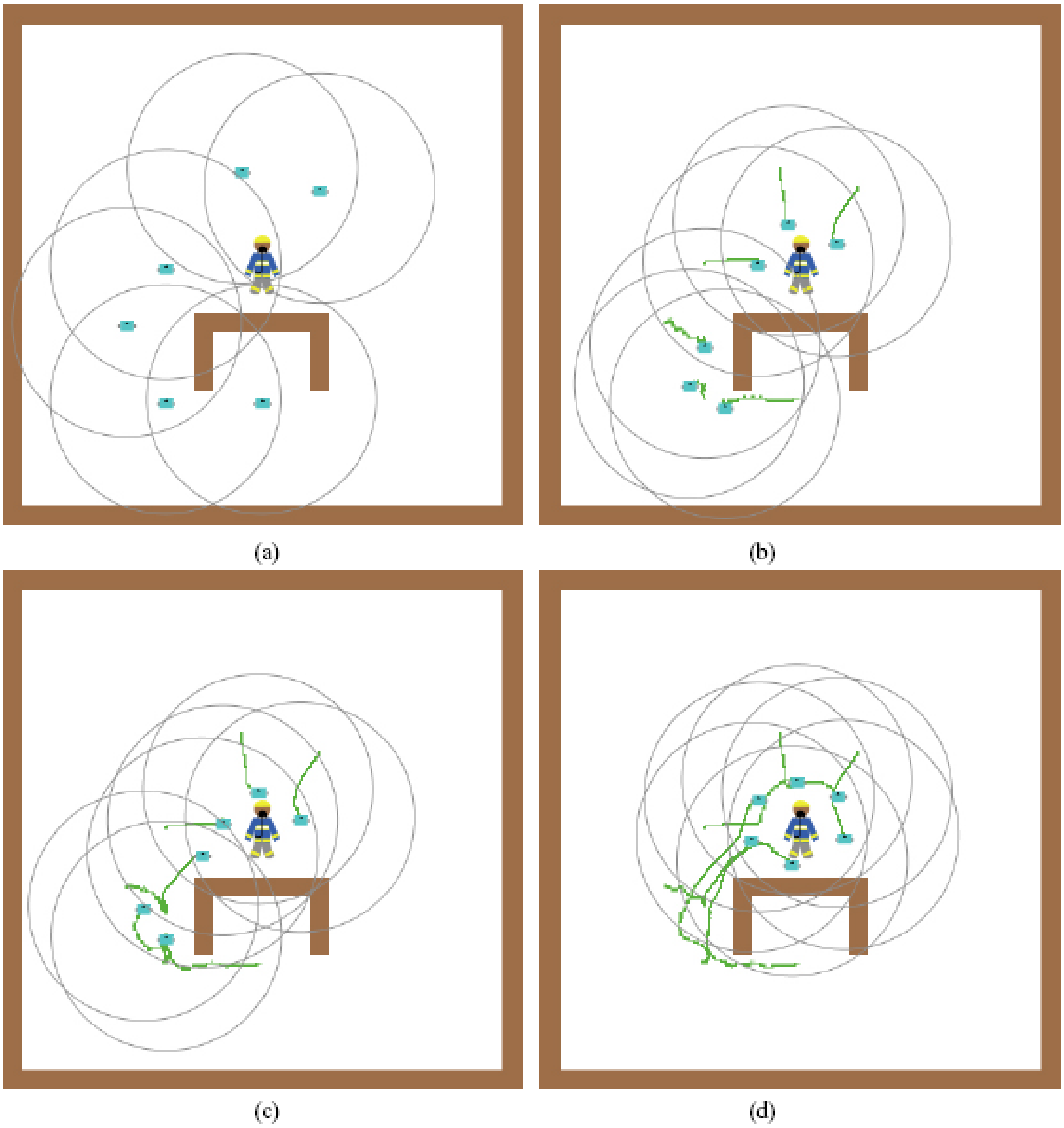


Figure 17 Robots 'escape' the trap of the concave obstacle.

6.2. Formation keeping

In this subsection we show the result of one simulation when the human is moving. The robots first form a formation around the fire-fighter when the fire-fighter is not close to the obstacle. The speed is important; we assume that the fire-fighter moves slower than a robot. The formation is kept in the presence of obstacles while the human moves on the site (see Figure 18). When the formation is generated the robots' group will follow the human also due to the attraction force exerted by the human on the centre of gravity *CG* of the group of robots. The robots move still in formation, but the shape of formation is deformed in the presence of obstacles and then re-established, which is similar to the results in (Schneider and Wildermuth 2005).

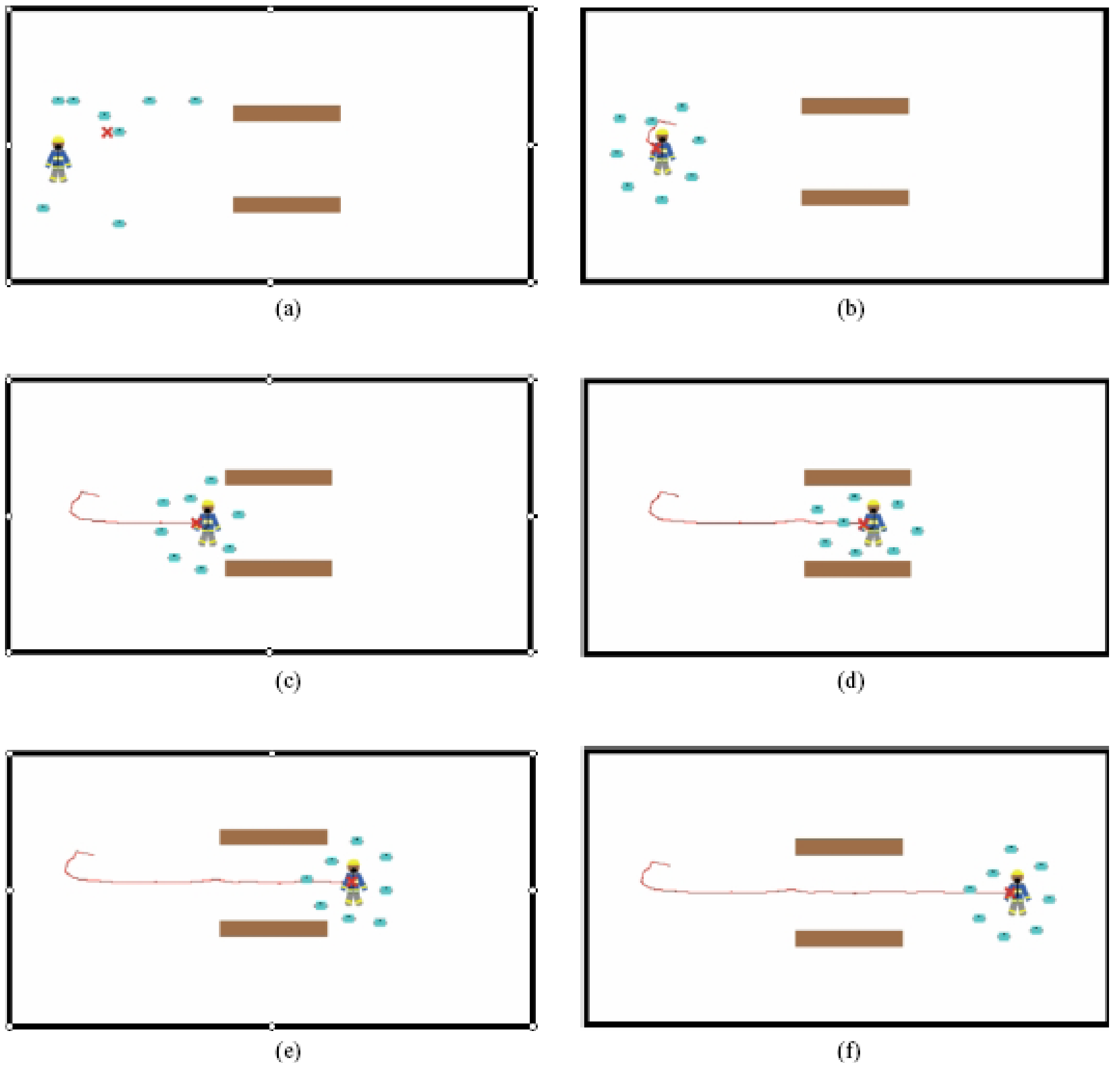


Figure 18 Snapshots of formation keeping while moving in an environment with obstacles (depicted as thick bricks).

7. Examples of Implementations of the algorithms on real robots. Challenges of the practical 'set-ups'.

In the previous chapters basic navigation behaviour patterns required from a (human-) multi-robot team in the GUARDIANS scenario have been presented together with reasons for their feasibility. We tested our algorithms using Player/Stage software. Player is a network server for robot control, and is language and platform independent. Stage is its simulation backend. The recent version of Stage allows creating a very realistic simulation environment. An example of a formation generation pattern (Situation 1.1) is given in Fig. 19.

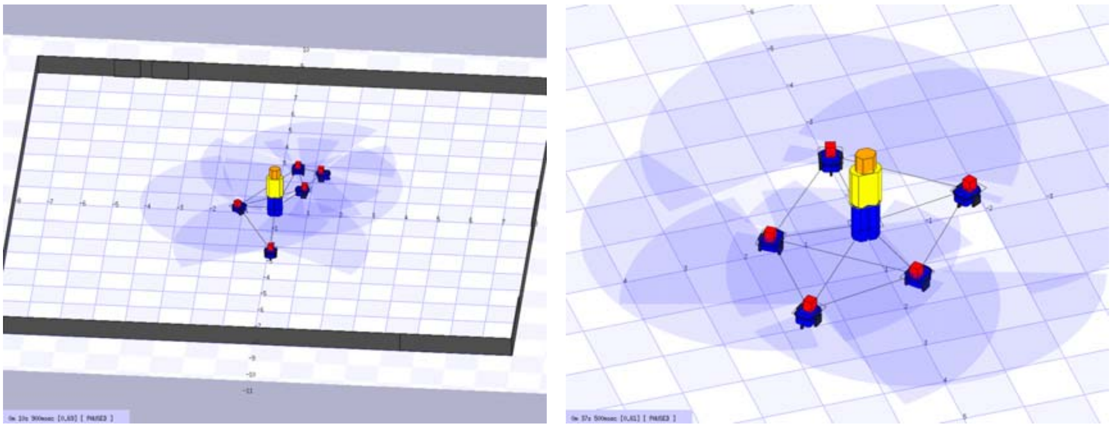


Figure 19 Snapshots of formation generation simulated in Stage: Left – initial configuration, Right – intermediate configuration.

The formation generation and keeping behaviours, by means of Player, were then implemented on real Erratics robots.

The algorithm for calculating corresponding forces acting on robots based on the social potential fields framework presented in Part 5 (Formalism) has been adjusted to a 'discrete' timing. Discreteness here means that while the global time is, of course, continuous, the speed of robots does not change continuously, but at certain intervals Δt_i of time. It gives more stability as robots move linearly for a (however small) interval of time. The maximum speed has been also determined in order to avoid collisions.

Robot-robot detection and consequent mutual distance estimation in real life environment represent challenging issues, and are still under development (see the next paragraph). Therefore, in order to test our algorithms the robots onboard computers were equipped with wi-fi, and a map of the environment has been given to robots. The map was not detailed as obstacles inside the environment were not depicted. The map allowed robots to localise themselves by using the Adaptive Monte-Carlo localisation method. JADE (Java Agent Development Environment) was used for communicating between robots, which allows them to estimate positions of each other and hence, estimate the distances.

Snapshots of video of the aforementioned implementation are given in Fig. 20. One of the robots (with a flag) 'played' the role of firefigter, and therefore was remotely controlled. Other robots were autonomous. The robots were also equipped with a Hokuyo Laser Range Finder in order to avoid obstacles and other robots.

(a)

(b)

(c)

(d)

Figure 20 Robots follow the leading robot –'fire-fighter', while keeping the formation.

7.1 Work in development. Approaches to practical 'set-ups'

In many real life situation the environment is unknown and no map is provided. Explicit communication can be also non-available or severed. In such situations robots should be able to distinguish other robots from obstacles; in particular if a 'social potential fields'-based framework is applied, which requires estimation of corresponding distances.

In the GUARDIANS scenario the use of cameras on robot's platform has been abandoned due to a potential low visibility and attention have been shifted to other sensors. The efforts have been firstly concentrated on the use of LRFs (laser range finders) for robot-robot recognition and eventual distance estimation. The approach is similar to the approach in (Howard, Mataric and Sukhatmel 2002), where the laser range finder was used for distinguishing between robots' nodes that carried a retro-reflective beacon and obstacles that did not. However the laser used had a 360 degree field-of-view (whereas the field –of-view of Hokuyo LRF is 240 degrees) and the approach has been tested in a simulated environment.

The ongoing work in GUARDIANS is on implementing a similar method on real robots.

For this purpose a special barcode is being designed, made of retro reflective material. The laser range finder will search for retro reflective targets and extracts its relative range and bearing. To realise this task the laser range finder has to perform the reading of intensity values to detect and find the reflective material. A typical reflective material returns a high intensity reading value which is clearly differentiable from the rest of intensity values reflected by the rest of materials and colours of the environment. Equipping the robot(s) and the fire-fighter(s) with a barcode made of a retro reflective material allows each robot not only to detect but also identify other robots and the fire-fighter and estimate their relative position (range and bearing) within a certain range. The detection of obstacles is thereupon straightforward, as obstacles will return lower intensity values than a robot or a fire fighter. This 'set-up' is under development.

However, in the case of the dense smoke, the LRF measurements become unreliable and other tools/techniques should be used. One of possibilities is to use the module similar to the Relative Positioning Module developed in (Pugh et al. 2009), which employs IR (infra-red) sensors for positioning as well as for communication. This approach has restrictions as by using infra-red sensor-based positioning system, only very short distances can be reliably estimated. Another approaches on which the consortium is currently working, is the employment of ultrasound and microwave sensors.

8. Conclusion

We presented basic behaviours for a group of heterogeneous agents such as robot-robot and robot-fire-fighter avoidance/attraction and robot-obstacle avoidance, achievable by using a social potential field-based approach. By exercising the basic behaviours more complex behaviours emerge, namely, formation generation and formation keeping. The given analysis shows that the proposed social potential field method is a suitable technique for formation generation, obstacle avoidance, navigation, and is robust to failures of individual robot and team's size in complex environments. We plan to study the characteristics of formations in more complex scenarios such as dynamic environments, or environments with narrow corridors and doorways. Other shapes of visibility domains will be considered. In the present paper the robots do not identify among themselves, but are capable to distinguish another robot or the fire-fighter from an obstacle. However it would be useful if the robots that 'sense' the fire-fighter would be able to 'communicate' this to other robots in their visibility domains. In this case the remaining robots will execute attraction forces only to the robots of the first group that could reduce occurrences of 'clustering' situations.

Possible practical 'set-ups' that would allow not only recognition of an agent of a certain class, but also its identification as an individual in a real-life scenario are currently under validation.

Acknowledgment

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Multi-robot team formation control in the GUARDIANS project

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Abstract. Purpose
The GUARDIANS multi-robot team is to be deployed in a large warehouse in smoke. The team is to assist firefighters search the warehouse in the event or danger of a fire. The large dimensions of the environment together with development of smoke which drastically reduces visibility, represent major challenges for search and rescue operations. The GUARDIANS robots guide and accompany the firefighters on site whilst indicating possible obstacles and the locations of danger and maintaining communications links.
Design/methodology/approach
In order to fulfill the aforementioned tasks the robots need to exhibit certain behaviours. Among the basic behaviours are capabilities to stay together as a group, that is, generate a formation and navigate while keeping this formation. The control model used to generate these behaviours is based on the so-called social potential field framework, which we adapt to the specific tasks required for the GUARDIANS scenario. All tasks can be achieved without central control, and some of the behaviours can be performed without explicit communication between the robots.
Findings
The GUARDIANS environment requires flexible formations of the robot team: the formation has to adapt itself to the circumstances. Thus the application has forced us to redefine the concept of a formation. Using the graph-theoretic terminology, we can say that a formation may be stretched out as a path or be compact as a star or wheel. We have implemented the developed behaviours in simulation environments as well as on real ERA-MOBI robots commonly referred to as Erratics. We discuss advantages and shortcomings of our model, based on the simulations as well as on the implementation with a team of Erratics.
Originality/value
This paper discusses the concept of a robot formation in the context of a real world application of a robot team (swarm).
Keywords: Collective robotics, Swarm robotics, Formation control, Urban Search and Rescue robots

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1 Introduction

The GUARDIANS[3] (Group of Unmanned Assistant Robots Deployed In Aggregative Navigation by Scent) project is an FP6, EU funded project, which aims at developing a team (swarm) of heterogenous autonomous robots to assist fire-fighters in search and rescue operations in an industrial warehouse in the event or danger of fire (Penders et al., 2007).

The challenge of the GUARDIANS project is to apply the team of robots to performing tasks in a real-life situation, when humans (possibly non-experts) are present on the field, and robots need to act alongside the humans and be capable of interacting with them.

The GUARDIANS scenario has been chosen after consulting the South Yorkshire Fire and Rescue Service, UK, referred to hereon as *SYFIRE*. They indicated that industrial warehouses in the emergency of fire are of major concern. Searching for victims is dangerous due to several, interrelated, factors. Firstly, the enormous dimensions of the warehouses already represent a challenge for a search, which only aggravates by the expected low visibility when smoke develops. Next are the time constraints; the amount of oxygen in the breathing apparatus of a firefighter which suffices only for about 20 minutes, crawling speed if smoke has been developed (approximately 12m a minute) - firefighters can proceed about 240m with a full tank. Taking into account that they have to negotiate 20 minutes of air between getting in and getting out the premises, the maximum advance they can make is only 120m which is less than the largest dimension of the modern warehouses. Another issue related to the time constraint is such phenomenon as *flashover*, which can occur very quickly (Clark, 1991). Flashover marks the end of an effective search and rescue, as it means the death of any living being in the blazing environment.
However, SYFIRE pointed out that apart from the presence of smoke, the warehouse is, in general, in a normal and orderly state. This implies that the ground is easily passable and therefore no particular restrictions on robot motion are imposed; even wheeled mini robots are suitable.
The multi-robot team in the GUARDIANS projects consists mostly of mini Khepera III and middle-sized Erratic robots, presented in Figure 1.
These robots are intended to be applied in some, possibly large, quantity. An exception is the robot called Guardian, developed by the partner Robotnik Automation. This robot can be a member of a team, but also can perform certain tasks where a more powerful robot may be needed, such as carrying tools for firefighters.
The paper is organised as follows. Section 2 gives a brief introduction to collective robotics, with a focus on GUARDIANS multi-robot team cooperation and the tasks to be

[3] GUARDIANS runs from 2007 to 2010, and involves the following partners: Sheffield Hallam University (coordinator), Robotic Intelligence Lab, Jaume-I University, Spain; Heinz Nixdorf Institute, University of Paderborn, Germany; Institute of Systems and Robotics, University of Coimbra, Portugal; Space Application Services, Belgium; K-Team Switzerland; Dept. of Electrical and Electronics Engineering, TOBB University of Economics and Technology, Turkey; Robotnik Automation, Spain; and South Yorkshire Fire and Rescue Service, UK.

(a) (b) (c)

Fig. 1. Team robots in GUARDIANS, (a) Khepera III (K-TEAM), (b) ERRATIC robot (Videre Design), (c) Robot Guardian

performed. Section 3 describes the GUARDIANS team members/agents in detail, their ‘sensing’ capabilities, and formation patterns that agents should be able to produce as a self-organising team. Section 4 is dedicated to the description of the basic control model in GUARDIANS project, that provides necessary navigation behaviour patterns required of a heterogenous group of robots in the GUARDIANS scenario. Section 4 concludes with discussion on stability analysis of the proposed system. Section 5 proceeds with a description of implementation of the algorithms based on the presented control model, on the Erratics robots, and indicates the encountered challenges. The sections contain short overviews of related work whereappropriate. We decided to follow this structure in order to provide a better understanding of the work done in GUARDIANS. Section 6 briefly discusses current work and concludes the paper. The work presented here is a further extension and updating of the work presented at ICIRA 2009 (Alboul et al., 2009).

2 Collective robotics

Collective, or Team, robotics can be divided into two major streams: *accidental or non-intentional cooperation* and *intentional cooperation* (Rybski et al., 1998). Conventionally, the Swarm robotics paradigm is associated with non-intentional cooperation; cooperation just happens and emerges from the group behaviour without being made explicit. Intentional cooperation can be described as combining particular behaviours aiming at an explicit goal. Robots interacting with people can comprise both aspects, whereas people, in general, interact intentionally with robots.

2.1 GUARDIANS robot team cooperation

The GUARDIANS robots team should exercise certain cooperative behaviours to fulfil the tasks assigned to them. The tasks can be roughly split into two main categories. The tasks of the first category provide direct assistance to fire-fighters, such as guiding a firefighter, accompanying them and providing them with environmental information such as indicating obstacles and locations of danger. The second category comprises the so-called supportive tasks that can be fulfilled without a human squad-leader, such as deployment on site, positioning as beacons and maintaining communication. Some tasks of both categories overlap, such as searching and navigating the environment; the main difference is that in the first category the robots act within the immediate vicinity of the human, and therefore their sensor range covers only a relatively small area of the environment, whereas in the second category of tasks the robots can disperse on site and therefore the perception of the environment is more global.

In both categories both non-intentional and intentional cooperation are applied. Therefore, some developments from the field of Swarm robotics are used. Swarm robotics research is distinguished by the following criteria (Sahin, 2005): a swarm consists of (*i*) a large number, of (*ii*) homogenous, (*iii*) autonomous, (*iv*) relatively incapable or inefficient robots with (*v*) local sensing and communication capabilities.

The GUARDIANS group of robots does not comply directly to this definition. First of all, the group consists of non-homogenous robots (different either by physical parameters, or by their functionality), and human agents can be also part of the group. Secondly, the number of robots in the group may not be very large in particular if robots accompany a firefighter.

However, some characteristics of a swarm are present as well. The GUARDIANS group does not have a predetermined size, and due to huge dimensions of a warehouse a large number of robots may be required to fulfil tasks in the second category (criterion (*i*)). Communication with the outside might not be possible and the human being will be busy ensuring their own safety, thus autonomy (criterion (*iii*)) is a requirement. A single robot cannot do much in a large warehouse (criterion (*iv*)) and as communication cannot be guaranteed the robot cannot help but rely on local information (criterion (*v*)).

Swarm robotics is also often divided into so-called communicative-less and communicative robotics. The former case, in general, means that 'communication' is assumed to be implicit, i.e. robots react to each other via 'sensing' the environment without explicitly exchanging messages, whereas in a communicative swarm robots can exchange information. In GUARDIANS both types of swarm robotics are used; some more details are given in Section 3 and Section 4.

The GUARDIANS project uses developments from the swarm robotics field whenever appropriate and in what follows the term 'swarm' is also used to describe corresponding behaviours.

In this paper we focus mostly on basic navigation behaviours of multi-robot or human-robot teams, which have to be achieved without central and on-line control. The behaviours described are needed in both categories of GUARDIANS robots' tasks, and they are essential when robots directly assist the firefighter. For more information on the second category of tasks see, for example, (Witkowski et al., 2008; Alboul et al., 2010). The navigation behaviours described in this paper, generally speaking, can also be achieved without explicit communication and therefore can still be applicable when communication links are severed. In this case we can speak of non-intentional cooperation. The generated global behaviour is relatively independent of the number of robots in the team, thus the team is also robust to failures of individual robots. These behaviours can be enhanced if the robots communicate, and thus cooperation becomes intentional. We touch upon this enhancement in Section 5.

2.2 Brief overview of swarm robotics research

Initially, robot swarm research has been focused on mostly centralised approaches (Liu et al., 1989; Barraquand et al., 1992), aiming either at motion planning (Latombe, 1991; Lee, 2004) or leader domination (Desai et al., 2001). However, large number of robots generate dynamic behaviour for which central control is computationally expensive and difficult and centralised motion planning is not appropriate when many agents are involved. Nevertheless, centralised approaches to path-planning are still used, in particular when a smooth trajectory is desired (Belta and Kumar, 2002). Recent research emphasises autonomy of the robots (criterion (iii)) and applies distributive control approaches which reduce computational complexity, scalable, provide robustness to failures, and is preferable when no high-order precision is required. Many of these approaches are inspired by natural phenomena. Such approaches include behavioural-based robotics (Balch and Arkin, 1998), artificial potential functions (Reif and Wang, 1999; Egerstedt and Hu, 2001; Gazi and Passino, 2004a; Gazi, 2005a,b), virtual agents or virtual structures (Bachmayer and Leonard, 2002; P. Ögren et al., 2002), artificial springs (Shucker et al., 2006; Li et al., 2009), and probabilistic robotics (Stilwell et al., 2005). Some approaches use optimisation criteria from game theory for navigation control (Wangermann and Stengel, 1999) and robot distribution or area coverage (Cortes et al., 2004). There are also works dealing with improving system performance through adaptation and learning (Patnaik et al., 2005; Uchibe et al., 1999; Asada et al., 1999). Some of these works use global information while others are based on local interactions and rules. Moreover, besides bio-inspired models there is current research interest in control-theoretic approaches (Desai, 2001; Muhammad and Egerstedt, 2003), as well as in combined approaches where cooperative control is based on a set of control rules (Tanner et al., 2003a).

Surveys on recent advances and the state of the art in swarms can be found in (Dorigo and Sahin, 2004; Sahin and Spears, 2005; Kumar et al., 2005) and a web database on swarm robotics related literature has been compiled at the site[4].

3 GUARDIANS team description

In the GUARDIANS scenario the main performers are robots, humans and obstacles, which we identify as classes of GUARDIANS agents. These classes are:

1. *Class of robots* r_i, $i = 1, 2, \dots, n$;
2. *Class of humans* (fire-fighters) h_j, $j = 1, 2, \dots, m$; and
3. *Class of obstacles* o_k, $k = 1, 2, \dots, l$.

The class of robots, which may be *heterogenous*, can be split in several sub-classes of *homogenous* robots and robots may be either *holonomic* or *non-holonomic*.

The agents are situated in a domain $D \subset \mathbb{R}^2$. In a real-life situation of fire fighting, humans in general move in groups of two: one person takes the role of the leader and the second follows and communicates with the outside (see Fig. 2).

[4]http://swarm-robotics.org/

Fig. 2. Demonstration of the search and rescue operation at the trial of the GUARDIANS system at the SYFIRE training centre

However, we assume that only one human being is present and that the human takes over the role of leader. Nevertheless the tasks of the robot team is not just to follow the human but also to assist him/her to navigate safely and prevent the human from colliding with obstacles. To a certain extent, robots take the role of the second firefighter acting as a reference unit. The human does not communicate to the robots and is in this context beyond control and performs two basic behaviours: standing still or moving. The robots have to organize themselves formations either surrounding or following the firefighter and maintain this formation throughout.

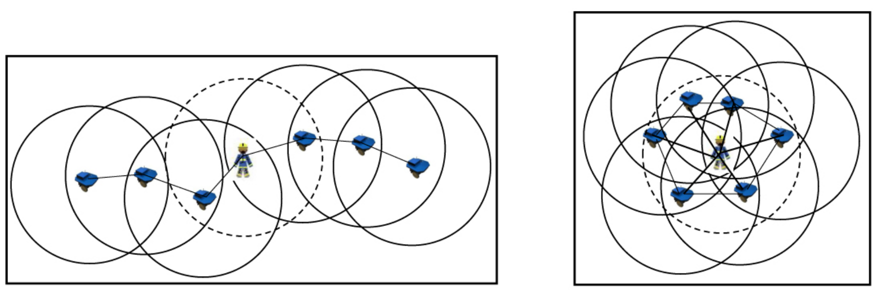
Robots and humans are referred to as *active agents*, and obstacles as *passive* correspondingly.

The robots act *independently* and *asynchronously*. We also assume that they are *oblivious*, meaning that they do neither remember observations nor computations performed in previous steps contrary to the assumptions made in (Fazenda and Lima, 2007). However, this assumption can be relaxed in order to produce more stable behaviours (see Section 6). The sensing range of each robot may vary from zero to infinity. We refer to the sensing range of a robot as its *visibility domain*. In the current section the *field of view* of each robot is supposed to be 360 degrees, resulting in a *circular* visibility domain. Let us note that a robot can have several visibility domains each for each sensor installed on the robot. However, we can select one main visibility domain and do all the reasoning with respect to it.

We assign to a human a *passive visibility domain*, which equate to the visibility domain of a robot. This means that if a robot has a human in its visibility domain, the human 'has' a robot in their (passive) visibility domain that coincides with the visibility domain of the robot. This assumption does not produce the loss of generality, but simplifies reasoning about the system.

We assume that each robot can 'recognise' humans and distinguish robots from obstacles and humans. In computational simulations this is done by indicating the class of an agent, for example, by assigning a specific flag to the agents of the same class. In practice, this can be achieved in various ways. Depending on the sensors a tracking system can be developed, focussing on characteristics of the stepping feet (of a human) (Nomdedeu et al., 2008). Other techniques (for communicating robots) which are being developed and tested in the GUARDIANS consortium, include the use of ultrasonic sensors, radio signal intensity, and Infrared sensors. In our implementation trials the robots are able to localise themselves and the other robots in their visibility domains by using a rough map of the environment provided to them. We do not involve here explicit interaction between a robot team and a firefighter, as human-robot interface development does not belong to the basic behaviours of the robot teams. We refer the reader to related papers of the GUARDIANS consortium members (Naghsh et al., 2008; Naghsh and Roast, 2008).

3.1 Human-multi-robot team formations



(a) (b)

Fig. 3. Two examples of human-multi-robot formations: (a) Maximal formation, (b) Minimal formation. The visibility domains of robots are indicated as circles with solid boundaries, and the (passive) visibility domain of the human is depicted as a circle with the 'dashed' boundary

In the GUARDIANS scenario, formations are defined as groups of agents establishing and maintaining a certain configuration without a predetermined shape (opposite to the assumption taken, for example, in (Gazi and Passino, 2004b; Baldassarre et al., 2003)) but without spreading too much from each other. One of the requirement for the GUARDIANS (human)-multirobot formation is its adaptability: formations can be stretched and deformed when obstacles are in the close vicinity since the firefighter has to be protected and escorted at all times. Considering a group of agents as a graph (network) where each agent represents a node, and agents are interconnected via their visibility domains, we can define formation as follows:

Definition 1. *The* GUARDIANS *formation represents a connected graph, where nodes are robots or a human and edges are virtual links between the nodes, with the property that each edge is situated in the intersection of the visibility domains of nodes to which the edge is incident.*

The definition implies that the distance r_i between neighboring agents (either a robot or a human) does not exceed the value d_{max}. This value can be defined to be either smaller or equal to the (smallest) radius of the visibility domains. It can be smaller in the case if we decide that a robot should react to the agents situated in its visibility domain, in particular, to obstacles, only if they locate within a certain distance d_{react}.
Our definition of formation is similar to the definition of the formation given in (Tanner et al., 2004).
Neither initial positions, nor final positions of agents are predefined. To some extent, this definition also complies with the definition proposed in (et al., 2004), where the group determines autonomously the most appropriated assignment of positions in the formation.
The definition of formation given above can be specified further.
Indeed, both configurations presented in Figure 3 comply with Definition 1. Both configurations can be useful for the GUARDIANS scenario. The one on the left can occur when a group passes a narrow passage, and the one the right may be desirable in an open space. The connected graph that describes a formation may contain loops.

Definition 2. *Degree g, $g = 1,...,n-1$ of a formation is defined as the minimum number of the visibility domains that contain a spanning tree of the graph of the formation. g is set to ∞ if there are agents without virtual links in their visibility domains.*

Note that if $g = \infty$ it means that there is no formation according to definition 1 of formation. In Figure 3 *maximal* ($g = n-1$) and *minimal* ($g = 1$) formations are depicted. In the former case, using the terminology of graph theory, we can say that the resulting formation represents a *path*. In the latter case the ‘visibility’ domain of the firefighter, which is depicted by a dashed line, contains all the robots, and the obtained graph can be varied from a *star* through to a *wheel* to a complete graph. For example, depending on the sensor used the visibility domain of a robot with respect to the human can be of (much) larger radius than the ‘robot-robot’ visibility domain, and in this case the star graph can occur. In the given picture the resulting graph is a wheel. For more detail regarding basic concepts of graph theory, we refer the reader, for example, to the book (Gross and Yellen, 1999).

3.2 Discussion on formation modelling

Formation control of a group of agents has received a considerable amount of attention in the literature. We can say that most of the papers where control strategies are applied concern one or another type of agent formation. Generally speaking, the term ‘formation’ is not uniquely defined. In many papers, formations are seen as fixed structures. Fixed might be either the shape, or the distance between involved agents, or the initial or final positions of agents (Baldassarre et al., 2003; Egerstedt and Hu, 2001;

Gazi, 2005b). In some applications this may be necessary, for example, if robots need to carry a certain object; however in many real-life applications, where dynamics is involved, this may not only be unnecessary but even undesirable. Indeed, if a group of agents needs to move around a complex environment, such as in the GUARDIANS scenario, flexibility is a must so that agents can be spread around or form a tight group depending on the geometry, other features of the environment or specific requirements. Also a desirable feature is the scalability of the formation, i.e. that loss or addition of an agent does not break formation. In (Kostelnik et al., 2002) the studied formations are scalable, however the shape of formation is required to be preserved. Also in (Kostelnik et al., 2002) each robot has a unique ID, contrary to our approach where robots, in most cases, are considered anonymous. Our definition of formation is similar to the concept of neighbouring graph in (Tanner et al., 2003a).
One of the properties of the formation graph in Definition 1 is that the graph is undirected, however the indicated property can be relaxed, for example, by assuming that an edge might be situated in the visibility domain of only one node. This situation is possible, when a group of heterogenous robots is involved equipped with sensors with different fields of view, and it will transform the formation into a directed graph. Another possibility is to consider formations as multi-layered structures, by taking Definition 1 as the basic layer, that can be further enhanced by attaching certain attributes to its edges and nodes. Such an approach may be particularly useful if dynamic interactions between agents are taken into consideration.

4 Control model

As follows from the description of the GUARDIANS multi-robot team, the robots should exercise the following behaviours: 1) collision avoidance, 2) obstacle avoidance, 3) formation generation, and 4) formation keeping. Our approach to achieve these behaviours is based on the social potential field framework, which was introduced by Reif and Wang (Reif and Wang, 1999).
The method for generating navigation behaviour patterns in mixed human-robot groups in complex environments has been initially discussed in (Alboul et al., 2008).
We define **Robot-Human, Robot-Robot and Robot-Obstacle Potential Functions**. The robots have to avoid collisions with the human and obstacles, and at the same time be able to approach and keep the human within their sensor range. While robots ‘sense’ the fire-fighter they execute repulsion behaviour among themselves. In the case if a group of robots has lost a fire-fighter in their visibility domain, we would like that the robot do not disperse and therefore an attraction force is applied towards the robots in a ‘lost’ robot’s visibility domain. We also take into consideration the physical dimensions of the robots and humans, therefore the general form of our potential functions is the following:

Definition 3. *The potential function P_{kl} is a nonnegative function of the distance d_{kl} between agents k and l, satisfying the following properties*

1. $P_{kl}(\|d_{kl}\|) \longrightarrow \infty$ *when* $(\|d_{kl}\| - w_{rkl}) \longrightarrow 0$, *where w_{rkl} is the distance at which a collision between the agents k and l may become inevitable;*

2. *P_{kl} has its unique minimum when agents k and l are positioned at a predefined distance; at this distance agents k and l will come to rest, if only one potential P_{kl} is applied ;*
3. *Depending on the situation, and the agent's type, P_{kl} may either $\longrightarrow 0$, near R_{vis}, which is the radius of the visibility domain of a robot, or, on the contrary, $\longrightarrow \infty$.*

Therefore, the potential functions are defined as follows:

1. Robot-human potential function P_{Human} between the robot r_i and the Human H is:

$$P_{Human}(d_{r_i}^{H}) = \frac{1}{(k_{hrr}(d_{r_i}^{H} - w_{hrr}))^2} + \frac{1}{(k_{hra}(d_{r_i}^{H} - w_{hra}))^2} \tag{1}$$

   where k_{hrr}, k_{hra}, w_{hrr} and w_{hra} are scaling parameters, and $d_{r_i}^{H}$ is the distance between the robot r_i and the human H.
2. Robot-Robot Potential function P_{Robot} between the robot r_i and the robot r_j is, in the presence of the human in the robot visibility domain, is defined

$$P_{Robot}(d_{r_i}^{r_j}) = \frac{1}{(k_{rr}(d_{r_i}^{r_j} - w_{rr}))^2} \tag{2}$$

   where k_{rr} and w_{rr} are scaling parameters and $d_{r_i}^{r_j}$ is the distance between the robot r_i and the robot r_j. Obviously $d_{r_i}^{r_j} = d_{r_j}^{r_i}$. In this case only the repulsion term is present. In the presence of the human we assume that robots avoid each other, by exerting on each other the repulsive force $IR_{(i,j)}$, the magnitude of which is determined by the derivative $P_{rr}(r_{ij})$ of $P_{Robot}(d_{r_i}^{r_j})$ with respect to $d_{r_i}^{r_j}$.
   In the absence of the human in the visibility domain of a robot, the force acting on the robot by other robots in its visibility domain becomes a combination of attraction and repulsion similar to the potential function between the robot and the human in order to avoid spreading robots in the site. The corresponding function is:

$$P_{Robot}(d_{r_i}^{r_j}) = \frac{1}{(k_{rr}(d_{r_i}^{r_j} - w_{rr}))^2} + \frac{1}{(k_{ra}(d_{r_i}^{r_j} - w_{ra}))^2} \tag{3}$$

   where k_{rr}, k_{ra}, w_{rr} and w_{ra} are scaling parameters, and $d_{r_i}^{r_j}$ is the distance between the robot r_i and the robot r_j.
3. Robot-Obstacle Potential function P_{Robot} is defined between the robot r_i and the obstacle O_s as

$$P_{Obstacle}(d_{r_i}^{O_s}) = \frac{1}{(k_{ro}(d_{r_i}^{O_s} - w_{ro}))^2} \tag{4}$$

   where k_{ro} and w_{ro} are scaling parameters and $d_{r_i}^{O_s}$ is the distance between the robot r_i and the obstacle O_s. We assume that robots avoid the obstacles and therefore do not introduce the 'attraction' term.

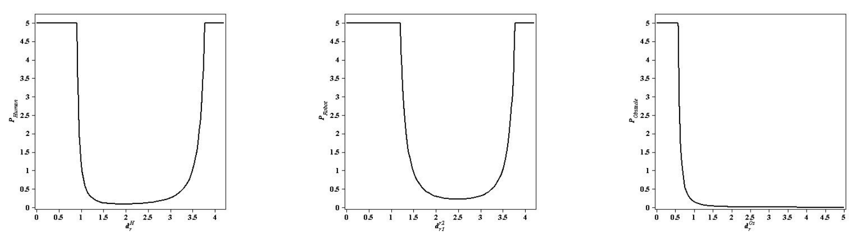
The social potential function P_{Social} of r_i is defined as the sum of the aforementioned potential functions:

$$
\begin{aligned}
P_{Social}(X_{r_i}) &= P_R^O(\mathbf{X}_{r_i}) + P_{r_i}^{r_j}(\mathbf{X}_{r_i}) + P_r^H(\mathbf{X}_{r_i}) \\
&= \sum_{s=1}^{S} P_{Obstacle}(d_{r_i}^{O_s}) + \sum_{j=1, j\neq i}^{M} P_{Robot}(d_{r_i}^{r_j}) + P_{Human}(d_{r_i}^{H}) \qquad (5)
\end{aligned}
$$

The artificial force $\overrightarrow{F}_{Arti}(X_{r_i})$ which is ‘acting’ on robot r_i is, therefore, computed as the sum of gradients of corresponding potential functions:

$$
\overrightarrow{F}_{Arti}(X_{r_i}) = \overrightarrow{F}_{Arti\_Obstacle}(\mathbf{X}_{r_i}) + \overrightarrow{F}_{Arti\_Robot}(\mathbf{X}_{r_i}) + \overrightarrow{F}_{Arti\_Human}(\mathbf{X}_{r_i})
$$

Graphs of the described Robot-Human, Robot-Robot (when the human is not present in the visibility domain of a robot) and Robot-Obstacle Potential functions are given in Fig. 4.



(a) (b) (c)

Fig. 4. Profiles of the control potential functions in GUARDIANS: (a) Robot-Human Potential, (b) Robot-Robot Potential in the absence of the human, (c) Robot-Obstacle Potential

Parameters The parameters of all the employed potential functions are shown in Table 1.

This selection is roughly based on the specifications and characteristics of the considered system. We use the dimensions of an Erratic robot (given in Table 2), but it can be easily adapted to other types of robots.

For example, the robot’s size determines the value of the contact distance, i.e. for the robot-obstacle potential function w_{ro} represents the distance at which the edges of the robot and the obstacle may come into physical contact. The value ($w_{ro} = 0.49$) is obtained as the sum of the Erratic robot radius $r_{Err} \approx 0.29$ and *safety margin*, which we put equal to 20 cm . Similar criteria are used for the robot-robot (w_{rr},w_{ra}) and robot-human (w_{hrr},w_{hra}) contact distances. In the case of robots the contact distance $w_{rr} = 0.98$ between two robots is chosen to be twice the contact distance determined for a robot and

Table 1. Values of the parameters used in the potential functions employed for simulation

Potential Function	Parameter Value	
Robot-Obstacle	$k_{ro} = 5.00,$	$w_{ro} = 0.49$
Robot-Robot	$k_{rr} = 2.00,$	$w_{rr} = 0.98$
	$k_{ra} = 2.00,$	$w_{ra} = 4.00$
Robot-Human	$k_{hrr} = 5.00,$	$w_{hrr} = 0.82$
	$k_{hra} = 2.00,$	$w_{hra} = 4.00$

an obstacle, as both robots can move. Both parameters w_{ra} and w_{hra} are equal to the radius of the visibility of a robot, which is equal to 4 m (the range of the LRF Hokuyo equipped on a robot). The parameter k_{ro} in the potential function (4) determines at which distance the repulsive potential starts pushing the robot away from the obstacle. Choosing $k_{ro} = 5$ ensures that robot r_i will not start avoiding the obstacles up to approximately $d_{r_i}^{O_s} = 1.5$ meters. This is done in order to decrease the possible oscillating of a robot.

In order to avoid very large forces acting on robots, we set the values of the potential functions to be constant. In the given examples this constant is equal to 5 at distances close to contact limits or to the radii of the visibility domains. Therefore are potential functions are non–smooth. There are similarities with the potential functions studied in (Tanner et al., 2003a), but they did not consider, for example, contact distances, and the forms of the functions used are different.

4.1 Stability considerations

Artificial potential fields have been extensively used for modelling collective behaviours and distributive control of a group of robots due to their capacity of expressing various interaction patterns. Potential functions have been used successfully in multi-robot navigation for obstacle avoidance (Krogh, 1984; Penders et al., 1994), robot aggregation (Gazi and Passino, 2004b,a), and robot formation keeping (Song and Kumar, 2002; Schneider and Wildermuth, 2005).

However, the control models, based on artificial potential fields, have drawbacks such as local minima. Therefore stability and convergence analysis is important in order to establish robustness and limitations of the proposed models.

Table 2. Basic parameters of the ERA-MOBI robot

ERA-MOBI	Parameter Value
Dimensions	$L = 40$cm, $W = 41$cm, $H = 15$cm
Maximum Speed	$2ms^{-1}$
Sensors	Laser Range Finder-Hokuyo (range 4m)

In general, the models based on artificial potential functions, are discontinuous which makes it hard to analyze behaviorial performance analytically, as the stability of the discontinuous dynamics involves, in general, differential inclusions and non-smooth analysis. Such analysis, if performed, often involves bulky computations (Song and Kumar, 2002; Ögren et al., 2004; Tanner et al., 2003b)
The stability analysis of our control model is based on geometric concepts which allow avoiding heavy computation while providing qualitative proofs of attainability of desired formations under certain conditions. Some results on stability analysis were presented in (Alboul et al., 2008). The results obtained are similar to those in (Tanner et al., 2003b), but achieved without performing bulky computations.
The main conclusions are the following:

Lemma 1. *(Sufficient conditions for formation maintenance)*

1. *In the absence of obstacles the robots are always gathered around the human, forming a minimal formation, if at the initial step the robots and human are in formation according to our definition;*
2. *In the presence of obstacles, if the human (at rest) and robot agents are in formation at any step, all robots will gather around the human. The deg_{fin} of the final formation does not exceed the deg_{init} of the initial one;*
3. *If the human moves and robots are in formation at any step, the robot team will follow the human.*

In cases 2) and 3) some robots may be lost due to the fact that an obstacle will appear in their visibility domain which may break the formation. We can conclude that formation maintenance depends on visibility maintenance of the robots involved.
The important condition that would prevent undesirable local minima is that the robots have to be in formation, as defined in Section 2, at any step. It means that a robot may not 'sense' the leader/human/goal at any step, but a chain (path) must exist consisting of 'formation' edges, that connects the robot to the leader/human/goal. Some authors realise this (without explicitly formulating neither sufficient nor necessary conditions). However, in order to avoid local minima, all robots are either assumed to be able to sense the leader or its equivalent at any step, or be able to reproduce the previous steps of the leader (Ögren et al., 2004; Fazenda and Lima, 2007). This leads to extensive computation and higher complexity of the corresponding algorithms.

5 Examples of Implementation

Our framework has been tested using and Player/Stage software[5] that allows their direct application to real robots. Simulation results comply with the theoretical considerations regarding formation generation and maintenance, and show that our algorithms are robust and capable to deal with teams of different sizes and failure of individual agents, both robots and humans.

[5]http://playerstage.cvs.sourceforge.net/viewvc/playerstage/papers/

Algorithm The pseudocode of the algorithm that uses the Social Potential Forces approach for the implementation in the real-world scenario is given in Algorithm 1. Each robot calculates the resulting social potential force (F_x, F_y) which determines the velocity of each robot (v_x, v_y). We use a discrete-time approximation to the continuous behaviour of the robots, with time-step Δt. The speed of the robots is bounded to a maximum velocity V_{max}. The output of the *compute motion* algorithm is a direction and a speed of the robot.

Algorithm 1 Compute motion

for all robots but current robot j **do**
    determine the distance r to robot i, $i \neq j$
    determine the polar angular coordinate θ to r_i
    $netForce = SocialPotentialForce(r)$
    $F_x \Leftarrow F_x(netForce)\ \cos(\theta)$
    $F_y \Leftarrow F_y(netForce)\ \sin(\theta)$
end for
$\Delta v_x \Leftarrow F_x\ \Delta t$
$\Delta v_y \Leftarrow F_y\ \Delta t$
$v_x \Leftarrow v_x + \Delta v_x$
$v_y \Leftarrow v_y + \Delta v_y$
if $\|v\| > V_{max}$ **then**
    $v_x \Leftarrow (v_x \times V_{max})/\|v\|$
    $v_y \Leftarrow (v_y \times V_{max})/\|v\|$
end if
$speed \Leftarrow \|v\|$
$direction \Leftarrow \tan^{-1}(v_y/v_x)$
move the robot with the calculated speed in the determined direction

System description The approach has been tested on Erratic's mobile platforms. Four Erratic platforms equipped with: 1) On board computer equipped with wi-fi; and 2) Hokuyo Laser Rangefinder (LRF), model URG-04LX (Finder), 'participated' in the trials. One Erratic is depicted in Fig. 5.

Fig. 5. Erratic with a mounted LRF Hokuyo

As one can see, the robot is equipped with a circularly-shaped additional structure. This has been done in order that robots can detect on another by using the LRF mounted on it. In the performed trial detection was used only for avoiding collisions between the robots, however the aforementioned structure can also be used for robot recognition (by analyzing the laser scan profiles). Initially the tests were conducted without a human agent; and one of the robots ‘played’ the role of a firefighter. Later the tests were performed with a human.

The implementation of our algorithms in the real-world scenario with the Erratic robots represented a challenging issue. Most of the efforts focussed on achieving a reliable way of detecting the components of the mixed multi-robot and human team without using any sort of tracking system. The considered solution required the design of an architecture environment capable of implementing different robot behaviors (aggregation and following), handle communication, run distinct robot navigation algorithms (localization and collision avoidance), define different agent types, interact with the hardware involved (actuators and sensors), interface with the users and everything combined with different software platforms (Player, Javaclient and JADE).

In order to mimic relative robot detection and distance estimation (still under development), robots were provided with a map of the environment in which they localise themselves by using the Adaptive Monte-Carlo localisation method. The map, however, was only approximate, as not all obstacles were included. The robots in the trials were communicating in order to exchange information about their positions.

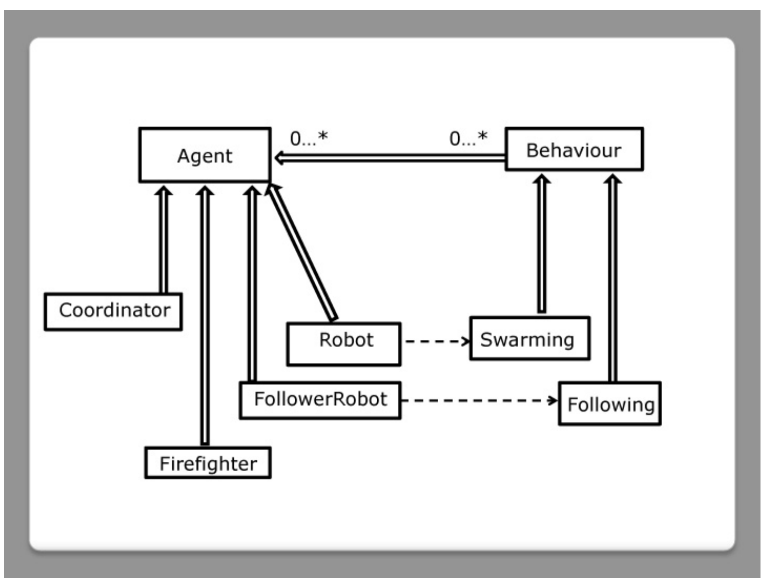


Fig. 6. Agents chart used in demos

JADE (Java Agent Development Environment)[6] was used to take care of the agent's life-cycle and other agent-related issues. JADE provides a runtime environment and agent communication and management facilities for rapid and robust agent-based developments. In our demonstration we have developed several different types of agent, each one having a clear role in the demo. Note that agents here are different from the agents described in Section 3.

Each agent is composed of a set of behaviours that determines how it acts or reacts to stimuli. For our demos we have developed several communication, swarming, and following behaviours, and assigned them in different ways to different agent types to get a set of multi-functional agents. By doing so, we are able to share the robots and human poses through the whole team, allowing swarming techniques to take advantage of these essential data.

JADE agents, used in the GUARDIANS system, are the following:

– PlayerRobotAgent. This agent represents the *n* robots that organise themselves into formation around the human. Each robot makes use of the map interface, the Erratic robot driver, the amcl (adaptive monte-carlo localization) interface, the potential field based motion coordination and the Javaclient for Player.
– CoordinatorAgent. This agent overcomes limitation of the sensors to distinguish and identify the robots relative positions. The main task of the coordinator is to collect the absolute positions of the robots and compile a list of other robots in absolute coordinates.
– PlayerFireFighterAgent. This agent runs on the laptop the human is carrying. It provides the ability to supply position and orientation data to the underlying Player instance and also to the coordinator agent. Both Player clients and JADE agents are informed of the Humans pose.
– PlayerFollowerRobotAgent. This agent follows the human, tracking his position relative to its own, and informing the PlayerFireFighterAgent of the human's absolute position within the environment.
– PlayerPosePublisherRobotAgent. This agent is used to simulate the human behaviour in the absence of human. Basically it is a remote controlled robot whose motion is totally independent of the other robots. It has the map interface, the amcl driver, the Erratic robot driver, the joystick interface and the javaclient for Player.

Some implementations were demonstrated during the evaluation of the GUARDIANS project's progress in Brussels in January 2009, later improved in Benicassim and finally demonstrated in Sheffield at the SYFIRE Training Centre where they were met enthusiastically by the audience.

In the first trial, described in (Alboul et al., 2009), the human was not present and its role was 'performed' by the teleoperated robot. In the later trial in Benicassim, the human was included in the team, but a special robot followed the firefighter by tracking their feet (Nomdedeu et al., 2008). This robot communicated the coordinates of the firefighter to the other robots. All robots were autonomous. As the set-ups in the trials were different, different combinations the JADE agents were used.

[6] http://jade.tilab.com/papers-exp.htm

In Fig. 7 and 8 a sequence of video snapshots of the experiments in Benicassim are presented demonstrating formation generation and formation keeping by a group of Erratic's robots and a human (playing the role of the firefighter).

(a) (b) (c)

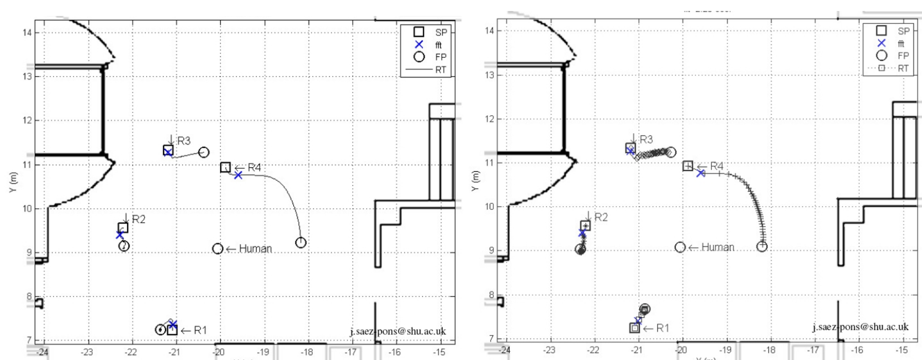
Fig. 7. Snapshots of experiments on formation generation in GUARDIANS: (a) Initial set-up, (b) Formation generation in process (c) Formation is generated

(a) (b) (c)

Fig. 8. Snapshots of experiments on formation maintenance in GUARDIANS: (a), (b),(c) Robots follow the human

Experiment evaluation There are no generally accepted global criteria to evaluate a swarm systems performance, except some notable exceptions as the measures of flexibility in (Fukuda et al., 1998), and the measures of behavioral difference in (Balch and Hybinette, 2000). From this, it follows that studies on performance have to address specific tasks, environments, and robots. The main goal of the implementation trials was to demonstrate that robots are able to generate a formation and keep the formation while following a human. The experiments consisted of placing the mobile robots at different starting positions but situating the human at the same starting point for all the different trials.
In our study, experiments have been set in such a way that it was possible to compare simulation and real-world experiments. In total there were 4 robots and 1 human. The map of the environment was taken and reproduced in the simulation environment. The

initial robots' positions and the position of the human in simulation experiments and in the real-world trails were set the same. Several parameters then were compared, such as time to generate a formation, trajectories of the robots and human, travelling time, distances between robots, computation time and others.
The results of one of the trials are shown in Figure 9 and Figure 10. In Figure 9 formation generation results are shown. At the beginning of each trial the human remained still and the robots started moving to generate a formation. Some time was given to the robots to reach their stable situation, which was achieved when the mobile platforms became motionless. In the left picture simulation results are presented, and in the right picture the results of formation generation by real robots are depicted.



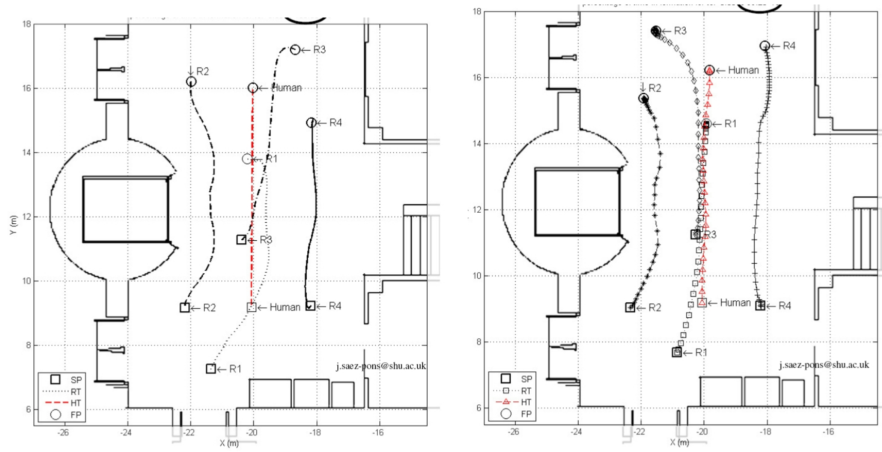
(a) (b)

Fig. 9. Snapshots of experiments on formation generation in GUARDIANS: (a) Simulation results, (b) Real-World experiment results

When the robots stabilized, the human started slowly moving a specific distance in a straight line; in our case this distance was approximately seven meters. When the human had reached the destination they remained still again until the robots had reached a stable position once more. At this point the trial was considered as over. The trajectories of the robots and the human both in a simulated experiment and in the corresponding real-world experiment are shown in Figure 10.

6 Work in development

The experiments implemented on real robots comply with the behaviour patterns predicted by the theoretical considerations and simulations results. Currently we are concentrating on generalisation of our control model by introducing limited memory to the robot agents, that we call the 'two memory steps' schema. In this schema a robot that is completely lost follows the direction of its previous time-step. At present, a robot that loses both robots and the human in its visibility domain, either stops or randomly moves. Simulation results are promising; lost robots are capable of rejoining the team when the environment is not too complex. Actually we are developing a framework



(a) (b)

Fig. 10. Snapshots of experiments on formation maintenance in GUARDIANS: (a) Simulation results, (b) Real-World experiment results. The path of the human is depicted in red

that will combine the described basic behaviours with other behaviours, such as wall following, ‘previous direction’ following and allow easy ‘switch’ between behaviours. We are also working on robot-robot recognition when there is no map. We are testing other sensors such as ultrasound, as well as methods based on special labelling, such as attaching to a robot a specific shape pattern. Experiments on the latter approach have already been performed and recognition worked well (Alboul et al., 2010).
In the future we are planning to extend the method to robot teams of arbitrary sizes and non-uniform visibility domains (either by their geometric profiles, and/or by ranges).
In our trials we will further evaluate performance of robotic teams with special emphasis on fault tolerance and scalability.

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REMOTE AND IN-SITU MULTIROBOT INTERACTION FOR FIREFIGHTERS INTERVENTIONS UNDER SMOKE CONDITIONS ⋆

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Abstract: This paper describes a real-world demonstration that involves two kinds of human-robot interaction: (1) In-situ interaction between a team of robots and a firefighter, and (2) the interaction between a remote operator and the whole system from a base station. The team of robots can provide the firefighter with environmental information to support and enhance its operation in situations where smoke can be present. First of all, the paper describes the overall system, focusing on the devices that are used, and the hardware/software architecture. Then, the paper explains the in-situ human-system interaction which is the way the firefighter interacts with the robot team, by obtaining the information directly to its helmet and by setting up a firefighter following behaviour using both laser and sonar/radio techniques. After that, the paper describes the way the whole system can be monitored and controlled remotely via a base station.

1. INTRODUCTION

The work covered in this paper is focused upon the use of robots in the high risk safety critical and pressurised setting of fire fighting. The problem setting concerns how firefighters working in a search and rescue are to understand and benefit from the robot swarm that are also present at the incident. The technical objectives of the robot swarm are to support fire fighting by in effect being ahead of the fire fighters to inform them about obstacles, suitable pathways to take and also potentially dangerous fumes and toxic gases and their volatility. The scenario fire incident of our project is based upon a fire in large single story warehouse. Such warehouses are usually as large as (400 x 200) m2 and in an incident can become filled with smoke and fumes. There have been notorious tragic examples where firefighters lost life during search and rescue. In the most recent tragedy in November 2007, four firefighters were killed in a vegetable warehouse blaze in Warwickshire.

The specific project that this work is concerned with is the design and development of a set of simple robots that can operate collectively as a swarm in order to support search and rescue tasks among others. An interesting and valuable feature of such a proposal is the potential for emergent intelligent collective behaviour, thus limiting the human effort devoted to dynamic robot configuration and tele-operation. In addition, the swarming approach adopted is one which is robust if individual units lose communication or even fail.

When attending a fire incident, firefighters are concerned primarily with assessing risk to life resulting from the fire and where necessary this may involve searching the warehouse during the incident. On occasions that a decision is made to search a big warehouses, firefighters use a 'guideline' which is a special line used to indicate a route between the Entry Point and the scene of operations. At larger scenes branch lines may be used. The individual firefighter wearers attach themselves using a personal line (1.25m) to the guideline or to each other. Laying the guideline, fire fighters would follow a wall or similar guiding structure, starting either to the left or the right of the point of entry. Firefighters use branch lines and personal lines to come away from the wall (see Fig. 1). However, such operation is very risky and there is often a drift in the movement which results in not being able to comprehensively cover the intended area.

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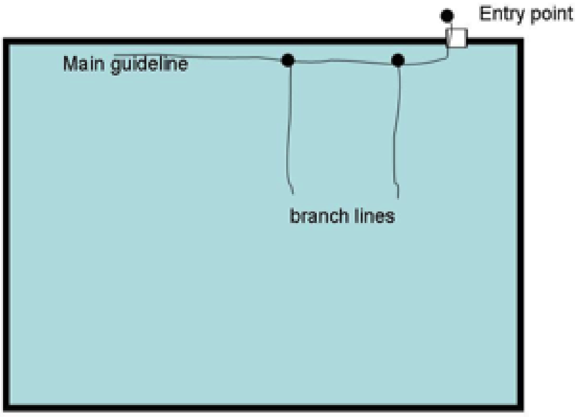

Fig. 1. Guideline Lay out

This paper presents several methods of human-robot interaction to assist a firefighter in an intervention:

- Direct Human-Robots Interaction (In-Situ) between the firefighter and a robot team composed of four Era-Videre Robots and the Guardian platform (Robotnik), all of them connected via a 802.11 wireless network. For this, the firefighter is provided with a computerized helmet that shows him navigation information using color patterns (see Naghsh et al. [2008]). Moreover, the robot team is able to follow the firefighter movements by using two different techniques, such as a laser range finder algorithm that detects the legs movement, and a TDoA (sonar/radio) system that is able to localize and follow the firefighter in smoke.
- Remote Human-Robots Interaction by means of a base station that is able to monitor the robots and the firefighter position in a map, and giving new paths (i.e. position goals) to the firefigther by means of its computerized helmet.

The Direct Human-Robots Interaction (In-Situ) approach needs the design of a localization method in smoke, which permits behaviours such as "Firefighter Following".To detect humans and robots in smoky conditions we could find very little works in the scientific literature. In Yamada et al. [1993] we can find a specific laser to detect obstacles in smoky scenarios which presents a range accuracy of 25cm. More recently Guerrieri et al. [2006] present an RFID technique to localize a firefighter in smoke conditions, this time including RFID tags in the scenario and a reader on the firefighter itself. On the other hand, many person following techniques has been reported by using camera vision Nishimura et al. [2007],Yoshimi et al. [2006],Takemura et al. [2007]. Moreover, other works use a laser range finder to apply pattern recognition and detect the firefighter legs Nomdedeu et al. [2008], which is very accurate in non-smoke situations and needs to be combined with sonar-based techniques to work in smoke. To permit the system to work in a firefighter scenario it is feasible to use localization methods based on technologies such as radio and/or sonar. Several methods have recently been proposed for determining the position of a mobile node by means of measuring radio signals - time of arrival (TOA), angle of arrival (AOA), received signal strength (RSS) - that could be an alternative, but they do not provide enough accuracy for a robot swarm (see Niculescu and Nath [2003]). To improve this, it is necessary to combine radio and sonar signals. In this paper a sonar/radio TDoA technique will be presented that works efficiently to implement a "Firefighter Following"behaviour even in dense smoke conditions.

From the Remote-Human Robots Interaction point of view, several methods have been studied. User centred HRI design is a common design approach derived from the more general, well known User Centred Design (UCD) philosophy, which basically consists in explicitly considering end-users needs and expectations along the different steps of the design. UCD in HRI design has been incorporated by designers for more than 15 years (Adams [1995], Mackenzie and Arkin [1997]), but has been getting widely spread and adopted in the community only more recently (roughly for the last 5 years). Alternative approaches to UCD have also been considered for HRI in the research community: in particular the Ecological Interface Design (EID) approach, that focuses on the work domain and environment rather than on the end user or specific task. This approach to interface design fits well applications involving multiple users with multiple perspectives, in complex systems (has been tested or applied in process control for power plants (K.J. Vicente [1990]), aviation (Hajdukiewicz and Burns [2004]), medicine, etc). It has been further proposed as a paradigm for mobile robotics teleoperation (introduced as 'Ecological Display') in Ricks B. and Douglas [2004] and Nielsen et al. [2007], from which our work takes some inspiration. In Guardians we started investigating approaches for merging the assets of both UCD and EID paradigms.

2. OVERALL SYSTEM DESCRIPTION

As seen in (Fig. 2) a team of mobile robots are accompanying a firefighter that wears a computerized helmet. The team of robots maintain a flexible formation around the firefighter and follow him sending sensors data to the base station. Moreover, (Fig. 3) shows a more sophisticated robot which is provided with chemical sensors and is able to follow the firefighter not only by using a laser scanner but also with a TDoA localization system in smoke. For this situation, as seen in (Fig. 4), the firefighter wears a radio/sonar transmitter around his leg, which enables calculating the distance and the orientation of the robot respect to the firefighter, with an accuracy of 1 centimeter. In (Fig. 5) we can see the Person Following Behaviour in very dense smoke conditions.

The base station is able to monitor the positions of the robots and the firefighter remotely, as well as to show some inputs from the sensors. Moreover, it is possible to select a goal in the map to be visited by the firefighter. Then, this information in sent to the computerized helmet that conducts the team to the desired position (see Figures 6 and 7).

3. SYSTEM ARCHITECTURE

In (Figures 8 and 9) we can see the Software and Hardware Architecture, which uses a Local Area Network with a Wifi 802.11 for the firefighter and the robots, and an standard Ethernet connection for the base station. The whole

Fig. 2. Team of robots that maintain a flexible formation around the firefighter

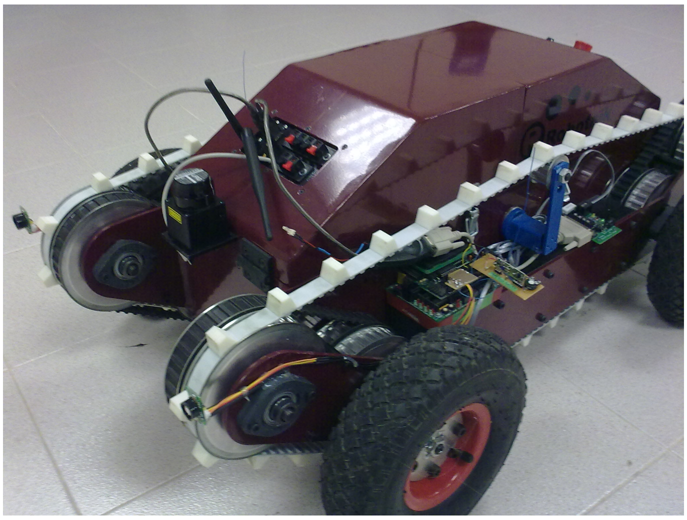

Fig. 3. Guardian Robot provided with chemical sensors and localization system in smoke

Fig. 4. Radio/Sonar firefighter localization and following in smoke using radio/sonar TDoA.

Fig. 5. Firefighter interacting with the Guardian robot in-situ using a Radio/Sonar transmitter in his leg

Fig. 6. Firefighter's Helmet that gets the goals from the base station and show them to the firefighter using color patterns

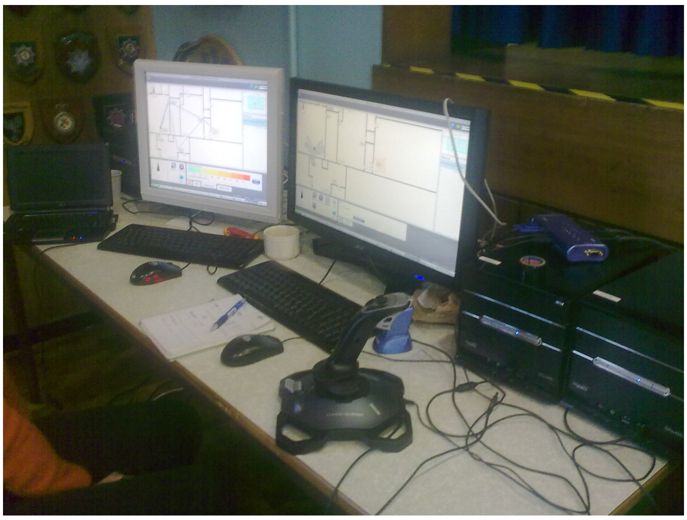

Fig. 7. Base Station that gets the information of the team (robots and firefighter's location, sensor inputs, etc.) and gives goals to the firefighter helmet from the outside

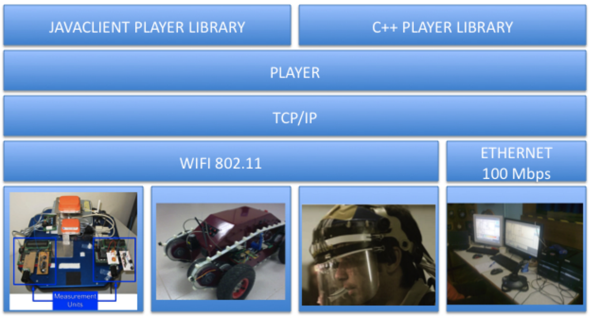

Fig. 8. Software Architecture

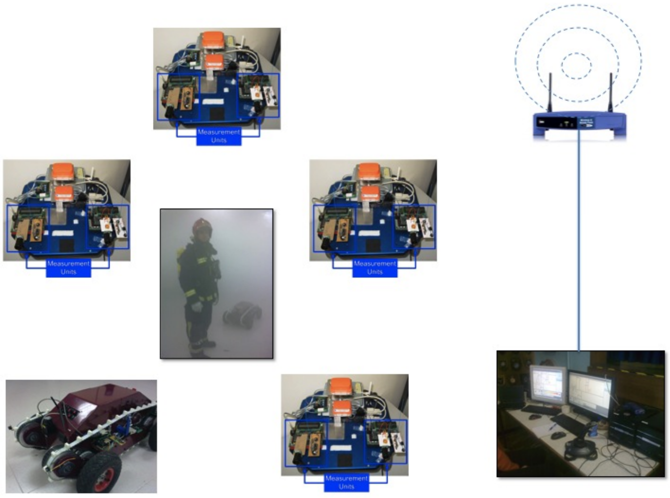

Fig. 9. Hardware Architecture

system is interconnected via TCP/IP protocol through the Player distributed model. Moreover, the behaviours are designed as Java Agents that interact with the player servers on each robot. The base station uses a C++ 2.1 Player Client for interacting with the team. More information about this software architecture can be found in (Nomdedeu et al. [2008]).

4. DIRECT/IN-SITU HUMAN-SYSTEM INTERACTION

4.1 Computerized Helmet for the Firefighter

The conceptual design for direct HRI was to ensure that the robot behavior and human robot interaction represented a minimal additional mental and/or communication load for fire fighters. Based on this, the conceptual model of the firefighter being treated as an exceptional swarm member was developed. The exceptional features being the predominance of the firefighter in terms of autonomy, skill and authority. In terms of interaction, this meant that the robots will in effect be in surrounding of the firefighters and move with them. The swarm of robots

Fig. 10. Prototype of Light Array Visor (LAV1)

determines a direction that fire fighter has to follow taking into account the fire fighter position, the position of possible obstacles that have to be avoided and the destination position. Whether assisting or leading, the swarm of robots should in general not increase the navigation related load (physical or cognitive) of a human being (see V. et al. [2006]). In cases where the robots identify hazards or specific safe routes they provide information for the fire fighter to employ and act on at their discretion. This conceptual model of HRI for swarms presents some questions about how to inform the fire fighters about potential hazards and potential safe routes to follow during the activity of fire fighting. In formulating the problem the fire fighters were consulted and shown likely or possible configurations using a simple display desktop based prototype. The prototype simply illustrated possibilities and also animated the intended robot operations through a number of animated storyboards (in e.g. MS Powerpoint). Through this consultation a peripheral visual display was chosen as the most appropriate means of helping direct firefighters. A simple operating hardware prototype was then developed to enable experimentation with alternative means of helping direct firefighters (see Fig. 10).

Based on a swarm recommended direction, the firefighter?s pose and direction is calculated and presented to him using the light array. Two key alternative approaches to visually depicting directions to the fire fighters have been considered:

- An analogical view where the light array is used to depict a direction directly. The angle of the illuminated light is computed to be the angle to the views head for the safe direction. The benefit of this is approach is that it is unlikely to require any effort to interpret. If in doubt the fire fighter can simply follow the light. Specific questions for which this approach needs to be refined concern the number of lights used represent the direction and the effective resolution in terms of number lights, light intensity and angular accuracy.
- A logical view where the light array is used to portray encoded commands to the fire fighter. At face value this has the potential to further burden the fire fighter as he'll have to interpret the encoded commands. Specifically this approach is likely to be more mentally demanding. The questions to be answered about such an approach concern identifying the appropriate command language and its portrayal.

Fig. 11. Light Array Visor [LAV2] using real fire fighting helmet

In order to assess the use of the alternative designs in a realistic setting a trial of a more realistic prototype was developed and conducted with firefighters (see Naghsh and Roast [2008]). A range of easily configurable versions of the two alternatives described above were prototyped to operate with the Light Array Visor (LAV1), for assessment with fire fighters at their fire station. At this stage in the project an operational robot swarm was not full developed hence the prototype was used to simulate robot swarm guidance to the fire fighter. The same prototype could also be operated by the experimenter for live direction control, hence providing a wizard-of-oz style set-up. The evaluation studies showed that subjects expressed a strong preference for a simplistic and unambiguous direction indicator. Hence, they showed a preference for low resolution analogical use of the light array, to the extent that array would be being used as though in a logical style. This is substantiated by one subject suggesting a clearer direction indicator be limited to basic angles such as -90, -45, 0, 45 and 90, and also suggesting that flashing and coloured lights would help to indicate when a change in direction is recommended.

A second version of the Light Array Visor was developed to include the inputs and feed back provided by the end user in to the design. A real operational fire fighting helmet was used for the second prototype to fit their gear to allow for more realistic trials (see Fig. 11).

4.2 Firefighter Following in Smoke

The robot team is able to follow the fire-fighter movements using TDoA between two physical signals: sonar and radio. This system consists of two parts: a ring of ultrasound transmitters, attached to the leg of the fire-fighter, and a dual receiver installed on each robot. With this approximation, we can determine the 2D position of any physical object (i.e. a robot or a firefighter) w.r.t. a mobile robot by using the time difference of arrival of two different signals each one with a known propagation speed.

The estimation of distances by measuring the time of propagation of ultrasonic waves can be useful for several localization methods based on the knowledge of some distances. Our experimentation demonstrates that this technique offers a good performance of the sonar sensors for distances up to 7-8 meters.

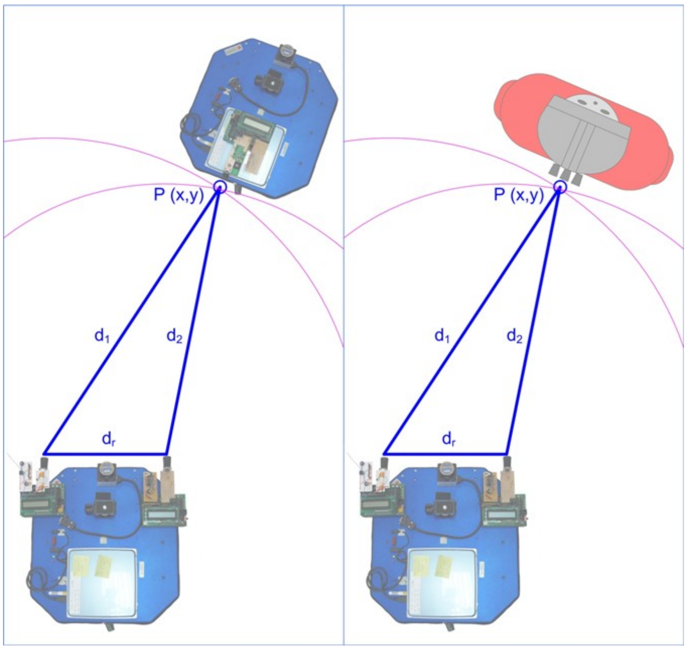

Fig. 12. Position determination by trilateration

Using two receivers mounted in front of each robot (see figure 12) and separated by a known distance of d_r, we can measure the distances from an emitter located at point P (see figure 12). The point P is the position of the object that we want to locate (i.e. a robot or a fire-fighter).

In order to obtain the (x, y) coordinates of the P point we proceed as follows: the P point is in the intersection of the two circunferences C_1 and C_2.

Let be the equation of the circumference,

$(x - a)^2 + (y - b)^2 = r^2$,

where (a, b) is the center, r the radius and (x, y) are the points of the circumference.

Knowing both center points $(-d_r/2, 0)$ and $(d_r/2, 0)$, and the distances d_1, d_2 from the object located at $P(x, y)$, we can write the following system of equations:

$$(x + \frac{d_r}{2})^2 + y^2 = d_1^2$$
$$(x - \frac{d_r}{2})^2 + y^2 = d_2^2$$

Solving this system of equations, we obtain the point $P(x, y)$ where the emitter is located:

$$x = \frac{d_1^2 - d_2^2}{2d_r}$$

$$y = \frac{\sqrt{-d_1^4 + 2d_1^2(d_2^2 + d_r^2) - d_2^4 + d_r^2(2d_2^2 - d_r^2)}}{2d_r}$$

Once we know the relative position of the P point w.r.t. the robot, a control algorithm computes the resultant linear and angular speeds for controlling the robot. Experimentation results showed good performance when trying to follow a fire-fighter even in very dense smoky environments.

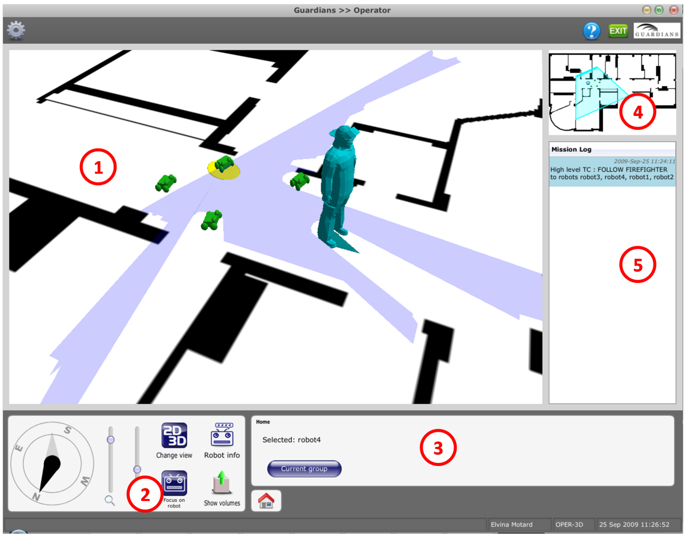

Fig. 13. Base Station User Interface Areas

5. REMOTE HUMAN-SYSTEM INTERACTION: BASE STATION APPROACH AND MECHANISM

In order to centralize robots' measurements and data, and to supervise the joint activities of the swarm of robots and the fire fighters, a remote monitoring and control station is being developed. Several categories of base station users, with different operational / analytical skills, have to cooperate during missions. For that purpose three roles have been identified: Robots Operators (RO) are in charge of teleoperating the robots; Sensor Data Specialists (SDS) are in charge of supporting decision making through monitoring of science data; Base Station Coordinator (BSC) is in charge of the overall mission and users coordination during operations.

As a baseline principle, we decided to promote touch screen interaction methods. The HMI display inspiration comes from Ecological Interface Design (EID), as explained earlier. The most noticeable way we applied Ecological Display recipes is through e.g. limiting the amount of potential eye catching points or areas in the GUI (and in particular the amount of gauges), and making as obvious as possible the status and characteristics of the robots in their environment, with a main area of the GUI representing in a synthetic way the contextually relevant robot information. The main operator's GUI is depicted in figure (13). Several areas can be identified: the main visualization zone (1), filling the largest screen space, provides with an overall, immediate understanding of the global situation in 2D or 3D; robots and firefighters are represented in their (known) environment. The viewport navigation (2) allows the user controlling different parameters of the main view. The operator actions area (3) includes a wizard to easily control the robots at a swarm level. The overall map view (4) helps understanding where in the overall space is situated the currently observed area. The mission log (5) displays notifications of essential events, either originating from the base station or from elsewhere in the system, during operations.

A number of Sensor Data Specialist concept views have been designed and implemented to support sensors data

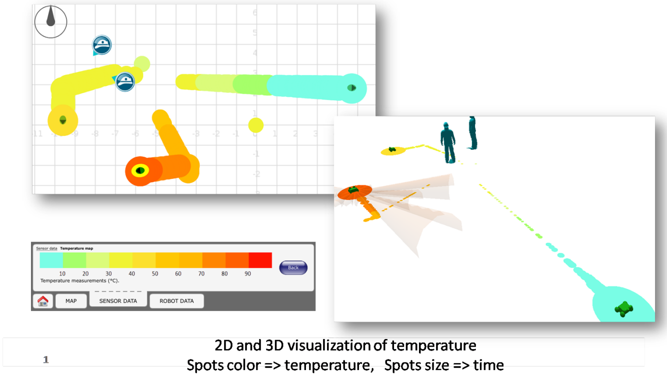

Fig. 14. User Interface Sensors Data Interpretation

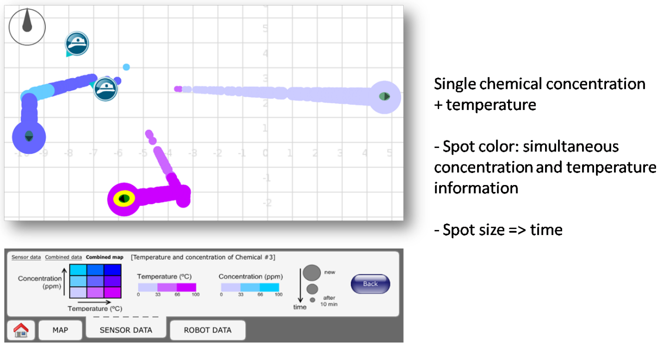

Fig. 15. User Interface Sensors Data Interpretation

interpretation, and in particular temperature and chemical data interpretation. These concepts are to be further tested with end users, to identify most appropriate concepts. See (Figures 14 and 15) for two examples of such concept views.

The base station HMI has been evaluated through a process focusing on the identification of usability shortcomings that may hinder proper robots teleoperation by the operator role users. Evaluation results have been produced on the basis of tests carried out by experts and representatives of the Guardians end-user community. The focus of the evaluation so far has been on the operator role. Three steps in the evaluation process have been carried out: early-prototype end-user test trial to gather qualitative user feedback, expert evaluation and formal end user usability evaluation session. Results confirmed a number of our design choices and helped fixing most shortcomings.

6. CONCLUSION

This work includes humans working in-the-field with robots during an incident. Supporting humans in-the-field is the focus of the research reported here, however the GUARDIANS project as whole also includes and integrates remote interaction and tele-operation of robots through a base-station, as well as the deployment of wireless communications and the use of advance chemical sensors. Moreover, a person following behaviour has as well been implemented to let the swarm localize the firefighter in smoke.

In terms of human robot interaction (HRI) this work differs from the majority of work in the robot assisted search and rescue in that the majority of work has not involved humans working in-the-field with robots and that robot swarms are rarely considered. Relevant research has mostly looked in to evacuating humans in the event of emergencies in a state prior to the search and rescue carried out by fire fighters or has looked in to the crisis management. However such works do not consider the specific context and conditions of this work.

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