GUARDIANS Final Report Part 1 (draft): A Robot Swarm assisting a Human Fire Fighter

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Abstract

Emergencies in industrial warehouses are a major concern for fire fighters. The large dimensions together with the development of dense smoke that drastically reduces visibility, represent major challenges. The GUARDIANS robot swarm is designed to assist fire fighters in searching a large warehouse. In this paper we discuss the technology developed for a swarm of robots assisting fire fighters. We explain the swarming algorithms which provide the functionality by which the robots react to and follow humans while no communication is required. Next we discuss the wireless communication system, which is a so-called mobile ad-hoc network. The communication network provides also the means to locate the robots and humans. Thus the robot swarm is able to provide guidance information to the humans. Together with the fire fighters we explored how the robot swarm should feed information back to the human fire fighter. We have designed and experimented with interfaces for presenting swarm based information to human beings.

keywords: Swarm robotics, search and rescue, human robot (swarm) interface, mobile ad-hoc networks.

1 Introduction

The GUARDIANS[1] (Group of Unmanned Assistant Robots Deployed In Aggregative Navigation by Scent) project is an FP6, EU funded, project developing a

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[1] GUARDIANS is running from 2007 to 2010, 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.

swarm of autonomous robots. Swarm robotics is a relatively new area of research and very diverse approaches are reported in the literature. However descriptions of everyday applications are as yet relatively rare. When we approached South Yorkshire Fire and Rescue (UK) to enquire about the applicability of our swarm of robots, they pointed out that industrial warehouses in the emergency of a fire are a major concern to them. Searching for victims will be dangerous because of the combination of the enormous dimensions of the warehouses and the expected low visibility when smoke develops. The searching of an industrial warehouse in smoke was subsequently made the central application scenario of the Guardians project.

A major role of the robot swarm in this scenario is to support human beings searching the warehouse by enhancing the human's navigation. Since no heavy physical task is assigned to the robots, the swarm may consist of small and even mini-robots. Whereas locomotion is not a problem, the smoke poses a problem for human beings as well as for robots. The low visibility causes a number of related problems: it hampers navigation as the sight on landmarks is lost and subsequently localisation and mapping turn problematic. Radio contact partially relieves these problems, however as we will discuss a warehouse is full of obstacles in the radio spectrum.

Support for humans is a final aim for the Guardians swarm of robots. However, whereas swarm robotics is a new but developing field, the development of interfaces for humans to interact with a group or swarm of robots is a just starting field. In the Guardians project the interaction of the human with the robot swarm is separated from the feedback that the swarm provides to the human. Human beings are autonomous members of the group and are free to behave as they wish. The feedback of the robot group to the humans consists in guidance and navigation instructions, on the basis of which the humans may or may not change their behaviour. The robots react similarly to the actions of the humans as they do to other group members. Thus, the behaviour of the humans influences the robot group, however the humans do not directly instruct any robot. Since the Guardians consortium first published these ideas [48, 49] several papers have appeared. However, only a few papers respect and take advantage of the autonomy of the robots: similar to our approach Hashimoto et al. [27] have a human being participating as a swarm member, while Bashyal and Venayagamoorthy [10] let a human remotely control one of the robots in the swarm.

The theme of this paper is the realisation of a swarm or group of robots assisting human fire fighters. The swarm becomes only useful when the swarms' navigation and communication problems are solved. We explain the swarming techniques which we apply to deal with the problems and discuss the results of our experiments with real robots. First, in section 2 we discuss the application scenario and draw some early conclusions which are guiding the further developments. Section 3 provides a brief overview of swarm robotics and the conditions under which the Guardians robot swarm will be applied. Section 4 discusses the swarm technology applied to make the swarm accompany human beings. This is the technology that also enables humans to influence the robot group. The wireless communication system plays an essential role in the navigation of the human and the robot group. In section 5 we discuss the communication network as well as localisation and mapping. This is also the point where the feedback from the robot group to the human has to be prepared. In section 6 we discuss the experiments with the human robot swarm interface. The main subject in this section is how the robot group feeds back to the human being. We finish in section 7 by drawing conclusions.

2 Warehouse search

Generally speaking warehouses consist of large open spaces alternating with storage areas consisting of vertical racks in which a multiplicity of materials is stored. Modern warehouses are usually single storey buildings in which stairs are not common; they can be as large as $400 \times 200\text{m}^2$. Large warehouses are divided into sections separated by fire resistant walls (that is, resistant for several hours). The typical dimensions of sections are in the order of $100 \times 200\text{m}^2$. (For convenience a section counts as a warehouse in the discussions below). The fire fighters have indicated that in the event of a fire, the fire will be confined to a certain area of the warehouse, however smoke may cover the whole warehouse. There might be some debris on the floor, but one may assume that most of the warehouse is in quite an orderly state. Thus, the ground will be easily passable; if the situation deteriorates fire fighters will not enter the building, because of the increased risk level[2]. For the robot swarm this implies that there are no exceptional requirements concerning the locomotion and even wheeled mini robots are suitable. Usually a map of the premises is available, however the map will show only the major constructive elements such as walls and doorways, but may not contain an interior design or contain an obsolete interior design.

When fire fighters have to enter a smoke-filled environment, they are provided with breathing apparatus to provide fresh air. However, the smoke reduces visibility dramatically and human beings easily get disoriented and may get lost. Rendered without sight fire fighters can only rely on their touch and hearing senses. However also these senses are restricted. The sense of touch is restricted by their clothing gear and the sense of hearing is reduced by the noisy breathing apparatus.

The large scale of a warehouse, the low visibility and the time constraints render the searching of a warehouse very risky. This is underlined by tragic examples. In the warehouse fire of 1991 in Gillender Street London (UK), two fire fighters died and in the 1999 warehouse fire in Worcester (USA), six fire fighters lost their lives. And recently in November 2007 a tragedy happened in Warwickshire (UK) , when four fire fighters were killed in a vegetable warehouse blaze.

In the Worcester case, first a crew of two fire fighters reported being lost 22 minutes into the incident; 30 minutes later, an emergency team consisting of four fire fighters got lost as well[3]. The Worcester warehouse was a six storey building with largest dimensions $40 \times 50\text{m}^2$, where thick black smoke developed. (Note that this floor space is only a tenth of the floor space of a section of the modern warehouses referred to above.) The communication link was frequently interrupted and the emergency teams were not sure on which floor the first crew got lost.

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[2] Firefighters will take some risk to save saveable lives; however they will not take any risk at all to try to save lives or property that are already lost. Source: Fire Service Manual, HM Fire Service Inspectorate.

[3] Refer for the Worcester warehouse to http://www.usfa.dhs.gov/downloads/pdf/publications

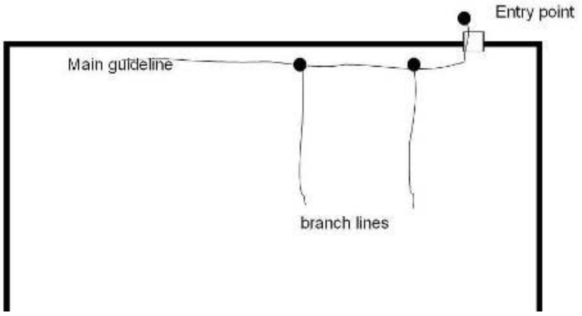


Figure 1: Guideline layout

The above indicates significant challenges if fire fighters are to work effectively with robots while searching:

- The search environment is highly oppressive for a human being:
  - poor visibility due to smoke;
  - poor tactile awareness due to safety-clothing and
  - limited hearing due to fire fighters headgear and ambient noise.

  This presents ergonomic and communicative design problems for direct human robot interaction.
- Fire fighters operate with established protocols to ensure safety, robot behaviours should complement these protocols to enhance the search and rescue tasks and not be disrupting.
- Fire fighters engaged in search and rescue are working under considerable mental and physical stress. When assisting, the swarm of robots should in general not increase the navigation related load (physical or cognitive) [33] of the human being.

2.1 Navigating in smoke

In the United Kingdom procedures are that a first team will lay-out and fix a guideline along a wall, refer to figure 1. Subsequent teams aiming towards the scene of operations follow the guideline but nevertheless they advance only at a crawling speed. We informally clocked a guideline following exercise by experienced fire fighters: they progressed 12m in about one minute. The amount of oxygen contained in the breathing apparatus suffices for about 20 minutes. Given the crawling speed, fire fighters can proceed about 240m with a full tank. Taking into account that they have to negotiate the 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. Robots guiding the fire fighters could speed up the search.

Smoke obstructs perception in the visible spectrum; this is the case for the human eye as well as for most robotics sensors such as cameras (mono or stereo)

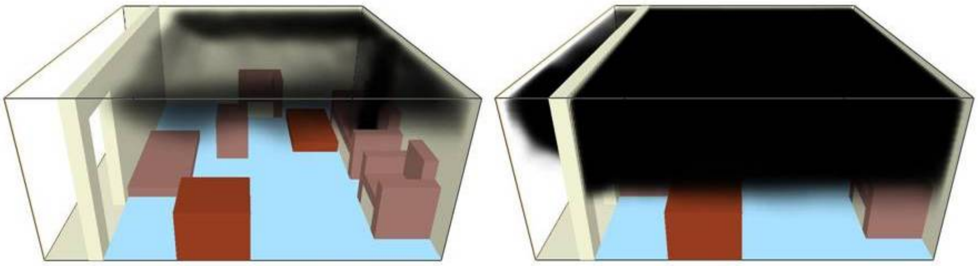


Figure 2: Smoke development simulation, left: the early stage where the sofa on the right catched fire; right: about 20 minutes later, thick black smoke is covering the room from the ceiling downwards.

but also for laser range finders (LRF) as our experiments confirmed [45]. What is perceived as smoke, consists of particles on which light is scattered. Critical concentration values depend both on the particle size and on the distance (depth of view). Our trials with smoke, showed that the maximum range of the laser depends on the spatial and temporal distribution of the smoke, this distribution is not uniform. This can be validated with the well known simulator and simulation results from the National Institute of Standards and Technology (NIST) [38] and their comparative studies of visibility in smoke, for example in [12]. Using the NIST fire dynamics software package, we have simulated a typical room environment in smoke with typical ventilation and air-flow constraints offered within the NIST database (refer to Figure 2).

The general conclusion is that we can say that starting from the walls the smoke concentration increases the further away one moves from the walls. Though we note that the actual behaviour depends, amongst other parameters, on the height of the room in which the fire is enclosed, usually the concentrations are lower closer to the floor. This justifies our working conclusion to retain the practice of the fire fighters, which is to guide oneself by using the wall boundaries. The walls provide (incomplete) position reference, and visibility closer to a wall is usually better. We also notice that as the robots are considerably smaller then a human being, their sensors operate closer to the floor where the smoke can be expected to be less dense and where also temperatures are lower.

2.2 Radio contact

Besides the problems with navigating in smoke, the tragic examples discussed above also show the need for 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 packagings. Within this metal cave, the transmission and reception of radio signals is problematic and communication connections get broken.

Applying a swarm of robots provided with radio transmitters and receivers, provides new opportunities. Having a swarm of robots allows that they can disperse over the area. While 'radio' obstacles might block a direct connection between all swarm members, individual robots will be within 'the line of sight' of some other robots and together the swarm can form a chain or mesh of robot-to-robot communication links. One or more chains may help to maintain the radio connections. However, if many robots are present in the same area, communication among them has to be well organized. If all robots are broadcasting at the same point in time, chaos will result: the interference between the signals will cause data losses and errors. Therefore we apply a so-called mobile ad-hoc network communication system, in which any robot may act as communication node. While the swarm advances some robots can become dedicated beacons to ensure communication coverage.

Smoke is not an obstacle for the radio signal, and in addition to the communication facilities, the ad-hoc network can provide position data to support localisation of the mobile robots and humans. Note that indoors localisation systems like GPS are not accessible. To enhance localisation also beacons are required and a suitable trade off is being sought for between beacons for communication purposes and beacons for positioning purposes.

The smoke in the warehouse may contain substantial concentrations of toxics or inflammables. The robots are provided with an artificial nose to warn for chemicals. The noses enable the robots to apply *olfactory-based* navigation and chemical plume detection [45]. However, we will not discuss olfactory-based navigation in this paper.

3 Swarm robotics

3.1 Brief overview of the state of the art

Swarm robotics is a relative new field of research building upon the pioneering work by Reynolds [52], who simulated a flock of birds in flight (using a behavioural model based on a few simple rules and only local interactions). Since then the field has witnessed many developments into various directions. In the spirit of Reynold's original approach, a considerable amount of works focus on influencing (controlling is in this context a too strong notion) the geometrical (2D or 3D) distribution of swarms of autonomous robots. Key terms are swarm aggregation, navigation, coordination and control. This type of works is relevant for our work and discussions below. Certain approaches focuss on basically autonomous individuals that can physically connect to for a larger 'organism', refer to the S-Bot project or the Replicator project. We also mention the Particle Swarm Optimisation PSO and Swarm Intelligence approaches which use swarm simulations to find problem solutions.

The geometrical oriented swarm robotic approaches are relevant to our work. Due to its dimensions, a warehouse requires a large number of robots. We apply many of the same robots as a single robot cannot do much in a large warehouse. Communication with the outside might not be possible and the human being will be busy ensuring his own safety. Thus, there will be circumstances where the robots have to rely on local information while autonomous decision making is a requirement.

Initial robot swarm research has focused on centralised approaches [37, 9], aiming at motion planning [35, 36] or leader domination [15]. However, the large number of robots generate dynamic behaviour for which central control is computationally expensive and hard and also centralised motion planning is not apt. Recent research emphasises autonomy of the robots and applies decentralised approaches which reduce computational complexity and provide robustness to failures. Such approaches include behavioural-based robotics [8], artificial potential functions [51, 17, 25, 23, 24], virtual agents or virtual structures [7, 42], probabilistic robotics [54], and others [55]. Some approaches use optimisation criteria from game theory for navigation control [58] and robot distribution or area coverage [13]. There are also works dealing with improving system performance through adaptation and learning [46, 56, 6]. 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. Surveys on recent advances and the state of the art in swarms can be found in [16, 53, 34] and a web database on swarm robotics related literature has been compiled at swarm-robotics.org.

3.2 Swarming in the Guardians environment

The GUARDIANS swarm is intended to support search operations. The project also includes operations involving robots only, however we mainly discuss the aspect of a team of robots enhancing the navigation for humans.

To operate successfully in the warehouse scenario the robots in the swarm will have to deal with several quite different situations. In situations where there is no communication link with other robots, a robot has to navigate on its own sensor inputs. When other robots are within the sensor range but communication is not possible, still certain group behaviours can be achieved: we call these the *non-communicative* behaviours. The robot swarm brings its own wireless communication network into the warehouse and while the swarm is advancing the communication network is to be extended. We classify the behaviours that are focussed on maintaining and expanding the communication network as *networking* behaviours. When communication is available and the swarm is in *communicative* mode, communication based behaviours can be performed, allowing ‘higher’ level cooperation, for instance collaborative localisation [21] and coordinated navigation. The distinction between non-communicative and communicative behaviours is also referred to as a distinction between explicit and implicit communication [43], however the latter also includes stigmergy which is not applied within the GUARDIANS project. Moreover, this dualism excludes the networking behaviours which are essential to cope with the communication problems in the warehouse scenario.

Non-communicative behaviours can be implemented without position tracking: the robots will stay together as a group, but the group will not know its position. The networking behaviours will try to avoid that any robot gets disconnected. A robot losing connectivity has a few options: either (*i*) return to a predefined site for (re-) initialisation, (*ii*) return to the last known position where the wireless signal was strong enough, or (*iii*) be opportunistic and search forward assuming some fellow swarm member will soon be found. For the first two options localisation and some mapping (SLAM) is a prerequisite and the map must be (relatively) reliable. The case (*i*), returning to a pre-defined position, does require reliable mapping while the revisiting problem must be solved (refer to [22]) which presupposes that the environment has not radically changed. Given the problems to be expected, we have designed algorithms (ref to section 5) to let the networking swarm advance in an orderly manner such that the loss of connectivity can (mostly) be avoided.

The aim of having the swarm supporting a human in a rescue operation is a novel aspect of the GUARDIANS project and we have called this the *'assistive'* swarming behaviours. The participation of a human being in the swarm of robots adds particular qualities. Swarm algorithms are built based on the autonomous operations of the robots, the GUARDIANS approach adds to this human originating tactical planning.

Our approach differs from the most works in robot assisted search and rescue. In the majority of works the humans are not working in-the-field with robots; moreover, robot swarms are rarely considered [20]. A human swarm interface is very different from the human-robot interfaces applied in telerobotics. In telerobotics (refer to PeLoTe project, IST-2001-38873, or View-Finder FP6-045541) several humans may operate one robot, in GUARDIANS however, the human beings cooperate with several robots. Several authors are developing remote interfaces for monitoring a swarm [14] or for monitoring and remote controlling [39] a swarm of robots. Bashyal and Venayagamoorthy [10] let a human remotely control one of the swarm robots. However, in our assistive mode the swarm has to interact directly and coherently with human beings in the field and this requires that appropriate and consistent behaviours as well as interfaces for the interaction with human beings have to be developed. Similar to our approach Hashimoto et al. [27] have the human being participating as a swarm member but there is no provision for feedback to the human, which is essential in the smoke.

The GUARDIANS swarm is build by connecting several types of behaviours. The human fire fighters are fully autonomous and go their own way. Non-communicative behaviours are used to make the robot swarm surround the fire fighter in a loosely defined and flexible formation. The behaviour of human team members is based on intelligent decision making and this behaviour influences the swarm as the robots react to this behaviour. The next section (section 4) describes and discusses our simulations and implementations of non-communicative swarm behaviours using erratic robots. Typically the swarm behaviours allow a varying group size. Thus when starting with a large group, several robots may 'withdraw' from the group, while the main swarm functionality will not be affected. The freed robots will occupy of maintaining the communication network; the networking behaviours, which are currently implemented on purpose built Bebots, are discussed in section 5.

Depending on the thickness of the smoke localisation and mapping can be a difficult problem. A systematically advancing swarm - as already required for maintaining connectivity - provides also a basis for localisation and mapping under harsh conditions. In section 5.2 we explain the information that can be retrieved from the networking behaviours and how additional sensors data are fused to improve the mapping.

When communication is available, the robot swarm can report to the human fire fighter as is essential for a mixed robot-human team. Note that the communication is only one way, from the swarm to the human being. Feedback from the humans to the swarm results from the humans adjusting their behaviour. The robots will follow the humans, as explained above, thus closing the loop. We discuss our implementation of assistive swarming in section 6.

4 Non-communicative swarming behaviours

Non-communicative swarming behaviours are typically achieved without central and on line control. Also the swarm typically consists of homogeneous but anonymous robots, the latter means that the robots are able to recognise another robot as a robot but they cannot identify other robots as a particular individual with a unique name. The advantages of this approach are that the swarming behaviour is relatively independent of the number of robots that are active, thus the swarm is resilient to failures of individuals and its size may vary considerably. A drawback is that the swarm behavior is at run time affected by many factors, making it hard predict the resulting behaviour in full. Swarm research therefore usually aims at behaviour types of a general nature.

The non-communicative behaviours that we have implemented are:

1. Navigation on static landmarks:
    (a) Obstacle avoidance
    (b) Wall following
2. Navigation on dynamic features:
    (a) Following a moving landmark
    (b) Robot avoidance
    (c) Acquisition/Maintenance of geometric formations

The listed behaviours are obtained by applying the artificial potential force field method, which was introduced by Krogh [32] and refined in [30], refer to [25] for a modern description. For biological simulations often *self-propelled particle* (SPP) models [11] are used, they were first introduced by Vicsek et al. [57] to simulate biological swarms. Whereas - as the name indicates - the potential fields method originate from field descriptions, the SPP models focus on describing the behavior of the individual agent similar to the model in [50]. Basically the two approaches are equivalent and should be able to generate the same behaviours. The two approaches are some times referred to as Gaussian (integrative field based) and Lagrangian (individual based) [44]. The advantage of the individual based SPP approach is that it is intuitive for empirical studies to observe individuals and build up a multiple robot system or swarm by adding individuals. In this paper we will follow the individual based approach.

Formal studies of swarm control usually assume that each robot has *perfect* information and knowledge, and knows the exact position of the other robots [51, 26] and [29]. However in practice the range of the robot's sensors is limited. Nevertheless the navigation decisions are to be based on the sensor data and the quality of the data has a considerable impact on the swarm behavior [47]. In the GUARDIANS environment of a smoke-filled warehouse the sensors are further restrained and in the worst case they might not provide any information at all [45].

4.1 The control model

In this section we discuss the control model that is governing the robots and the swarm. Each robot a calculates a force $\overrightarrow{F_a}$, which is the generator of the new velocity vector of the robot. In its general form the control model depends on four terms:

$$\overrightarrow{F}_a = \sum_{g \in G} \overrightarrow{EA}_{(g,a)} + \sum_{o \in O} \overrightarrow{ER}_{(o,a)} + \sum_{r \neq a}^{Sw} \overrightarrow{IA}_{(r,a)} + \sum_{r \neq a}^{Sw} \overrightarrow{IR}_{(r,a)} \qquad (1)$$

The first two terms represent the external influences; $\overrightarrow{EA}_{(g,a)}$ is the *attraction* of goal g on robot a and $\overrightarrow{ER}_{(o,a)}$ is the *repulsion* caused by the obstacle $o \in O$ on robot a. The second pair of terms in (1) consists of the internal forces, which originate amongst the robots in the swarm Sw. They are the attraction $\overrightarrow{IA}_{(r,a)}$ and repulsion $\overrightarrow{IR}_{(r,a)}$ between any swarm member r and robot a. The attraction points directly towards the source object and the repulsion points into the opposite direction, away from its source. Our description focusses on the individual robot (Lagrangian), however if we consider a to be a point and let it range over the two dimensional plane, each of the terms in (1) but also the terms together generate particular potential force fields, depending on the functions applied in the terms. Usually, the functions for attraction and repulsion are chosen such that on large distances the attractions $\overrightarrow{EA}$ and $\overrightarrow{IA}$ dominate while on short distances the repulsions $\overrightarrow{ER}$ and $\overrightarrow{IR}$ dominate.

The internal attraction $\overrightarrow{IA}_{(r,a)}$ and internal repulsion $\overrightarrow{IR}_{(r,a)}$ are sometimes called the artificial social potential functions [51], as their combination induces coherence in the swarm. At a particular distance internal attraction and repulsion balance; this is called the *equilibrium distance* [51].

Returning to the list of basic behaviours, obstacle avoidance is governed by $\overrightarrow{ER}$ and robot avoidance by $\overrightarrow{IR}$. In wall following, the term $\overrightarrow{EA}$ is determined by values assigned to or collected in the environment. Important for the GUARDIANS swarm is detecting and searching for a communication signal; in this case the values for $\overrightarrow{EA}$ are determined by the radio signal strength in the field. Note that if only internal attraction applies but no repulsion, the robots will chase each other and clutter; if only repulsion applies the robots will disperse indefinitely [50].

4.2 Human-swarm formations

In this section we further detail of the control model as applied to a robot swarm accompanying a human being. In this case the system consists of three classes of entities:

1. A class of robots r_i, $i = 1, 2, \ldots, n$.
2. A human being (fire-fighter).
3. A class of obstacles o_k, $k = 1, 2, \ldots, l$.

We assume that one human being is present and the human makes autonomous decisions and is assigned to be the moving landmark for the robots. Thus the human is implicitly the group's leader. The robots not only follow the human but also assist him/her to navigate safely and prevent collisions with obstacles. 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 in a flexible formation around the fire fighter and maintain this formation throughout.

The robots act *independently* and *asynchronously*, but they are *oblivious*, meaning that they do neither remember observations nor computations performed in previous steps. We refer to the sensing range of a robot as its *visibility domain.* In the simulations in figure 4 the *field of view* of each robot is 360 degrees, resulting in a *circular* visibility domain. In the demonstration with erratic robots in figure 6 the field of view of is reduced to 240 degrees, which is the range of the Hokuyo lasers. We assume that each robot can recognise humans. In practice this can be achieved in various ways; the GUARDIANS project applies a tracking system based on the characteristics of the stepping feet of the human [41].

Formations

Moving a group of agents in formation has received a fair amount of attention in the literature, however there is no unique definition of the term '*formation*'. The 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 at all times. Thus, the formation does not have a predefined shape. We define a formation as follows: over time the robots might form one or more groups, where within a group the distance d_r of any individual robot r to the agent closest to it (either a robot or a human) does not exceed the value d_{max}, refer to [2]. To some extent, this definition complies with the definition proposed in [19], where the group determines autonomously the most appropriate positions in the formation.

For each of the classes of entities we have to define attraction and repulsion. In the human robot formation we do neither apply attraction between robots, nor between robots and obstacles. Roughly, repulsion is defined as the inverse of the square distance between the entities; scaling parameters are applied to further modify the behaviour. To explain the principle, we discuss the forces between the human and the robots, for further details refer to [2, 3]. The robots have to avoid collisions with the human and at the same time keep the human within sensor range. We define the potential function P_{Human} between the robot r and the human H as

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

where k_{hrr} and w_{hrr} are scaling parameters for repulsion, k_{hra} and w_{hra} parameters for attraction and d_r^H is the distance between the robot r and the human H. The repulsive term prevents the robot from colliding with the human and the attractive term keeps the human within its visibility domain.

Figure 3 shows an example of the robot-human potential function. In this example we have a robot r and a human H in a two dimensional space, d_r^H is the distance between them. When r is too close to H the $P_{Human}(d_r^H)$ pushes r away from H preventing the robot from colliding with the human. When r is too far the $P_{Human}(d_r^H)$ pulls r towards H.

Figure 4 shows simulations in NetLogo of the formations of a group of robots and a human being. The formation shape achieved depends on the number of

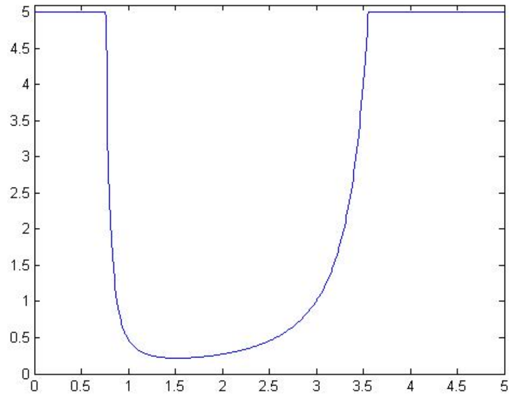
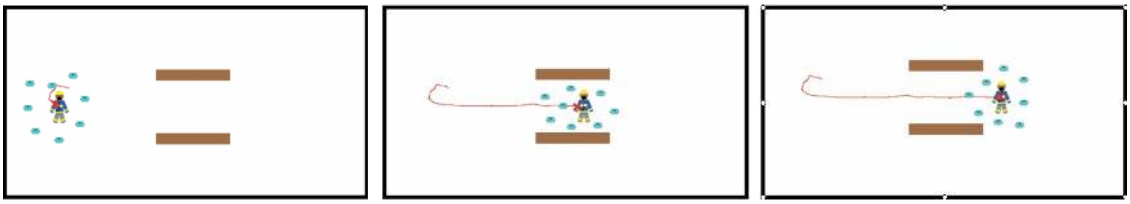


Figure 3: Example of the robot-human potential function; P_{Human} on the vertical axis, the distance d_r^H is on the horizontal axis.

robots, which differs from the work [26], where a predefined shape for a given number of robots is considered.



(a) (b) (c)

Figure 4: Left to right: simulations of the formation of a group of 8 robots and a human being passing a corridor.

Real Robots Implementation

We have tested our algorithms on the Erratic mobile robot platforms. Four Erratic platforms each equipped with: on board computer, WI-FI and Hokuyo laser range finder. The main goal of the implementation was to demonstrate that robots are able to generate a formation and keep the formation while following a leader robot (or a human). The major challenge was to achieve a reliable way to detect the members of the multi robot human team without using any sort of tracking system. In order to mimic relative robot detection and distance estimation robots were provided with a map of the environment in which they localised themselves by using the Adaptive Monte-Carlo localisation method.

As part of the solution we designed an architecture environment for implementing: different robot behaviors (aggregation and following), handle com-

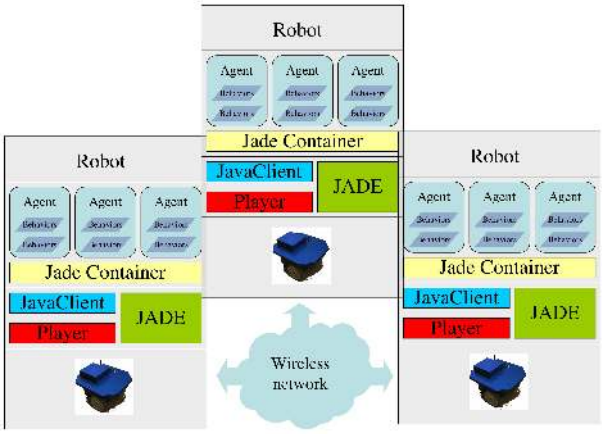


Figure 5: Software components used for demo.

munication, 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). JADE (Java Agent Development Environment) [4] 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 agents-based developments. In our demonstration we have developed 4 different types of agents where each one had a clear role in the demo. Note that agents here are different from the classes of agents determined in Section 4.2. Each agent is composed of a set of behaviours that determines how this agent acts or reacts to stimuli. For the demo 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.

In Figure 5 we can see the combination of software pieces that plays in our team. Player, from Player/Stage, acts as a Hardware Abstraction Layer, allowing us to forget specific hardware problems. JavaClient allows us to connect to the Player server from a Java environment, while JADE provides us the ability to use Agents. In terms of runtime, Agents, and their behaviours, run on top of an agent container provided by the JADE, making use of the JavaClient to access Player facilities.

Some of implementations were demonstrated during the evaluation of the GUARDIANS project's progress in Brussels in January 2009, and were met enthusiastically by the audience. In Figure 6 snapshots of video of the experiments on formation generation and keeping on a group of Erratic's robots are presented. The one robot provided with a flag, is the leader and simulates the role of the fire fighter.

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


(a) (b)

Figure 6: Two snapshots of experiments on formation generation and maintenance using Erratic's.(a) Formation generation around the leader in the middle; (b) Formation maintenance while following the leader on the left.

5 Networking

The networking mode is aimed at setting up and maintaining a communication infrastructure. This work faces two major challenges. The first is that the metal present or solid concrete in the warehouse partitions the warehouse into cages which render the reception of the radio problematic. The second challenge is that position detection or localisation is needed. For indoor environments GPS is not available and localisation and mapping (SLAM) has to be based on other sensors. However, because of the smoke the conventional light based sensors may not produce useful data. The radio signal for the wireless communication will not be disturbed by the smoke thus the radio network has to serve as a (maybe coarse) fall back.

5.1 Communication Infrastructure

For communication various wireless technologies are available including WI-FI (Wireless LAN), Bluetooth and ZigBee on our communication platform. As auxiliary technologies a radio system being able to measure time of flight and a sub-1-GHz communication communication system is available to complement above mentioned technologies. A wireless communication network usually consists of network nodes and clients. The robots in the Guardians swarm can act both as clients and as network nodes. I.e., all robots are equipped with a communication module that provides routing functionalities for forwarding messages but which also may serve as a client. So called *mobile ad-hoc networking* protocols (MANETs) are used to structure the communication traffic. An ad-hoc network is self-organising in terms of node discovery as well as message routing and assign certain robots as network nodes to form the backbone of the communication network. The topology of the network may change as the circumstances require, for instance to adapt to connection failures. On top of this, the mobility of the robot-nodes further enhances flexibility and enables the swarm to build reception pathways that bridge the transmission gaps.

The physical communication device has been realized as a gateway module. The gateway manages all required functionality for operating an mobile ad-hoc network including node discovery, maintenance of routing tables, and massage routing. Besides realizing the core functionality of robust message routing the gateway has been developed to support different techniques for energy saving like dynamic frequency and voltage scaling as well as dynamic power down of non-used hardware components including wireless communication processing. Therefore the gateway is equipped with Texas Instrument's (TI) new OMAP 3 processor. This high-performance applications processor consists of a 600 MHz ARM Cortex-A8 processor that has a comprehensive power and clock management enabling high-performance, low-power operation via TI's SmartReflex adaptive voltage control. It offers more than 1200 Dhrystone MIPS with maximal power consumption from less than 2 W. The memory is implemented by a package on package solution on top of the processor and connects the processor to 512 MB NAND Flash and 256 MB mobile low power DDR SDRAM. A Bluetooth-WI-FI system in a single package integrated into the gateway with a commonly used Bluetooth chip and ultra low-power WI-FI offers flexible but efficient use of two communication technologies. An integrated coexistence solution ensures simultaneous operation of Bluetooth and WI-FI. Additional wired communication standards like I^2C, SPI, UART and high speed USB allows variable expansion of the gateway. This can be used to easily connect additonal components like sensors (e.g. chemical sensors for detection of hazardous agents), actuators, robots or computers to the gateway and enabling optimized heterogeneous communications devices meeting several communication demands.

The Software environment for the gateway is automatically generated via OpenRobotix ([1]). OpenRobotix is an extension of the OpenEmbedded development environment and the Angstrom distribution to meet the needs of miniature (mobile) devices including robots. It generates a complete software development environment and memory images for autonomous systems. The software interface to the gateway is based on Player and allows an easy integration of all important gateway information and configuration into the base station and the robot system. This interface allows the base station to monitor the wireless connection neighbours of a gateway or gives the robot the possibility to detect connection lost to automatically switch to non-communicate swarming. The modular software and hardware environment allows the direct equipment of the gateway with additional sensors and simplifies the integration of these sensors into the network via a Player driver. The integration of computers and robots (clients) into the ad-hoc network take place via the mobile ad-hoc communication gateway. This gateway is connected via USB to a client. Over this USB connection an Ethernet over USB protocol is implemented. This protocol is supported by the Linux Kernel USB Communication Device Class (CDC) driver and therefore no additional driver is required on the client. After connecting the client to the gateway the client creates a virtual network interface and configures this interface via standard DHCP. Through this interface the gateway module assigns an IP address and default network gateway to the client. The IP address belongs to the gateway and allows a simple identification clients via the gateway address. The gateway module automatically publishes this IP of the client to every gateway in the whole network and thereby makes it available to the other clients in the network. The default network gateway configuration causes the client to route all network communication to the gateway module. Through this technique the complete routing of the communication is transferred to the gateway and thereby to the mobile ad-hoc communication system. Altogether enables a standard TCP/IP based network communication between the gateway and client as well as client and other clients in the network.

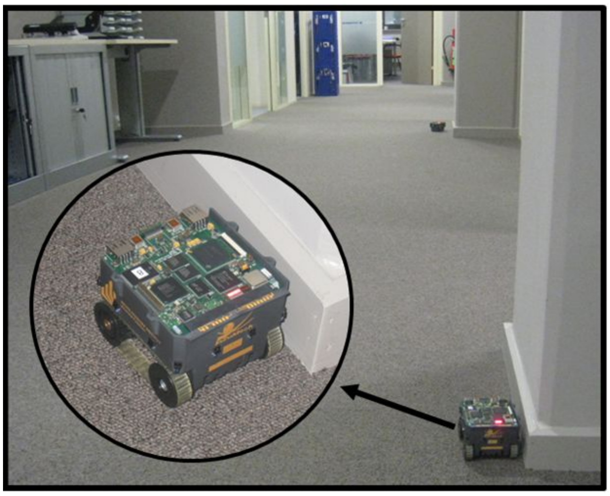

Figure 7: The Bebot robots forming a chain of communication nodes. Long distance communication is realized via multi-hop transmission.

As an important feature this simplifies the integration of arbitrary nodes into the mobile ad-hoc network and separates as well as hides the network implementation from the application, e.g. all robots, base station, networked position beacon.

Small size but versatile robots called Bebots [28] have been developed for implementing mobile ad hoc networking, refer to figure 7. The robots support the standards WI-FI, and Bluetooth. Compared to Bluetooth, ZigBee provides slight power consumption savings, which is not critical in our case scenario. Therefore, ZigBee was omitted which also eases design complexity. In addition we have tested a Sub-1-GHz (CC1110 by Texas Instruments) communication technology that provides different wave spreading properties compared to WI-FI and Bluetooth communicating in the 2,4 GHz band. Sub-1-GHz technology in our case is considered to be a fall back option if the 2,4 GHz band is jammed: simple status data can be transmitted to reestablish WI-FI communication but with lower throughput.

Topology and routing

Many methods have been developed for topology control and modification of ad-hoc networks. The routing techniques are divided into two categories: routing in infrastructure-less MANETs and routing in MANETs with relay nodes. In infrastructure-less MANETs routing can be based on a positioning system for instance on GPS, however GPS is not applicable indoors. Alternative methods aim to set up graphs to form a triangulation. The backbone can then be defined for instance as a minimal spanning tree of the graph. As the topology of the network is not fixed, the routing method has to define and redefine the topology. This can be done by frequently distributing (up dated) *Routing Tables* or by flooding the network with *Route Request* packages.

Nowadays there are two main routing protocols used in most sensor and ad-hoc networks applications; pro-active and re-active routing. Of course there are other types like hybrid and hierarchical, but these are more complex and are used mostly for large or other specialized networks. First we thought of using re-active routing since it is simple, fast and bandwidth efficient, but after performing simulations, and since our scenario requires transmission of critical and real-time data, we decided to switch to pro-active routing [61]. Pro-active routing protocols are divided into two main families: Distance Vector (DV), which relies on distance measurement for routing, and Link State (LS), which is newer and more preferred nowadays since it relies on reliable links rather than shortest distance only. In LS protocols, each node needs to store two tables: NB (neighbour) and R (routing) tables. NB table is obtained using neighbour list passing method; where each node passes its neighbour list to adjacent neighbours. After one communication cycle each node will be able to store a list of its neighbours as well as nodes in two-hop distance and after x cycles, each node receives the full NB table of the whole network. The routing table (R) is obtained by storing the next hop for each destination node. Some new LS protocols had emerged like Optimized Link State Routing (OLSR) and Fisheye State Routing (FSR), trying to reduce number of nodes used for routing and forwarding messages. This has the advantage of: reducing message flooding, reducing message overhead and size, and providing more stability and robustness. The first implemented LS algorithm is called Global State Routing, which uses all nodes for forwarding messages for the periodic updates. OLSR uses fewer nodes (called multi-point relays, i.e MPRs) for forwarding messages for better bandwidth usability. This makes it appropriate for mid sized networks with high mobility, like in our case scenario. FSR on the other hand, instead of reducing number of nodes used for forwarding messages, it reduces the number of flooded messages itself. This is done by assigning higher refresh rates for nearer nodes rather than (far) distanced ones. OLSR protocol is chosen for our scenario. As a firmware, OLSR daemon is used, which is widely tested and approved. The code can be easily modified to switch to FSR or back to GSR. Also both FSR and GSR need to be tested, and the one providing the best performance for our scenario will be finally chosen and optimized [18].

The first successful trial of our ad-hoc mobile network used the three robots currently available and a base station. Initially robot3 was put in such a position that it could not directly connect to any other robot. Robot2 was via robot1 connected to a base station and could be operated from the base station with a joystick. Figure 7 shows robot1 and robot2, while the base station is in the room on the left of robot1; robot3 is around the corner on the far end. Exploring the area, at a certain point in time robot3 was found, that is to say it got into contact with robot 2. At that point the communication backbone reconfigured itself with robot2 becoming a stationary node. Figure 7 shows robot1 and robot2 as stationary nodes forming the communication backbone. Subsequently robot3 became the exploring robot, with the joystick getting control over robot3; thus we have in principle shown how the robots could restore contact with a lost fire fighter. In this example a line of robots has been formed to extend the communication range. For covering a large space in the warehouse and to realize redundant links a mesh consisting of triangles is formed.

5.2 Localisation and Mapping

Our routing method for the ad-hoc network is based on infrastructural nodes. These nodes will manage the whole communication network, including monitoring the movements of robots, storing their location data, assigning communication channels and establishing data links. However, these robot nodes first have to be distributed over the operation area. We briefly describe the basic ideas behind the so-called dynamic triangulation method which we are developing. More details on optimizing the placement of the robots based on the dynamic triangulation scheme are given in [60].

Localisation

The challenge is to place the robots as communication nodes but also as localisation beacons in well-defined positions in a largely unknown area [60]. Note that only a rough basic map of the building is available. We apply a procedure for entering and dispersing that attempts to avoid the disconnection problems. As explained above, disconnected robots have a serious problem.

We aim at a final distribution of the robots in a mesh of triangles, where each node is connected at least to two others. In order not to get disconnected, each robot has to check the strength of the wireless signal frequently (RSSI) and when applicable search for a (better) signal. In case of periodically data transmission the packet loss rate is used as an additional measure for the connection quality.

To aid localisation a beacon structure forming mesh of (nearly) equilateral triangles of beacons is preferred. Our procedure for (*dynamic triangulation*) [59] is as follows. The first robot enters the building and stands right next to the door. This robot will remain there throughout as the main reference point for the exit. The second robot enters the building, moves a predefined distance along the wall and stops. The next robot, robot three, navigates to its position, the third vertex of the equilateral triangle, using the first two robots as beacons. In order to take advantage of the security offered by the walls, the mesh is in first instance rolled out along the wall. Therefore, robots move along the walls and every second robot is assigned a position along the wall. In case obstacles prevent a robot from getting to its required place, an alternative position is taken and the network topology reconfigure autonomously. Figure 8 depicts a developing network and shows the triangles of nodes and the communication lines between relay nodes.

The robots are to operate in a possible smoky environment and measuring distances for the (temporary) placement of communication nodes might not be straight forward. We apply two approaches to measure distances. The first approach is based on a radio communication technique using the so called NanoLoc-chip from Nanotron. This chip is able to measure the time of flight of signals (two-way ranging) between nodes resulting in distance measurements with an accuracy of about 1 meter in indoor scenarios [18, 40]. In the second and parallel approach we use a laser range finder (LRF), to obtain when possible more accurate data.

Mapping

The major objective of the GUARDIANS project is to provide guidance to a fire fighter. Mapping of the warehouse has to support this, but we are not aiming

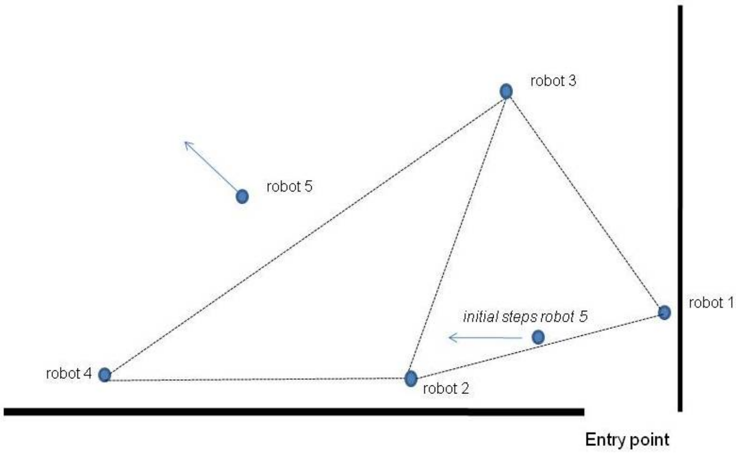

Figure 8: Distribution of infrastructure nodes. Dots symbolize robots, robot 5 has entered and is extending the covered area.

for a full map. A rough map of the building is available, refer to section 2, and a coarse indication of the position of the fire fighter and the robots on the map is sufficient.

The communication backbone is a dynamically evolving graph which also provides a basis for relative position determination of the swarm members [31]. The radio communication is not hampered by the smoke, thus the distances between the static nodes can be quite large. Within this grid the other swarm members are operating. As measurements might be failing or be very inaccurate, we initially consider the topological map as carrying no metric information. The moving robots will be able to measure the shorter distances among themselves and some of the beacons. Thus, the topological information is enhanced by metric information, and the initial topological graph transforms into a geometric graph. Imposing on this graph further information gathered by the robots will yield an initial 2D metric map, represented as a collection of non-regular occupancy grid cells.

An advantage of multi-robots teams is that multiple robots may produce more accurate maps, by reducing cumulative sensorial errors. Using the communication link, we have analyzed exploration algorithms which provide a significant speed-up for multi-robot exploration of (warehouse) areas. The underlying navigation technique is based on a local navigation strategy which provides full area coverage if a communication system is available and positions can be determined based on a map building process [4, 5].

After the distribution of the robots in the environment the network layout can indicate the boundaries of the environment as well as obstacles present, refer to figure 9. When no visible obstacle is present the network forms a complete triangulation. Small obstacles might be hidden within a triangle, but larger obstacles are detected as communication links are missing (holes in the triangulation, or cycles of more then three nodes in the local network). In order for a hole to indicate an obstacle with a sufficient probability, robots are

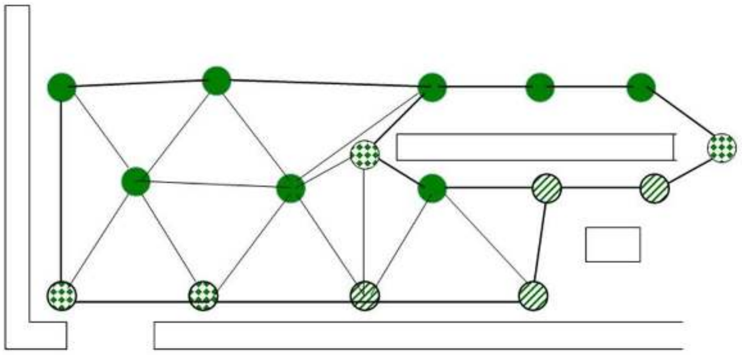

Figure 9: A full triangulation with obstacles. The dotted robots are beacons, striped robots represent possible beacons. The thicker solid lines indicate the boundary of the environment, covered by the built network.

not allowed to move further than half of the maximum distance at which they still can communicate. Estimates of the angle between two neighbouring edges contributes to the map building process. The capacity to measure angles can also help with building a local network and increases the robustness of wireless communication. Positioning using only the radio signal is intended as a fall back. We may assume that the robots not always find themselves in the worst scenario and other sensors will provide supporting metric information.

6 Assistive Swarming

The aim of assitive robot swarming is to support human led rescue operations. In section 4.2 we have described the behaviours of a team of robots in the presence of a human being. At the basic level the human interacts with the robots as he moves; the robots react autonomously to these moves. Thus, the interaction from the human to the robots is very direct and does not require information transmission via the wireless communication system. A fire fighter is an exceptional swarm member, being the predominant in terms of autonomy, skill and authority. In terms of behaviour, this means that the robots will in effect surround the fire fighters and move with them.

In the current section we look at the other interaction aspect, that is the feedback from the robot swarm to the human. For this we have to presuppose a solid (one way, short distance) wireless connection from the robots to the human. The main research problem in this context is how a fire fighter is to understand and benefit from the surrounding robot swarm. In formulating the problem and designing the interface the fire fighters have been consulted.

On occasions that a decision is made to search a big warehouses, fire fighters use a guideline, refer to figure 1. Individual fire fighters attach themselves using a personal line (1.25m) to the guideline or to each other. Despite the precautions, such operations are very risky and there is often a drift in the movement which results in not being able to comprehensively cover the intended area.

As noted in section 2 there are significant challenges to work effectively with robots while searching.

- The search environment is highly oppressive presenting ergonomic and communicative design problems for direct human robot interaction.
- The robot behaviours should complement the existing protocols to enhance the search and rescue tasks and not be disrupting.
- Fire fighters are working under considerable mental and physical stress. The swarm of robots should not increase the navigation related load (physical or cognitive) of the human being.

The swarm is intended to support the navigation of the human. Also, and not less important in search and rescue situations, the swarm maintains the communication connection and may warn for chemicals. The tasks of maintaining connectivity and warning for chemicals do not require intensive interaction with the human being. Navigation support however, assumes continuous interaction. The swarm may assist the humans to the exit point, towards the scene of operation or towards any specific area of interest. Nevertheless, since the safety of the human fire fighter has priority, safety critical information ranks highest. The indications of hazards should be most noticeable, while direction guidance has lower priority and should be noticeable but should not distract the fire fighters.

The interaction between the swarm and the human has to be simple, direct and coherent. The interaction of the human with the robots takes place as the robots react autonomously to the human's movements, as described above refer to section 4.2, this requires no additional effort from the human. Regarding the feedback from the robots to the human being, the environmental conditions restraint the human senses and the interface cannot fully rely on the commonly used audio-visual communication means. The feedback interface is therefore designed in two stages. We first developed a visual device installed within the fire fighters' helmet. Currently, in the second phase, we are developing a tactile interface that can be installed on the fire fighter's body. Below we discuss the design of the visual interface and the experiments carried out with professional fire fighters of South Yorkshire Fire and Rescue as subjects. The conclusions from these experiments are also relevant for designing the tactile interface.

The swarm of robots determines a direction for the fire fighter to follow. It takes into account the fire fighter's position, the position of possible obstacles and the destination position. Based on this information and the fire fighters pose the direction is calculated and visually illustrated to fire fighter.

The first operating hardware prototype of our *Light Array Visor* consisted of an array of LEDs mounted on a helmet, refer to figure 10, left photograph. The light array depicts a direction straight forwardly: illuminated LEDs indicate the safe direction. The device was used in experiments with several professional fire fighters. Following some brief training, the fire fighter was asked to undertake regular search and rescue activity with the understanding that the visor lights can help provide the best direction to follow. To create a more realistic context the fire fighter was asked to engage in additional tasks: (i) counting the number of times another peripheral light flashed, while also (ii) verbally reporting to the experimenter about his progress. The second task reflects common practice in fire search where colleagues continuously report verbally to one another about

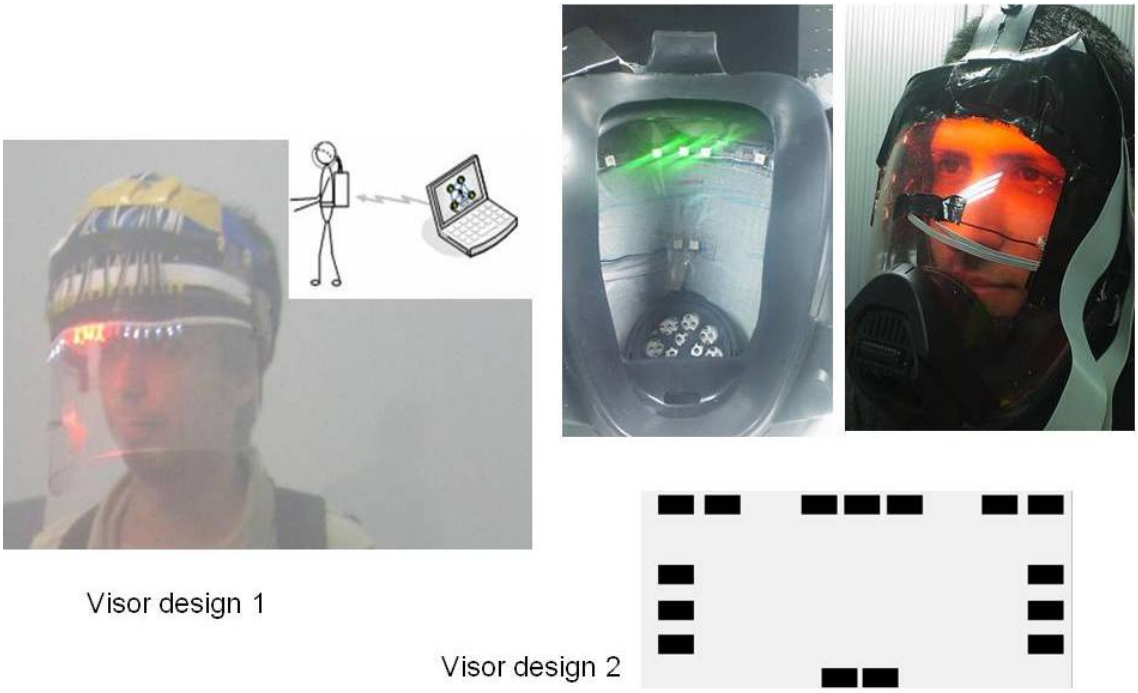

Figure 10: Left: the first prototype array visor with LEDs; version 2 of the array visor with LEDs .

their progress. After the trial the fire fighter was interviewed about the process and encouraged to critically assess the light array visor and the manner in which it operated.

In the trials subjects' performance with respect to the distracting additional tasks was on the whole good. However, adhering to the lights as direction indicators was poor, on occasions subjects moved ignoring the direction indicated by the lights. Subjects expressed a strong preference for a simplistic and unambiguous direction indicator. This was substantiated by one subject suggesting the direction indicator to be limited to basic angles such as -90, -45, 0, 45 and 90, and also suggesting that flashing lights would be help indicate when a change in direction is recommended. It was also pointed out that confidence in position and bearing is extremely important in real fire incidents. In search and rescue protocols keeping position and bearing is enabled by keeping to, and following building walls. In the trial setting the familiarity of a wall or any other physical landmark to provide a bearing was avoided. As a consequence the fire fighters suggested there was a lack of realism and the light array did not provide any indication of bearing that they were confident with. Being away from a wall or a physically stable point of reference is particularly problematic for fire fighters. Very rarely will they do this because of the risk of disorientation and its potentially fatal consequences. In subsequent discussions, it was suggested that the swarm would be more useful if it could provide directions to and from the wall.

The second version of the Light Array Visor was developed using a real op-

Figure 11: Searching fire fighters in a trial of the second version visor

erational fire fighting helmet. The style of the interfaces is adapted and consists of RGB LEDs positioned in a logical layout, refer to figure 10, photograph on the right. In the second design an internal measurement unit (IMU) sensor was also integrated in order to detect the human's orientation while following commands, in the trials the operator did not have to compensate if the fire fighter turned unintentionally. In the second trial a group of two fire fighters was asked to take part in the trial as fire fighters are used to work in groups of two or more. In addition, to add to the stress, two different coloured peripheral lights were used, each light flashed at a random interval and fire fighters were asked to count the number of the time each of them flashed. Similar to their usual practice, one crew member worked as the leader while the second followed his directional commands. The lead fire fighter was provided by the visor prototype and the second fire fighter was asked to follow the leader according to the reported commands. Both of them were blind folded. Also the two fire fighters were connected through a rope, refer to figure 11.

The result clearly showed that fire fighters were under more stress, they also mentioned the stress load and the attention they had to pay to the flashing lights to be able to count them, while trying to navigate and report at the same time. As it was observed, the fire fighters managed to correctly follow the commands, although there were drifts, and in such cases the data provided by IMU about the Leader's orientation was used to update the navigational commands displayed on the visor. Different from the first trials, in which the direction information was continuously up-dated, in the second trials the commands were sent less frequently. An interesting result was that in the follow-on interviews there was a clear shift in fire fighters attention from how the interface (that is the visor) should operate to what information it can provide using the robot swarm and what other functionality the swarm may support. This result can be interpreted as a constructive progress in allowing the end-users to become more involved in the exploratory design process. Again the point was raised that it would be useful to the fire fighters if the provided information would enable them to come off the wall when searching. Also, it was mentioned that it would be very useful if the swarm/visor could simply show them the direction to go when they are at the wall.

A general point is that fire fighters are highly trained select group, not to be confused with broader more common user groups. They are highly skilled experts and as such may have a different perspective upon the use and value of tools. Within the fire fighting context the tools used have to be reliable and well understood by the team. Their communication protocols tend to be precise, clear and well organised. In such a setting the expectation is that tools operate in a similar clear and well defined manner.

7 Conclusions and future work

Many current swarm-based projects seek to investigate the effect of swarming in theoretical and controlled environments. The Guardians project aims to take this to the next level by trying the research in a real-world application. We have selected to apply the robots in the scenario of a warehouse in smoke, which calls for a mixture of tasks.

We have first explained the algorithms making the robots follow a human fire fighter. These algorithms require no communication. Next we discussed the wireless communication system consisting of a continuously evolving ad-hoc wireless network. Several solutions for localisation based on a range of sensors are available, however within thick smoke most sensors are failing. The radio communication network provides a fall back, though very coarse it provides means to locate the robots and humans.

We also discussed the interface between a human and the robot swarm. The interaction from the human to the robots is very distinct from the interaction of the robots with the human. Simply by moving around a human being provokes reactions from the autonomous robots; the swarming algorithms provide this functionality. Thus we have designed a human to robots swarm interface requiring very little cognitive effort. The robots can transfer guidance information to the human. In collaboration with the fire fighters we have designed and tested several interfaces for obtaining guidance from the surrounding robot swarm. An outstanding issue is whether a feel of confidence can be created. When searching a fire ground, the fire fighters follow walls for position and bearing. Our experimentation with the fire fighters showed that it is against their sense of good practice to give up the bearing of walls etc. We have discussed tragic examples of human fire fighters who got lost in such circumstances.

Overseeing our work, the hardest problem seems to be localisation and mapping under smoke conditions causing poor visibility. A swarm of robots bringing in a variety of sensors and communication equipment provides advances. However, though the loss of a single robot could be acceptable, chances of losing the whole group would undermine the reliability of the solution. To reduce risks and to enable localisation and mapping under the worst conditions we decided to copy current practice of the fire fighters and utilise, wherever possible, building walls for orientation and bearing.

Future work

In this paper we have not discussed communicative swarming and olfactory based navigation, nor have we discussed the base station where date from all the robots come together. Currently, the different behaviours for the robot swarm are being developed separately. An important challenge of the research project is to integrate these to obtain smooth and seamless switching between the behaviours whenever required by the circumstances. In the testing with fire fighters we observed a lack of confidence. A human operator at the base station staying in contact with the searching fire fighter might be able to enhance the confidence.

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