GUARDIANS Final Report

Jacques Penders, editor

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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 report we discuss the technology developed for a swarm of robots searching and 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 one of the means to locate the robots and humans. Thus the robot swarm is able to locate itself and 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.

Contents

Note: The current report is the Final Report of the Guardians project.

Several parts of this report are updated sections from the paper: *A Robot Swarm assisting a Human Fire Fighter* (20 pages) which will be published in the Journal *Advanced Robotics*[54]. The particular sections are section 2, 3, 5, 6, 7 and 8

1 Preface, Remarks by Fire Fighters

In the course of the Guardians project we have cooperated with South Yorkshire Fire and Rescue (they are project partners) as well as with several other fire brigades. South Yorkshire Fire and Rescue were involved from the definition and proposal phase of the project as end-user advisor. They have organised a one day fire training at the kick-off of the Guardians and ViewFinder projects. The project members experienced this as very useful as it shaped their perception of what what a rescue operation involves. In return, the final demonstrations of the Guardians and ViewFinder were organised at the training station of South Yorkshire Fire and Rescue. Below are the major comments received from fire fighters reflecting on the research work.

The overall comment of South Yorkshire Fire and Rescue about their involvement in the Guardians as well as the ViewFinder projects is the following. As a Fire Brigade we do not have the means to be at the forefront of science and technology developments. However, we are looking at technology to help us improve our service. Improvements can be in risk assessment as well as direct support for the rescue operation. Being involved in these projects has made our officers better aware of available and up-coming technologies. The final demonstrations at our premises certainly got more of our staff involved to look at what was available.

Comments on the technology. Breathing Apparatus wearers progress at crawling speed. A group of robots guiding the fire fighters could speed up the search. Robots are considerably smaller then a human being thus their sensors operate closer to the floor where the smoke is less dense and temperatures are lower.

Despite advances in communication technology, the problem of maintaining radio contact in indoor incidents is still not solved; the ad hoc mobile network provides is a very interesting solution that seems to tackle the main problem of by passing obstacles in the radio spectrum. Such a network would fit in very well and enhance the communication system applied in the new Command Support Vehicle developed by South Yorkshire Fire and Rescue. The main idea behind this vehicle is to collect from and distribute to the officers (on site as well as off site) relevant and up-to-date information about the incident.

The base station developed would also be very well situated in this vehicle, and add to the info available during an incident.

Risk assessments relating to the possible presence of Hazardous Chemicals are very time consuming, robots with a mobile detection unit would certainly speed this up. The QCM chemical sensors has been designed for in-situ detection of low as well as high concentration of VOCs and toxic gases. Applied on a robot we can take more risks and contamination and in particular decontamination would not be as a big an issue as it is related to human beings.

Pictures of the early stage of an incident are very useful for forensic investigations and debriefings; however our staff is focussed on the rescue operation. Robots could simply store their data for post-incident off-line review.

European context. The two projects (Guardians and View-Finder) have presented their results to representatives of rescue services in the United Kingdom, Spain, Belgium, Poland and Italy. The usefulness of both projects was widely recognised. Also several problems were identified:

- The registration of on-site Chemicals is not uniform over the EU countries, several countries do lack good registration.
- An overall requirements list and possibly a set of specifications for intervention and rescue robots would be very useful.
- Training of staff to apply robots was indetified as a potential problem in several countries.

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 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 is 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 become 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 in its infancy. 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 [53, 55] 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. [29] 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 searching on its own or assisting human fire fighters. Obviously, 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

[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.

problems and discuss the results of our experiments with real robots. First, in section 3 we discuss the application scenario and draw some early conclusions which are guiding the further developments. Section 4 briefly describes the robot applied; adapted off-the-shelf platforms as well as purpose built robots.

Section 5 provides a brief overview of swarm robotics and the conditions under which the GUARDIANS robot swarm will be applied. Section 6 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 7 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 8 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 10 by drawing conclusions.

3 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 these senses are also restricted. The sense of touch is restricted by clothing gear and hearing is reduced by 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

[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.

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.

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 and 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) [36] of the human being.

3.1 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) but also for laser range finders (LRF) as our experiments confirmed [50]. 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

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

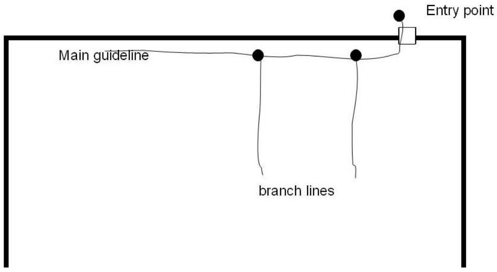


Figure 1: Basic principle for Guideline layout in a search operation.

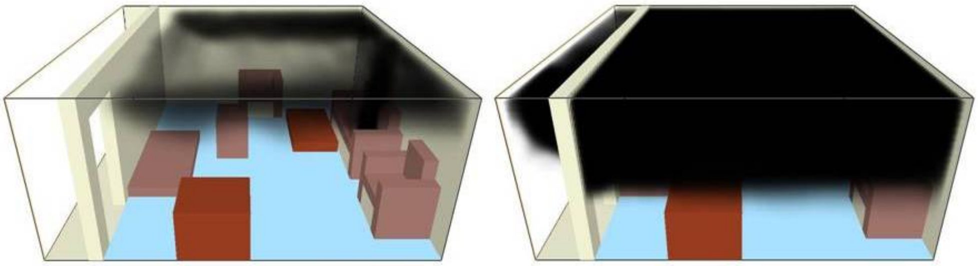


Figure 2: Smoke development simulation, left: the early stage where the sofa on the right catched fire; right: about 20 minutes later, thick black smoke is covering the room from the ceiling downwards.

(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 non-uniform. This can be validated with the well known simulator and simulation results from the National Institute of Standards and Technology (NIST) [41] 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. Moreover, closer to the floor temperatures are lower as well.

3.2 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 indoor localisation systems like GPS are not accessible. To enhance localisation beacons are required and a suitable trade off is being sought between beacons for both communication purposes and 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 [50]. However, we will not discuss olfactory-based navigation in this paper.

4 Robot Platforms and Sensors

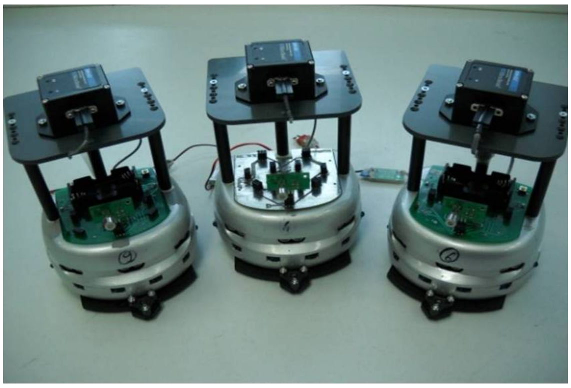
Four main robot platforms have been used for experimenting with the different aspects of the Guardians project. The off-the-shelf Khepera III (mini robot) platform of K-Team was applied for the small-scale experiments in map-building and olfactory-based navigation. The middle mid-sized platform Erratic robot was used for testing and validation of robot swarming and human robot-swarm implementations. A new mini robot called *BeBot* was built to aid advanced research in mobile ad-hoc communication. The real scale Guardian robot was developed within the project and is intended as the type of robot for operational implementation of the project results.

Cross-platform development was ensured by the choice of a common software platform based on the open-source framework Player/Stage. For each robot type the necessary Player drivers where developed.

4.1 Adapted off-the-shelf platforms

Regarding the Khepera robot platform, refer to figure 3(a), its ultrasonic sensors were upgraded to have better results. A new toolbox for Khepera III was presented (Khepera III toolbox from EPFL) providing better access to odometry. And the new linux Kernel 2.6 for Khepera 3 was completed and distributed. Among other features, it now supports USB cameras. As the GUARDIANS swarm is to be applied in smoky conditions two sets of sensors appropriate to detect gases, heat and flames was built and interfaced to the Khepera III mobile robot: the Khe-nose shown in figure 3(b) and the QCM sensors show in figure 13 and discussed in section 4.3 below.

(a)



(b)

Figure 3: Khepera III robots: left mounted with a Hokuyo laser, right with the Khe-nose

For the test scenario of the human robot-swarm interaction described in section 8 the Erratic platform was used, refer to figure 4. On top of the Player/Stage software an agent-based architecture has been programmed using the JADE framework. Different behaviours for fire-fighter localisation and following were performed. This work is described in section 6.

4.2 Purpose built platforms

BeBot. In the scenario to test the mobile ad-hoc communication network (discussed in section 7), the BeBot robot platform was used, refer to figure 5. This robot has been used to test the mobile ad-hoc communication. The BeBot has been developed at the Heinz Nixdorf Institute, University of Paderborn. It has a size of approximately 9cm x 9cm and a height of about 5cm. The chassis uses MID (molded interconnect device) technology and has traces directly on the surface which offers new possibilities for the synergistic integration of mechanics and electronics. This technique is used for mounting 12 infrared sensors and two microcontrollers, several transistors and resistors for preprocessing directly on the robot chassis. The drive of the robot consists of a chain drive. Together with two 2W DC gear motors with built-in encoders the robot offers robust motion even on slightly rough ground. The complete system is supplied by a 3.7V /

(a) (b)

Figure 4: Two experiments (a) Team of Erratic robots maintaining a formation; (b) Team of Erratic robots maintaining a flexible formation around a human being

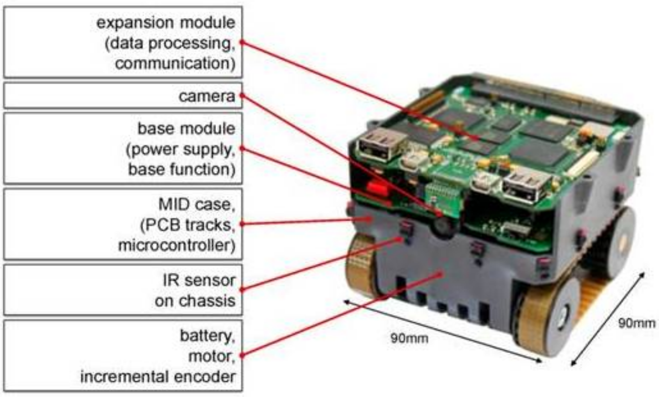


Figure 5: BeBot miniature robot with the main hardware components

3900mAh lithium-ion accumulator.

The BeBot has two slots for extension boards to implement a modular concept of information processing. The lower board (base module) implements basic functions like motor control and power supply. An ARM 7 based microcontroller allows low level behavior realization. The module also contains a three axis acceleration sensor, a yaw rate gyroscope and a sensor for battery monitoring. The upper slot (expansion module) provides a more powerful information processing and wireless communication. It is equipped with a low power 520MHz processor, 64MB main and flash memory. An FPGA (field programmable gate array) enables the use of reconfiguration on hardware level. This allows the computation of complex algorithms through the use of dynamic coprocessors. The integrated wireless communication standards ZigBee, Bluetooth and external IEEE 802.11 wireless LAN offer communication with various bandwidth and power consumption. The board provides a variety of additional interfaces and

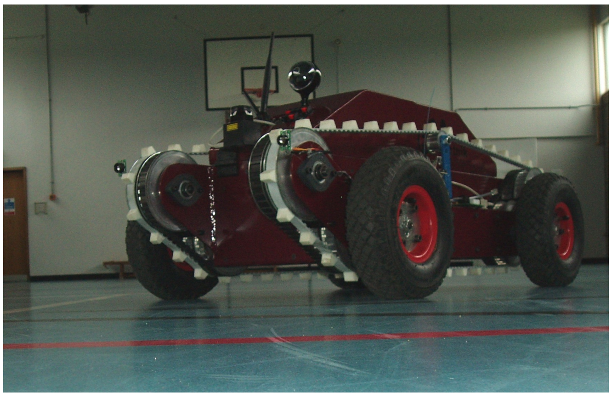


Figure 6: The Guardian robot, provided with Ultra Sound and Laser Rage Finder

expendabilities, like IC, UART, USB, MMC/SD-card, audio, LCD and camera.

The central communication device for the wireless network is HNI's gateway module. This mobile communication gateway is optimized for the mobile usage and therefore supports different techniques for energy saving. Some of these techniques are dynamic frequency and voltage scaling as well as dynamic power down of non-used hardware components. It is equipped with the new OMAP35xx processor, which delivers more than 1,200 Dhrystone MIPS at low power levels. The standard configuration supports the wireless communication standards Wi-Fi and Bluetooth. Based on a modular concept it can be equipped with additional Ethernet or NanoLoc communication. The latter communication module offers distance measurement between wireless network nodes. Additionally the wired communication standards IC, SPI, UART and high speed USB allows variable expansion of the gateway. Therewith it is possible to connect sensors, actors, robots or computers direct with the gateway and thereby with the communication network. The gateway can be connected to any kind of robot to act as a mobile communication device. But it can also be used as static device for example to locally capture sensor data and to transmit these data to the base station. More details of the gateway device are presented in workpackage 3 description and in deliverable D.3.5.

Guardian. The Guardian platform, refer to figure 6 and 7, has been developed by Robotnik within the Guardians project. It is a medium sized robot platform of a size and scale that allows application in a real case. Main features of the mobile robot are:

- Size: 970 x 570 x 395 (L x W x H)
- Max. Speed: 1 m/s
- Weight: 110 Kg
- Max. Load: 100 Kg

The algorithms and solutions tested in the small scale and laboratory environments using the smaller robots described above, are being transferred to the

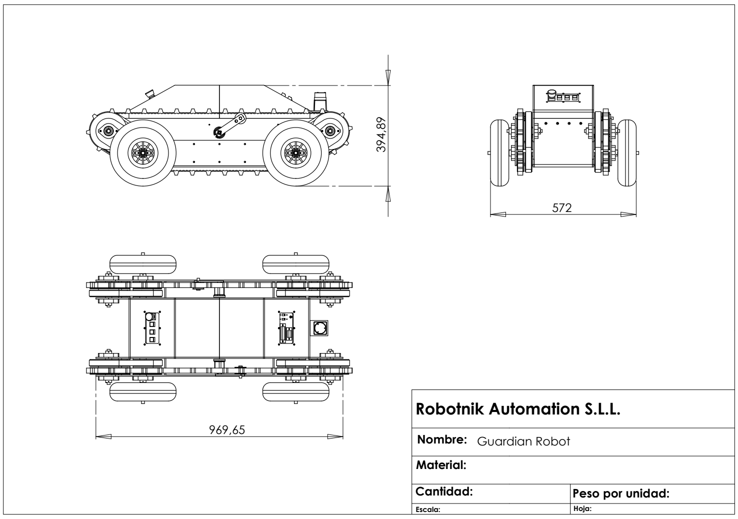


Figure 7: The Guardian robot, Main construction and Dimensions

Guardian robot. The Guardian robotic platform offers the possibility of testing in real user scenarios, meaning rough terrains, debris, slopes or even stairs. The Guardian robot could be applied for real assistance tasks as it provides high mobility, high speed and can carry firefighting tools. Further improvements focus on extending the capabilities for fire-fighting applications such as foam spraying and enhanced heat resistance. The robot has been tested to follow a human fire fighter using Ultra Sound sensors and a Laser Range Finder, these are described in subsection 7.5. It has also been used as part of the ad-hoc mobile communication network described in section 7, and the QCM sensors (discussed in the next section) are mounted on it as well.

4.3 Chemical Sensors

The possible presence of hazardous materials at an incident is a considerable risk factor. The Guardians project dedicated considerable work to the development of a sensor array for the detection of volatile organic chemicals (VOCs) in low and pre-explosive concentrations as well as for olfactory robotic navigation. Two types of chemical sensors are used (commercially available) Metal-oxide semiconductor (MOS) and home built quartz crystal microbalance (QCM) sensors. The MOS sensors are applied to detect low concentrations, while the QCM are appropriate for high concentrations. In the Khe-nose (refer to figure fig:khepera(b)) built by ISR only MOS sensors are applied. Below we describe the sensor array built by SHU, which combines both types.

4.3.1 Array of QCM and MOS sensors

In fire fighting the risk of the presence of an inflammable substance is divided into three levels, marked off with the respective dividers: LEL (lower explosive level) and UEL (Upper explosive level) as shown in Figure 8. In order to be

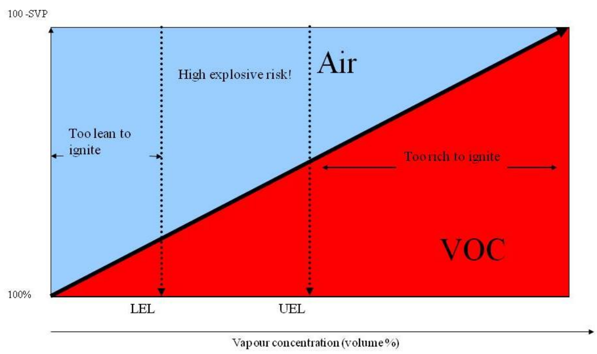


Figure 8: Graphical representation showing the flammable properties of a typical organic solvent, LEL and UEL levels.

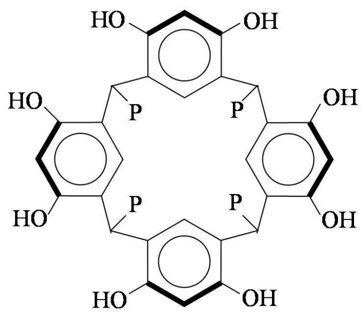


Figure 9: Calix(4)resorcinarene with 'P' representing the hydrocarbon tail composition.

effective risk assessors, the chemical sensors have to detect low concentrations as well as high concentrations. In the tests we performed, low concentrations are below the LEL and the high concentrations are above the upper explosive risk level (UEL).

We developed the sensor array to detect volatile organic chemicals (VOCs) in pre-explosive concentrations; the sensors are also used for olfactory robotic navigation. The QCM (quartz crystal microbalance) sensors are built utilising quartz crystals. They are spun-coated with different thin films of amphiphilic calixarene molecules to provide an array which is the basis for pattern recognition. By altering the length of the hydrocarbon tail, selectivity between target analytes has been achieved. Figure 9 shows the chemical structure of amphiphilic calixarene. These QCMs start responding when the concentration is below the LEL zone, but operate most effective when the concentration gets into the explosive risk zone.

The table in figure 10 shows the LEL and UEL for some selective VOCs where the both levels were determined out of 100% of vapour saturation for each individual VOC. The concentration is in the ppm unit. The coated QCMs sensitivity is VOC category dependent. Generally, sensitivity is reduced below

Chemical (VOC)	LEL		UEL	
	(%)	ppm	(%)	ppm
Hexane	1.1	1845.5459	7.5	12583.268
Ethanol	3.3	2932.215	19	16882.45
Acetone	2.5	5921.54	12.8	30318.285
Propane	2.2	434.247	13.7	2704.1745
Toluene	1	286.20775	7	2003.4542

Figure 10: the LEL-High explosive risk-UEL zone for each of the VOCs.

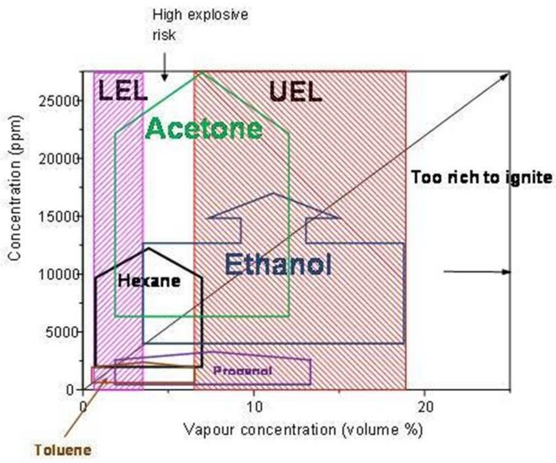


Figure 11: LEL and UEL for five different types of analytes.

the 500ppm level but sufficient for the levels above that. Accurate detection of common VOC's above 500ppm has been achieved, at concentrations below 500ppm a simple binary alarm system warns of a potentially hazardous leak and or explosive risk.

Figure 11 illustrates the LEL-High explosive risk-UEL zone for each of the VOCs considered in the table in figure 10.

Membrane recognition/sensor selectivity Analysis of the experimental data shows that the best combination of QCMs for analyte recognition is the following: *(i)* calix[4]resorcinarenes with alkyl chains of different lengths named C15H31 and C5H11; *(ii)* the same calix[4]resorcinarenes with alkyl chains of C4RA-C15 and C4RA-C5, *(iii)* tetra-tertbutyl calix[8]arene named as C8A-ttb. Figure 12 shows a 3D plot of the three QCM sensor responses and highlights the levels of separation between the analytes which leads to the individual detection identification and quantification Acetone, Ethanol and Hexane vapours. The space between curves and curve diversity approaches the recognition code of the analytes. The ANN was built to read this VOC diversity and identify.

Sensor recognition and reproducibility The sensitivity recognition code

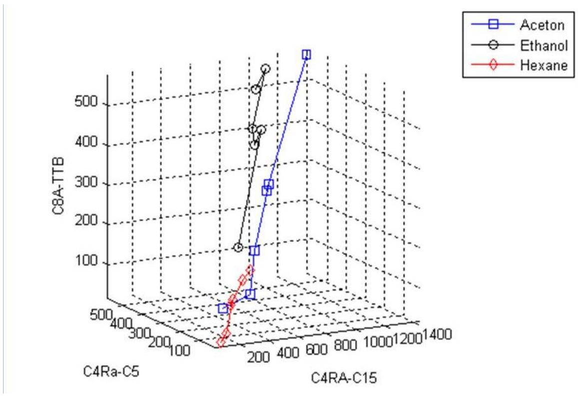


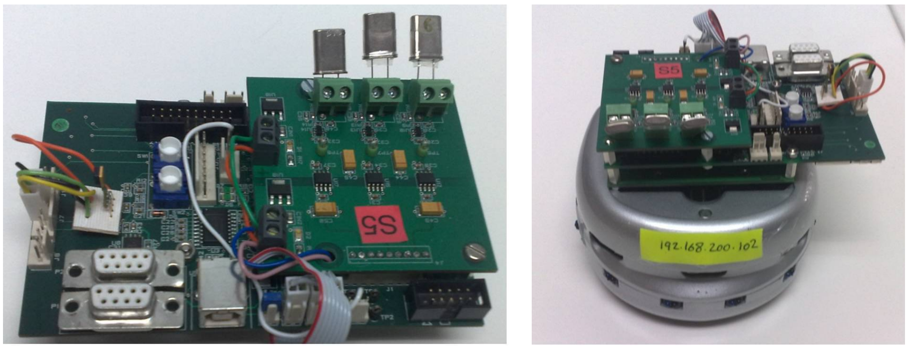
Figure 12: The concentration range of this recognition test is up to 40000ppm.

for Acetone, Ethanol, Propane, Toluene and Hexane were investigated many times to establish the reproducibility and stability of the coated QCMs (C4RA-C15, C4RA-C5 and C8A-TTb) for such VOCs. Some of the QCM provide high stability and a significant reproducibility. Whereas, the sensitivity of C4RA-C15 is varied between 0.006 to 0.008 for Acetone and 0.003 to 0.005 for Hexane and the sensitivity of C4RA-C5 s varied least (0.002-0.003), as shown in figure 12. This variation is still within the responding diversity of the coated QCMs and it is not affecting the recognition signal code reading. Further sensitivity codes are given in Deliverable 2.2.1.

Electronics Prototype Two prototype sensor arrays have been constructed consisting of QCM devices. The sensing membranes applied to the QCM have been optimized for the target analytes required. Prototype Printed Circuit Boards (PCB) has been produced and a microcontroller based data acquisition system has been developed. The sensor responses are output from the microcontroller using the RS232 interface to a PC where further data analysis and logging takes place. The first sensor array has been constructed using 8 QCM sensors; this number however was decreased later to comfort application on the mini robots. The sensing elements are separated from the driving electronics (on a different PCB) to allow controllable gas exposure within a purposely built FPGA. The QCM oscillators have been designed and fabricated in house. The QCM have been coated with a range of calixarene derivatives which provide very fast and fully reversible responses to the majority of Volatile Organic compounds (VOC), as we mentioned before.

A new prototype was required using less power and a small number of sensors than the prototype in stage one. This new board needs to be integrated to a small robot for gas navigation. Three QCM sensors were selected using the best combination of QCM sensors. The sensing elements are collecting the data and send it through the wireless communication to the base station for recognition analysis. Figure 13(a) shows the 3 QCM prototypes. The oscillator drivers were constructed on a separate PCB which is pluggable into the main processor board. The multi channel frequency counters and filtering were implemented using an FPGA.

Data from the FPGA is processed in the microcontroller this allows an easy



(a) (b)

Figure 13: The Chemical Sensors (a) 3 QCM prototype; (b) Khepera robot integrated with chemical sensors.

programming interface and access to a range of data storage (SD and internal flash) and communication interfaces (UART, SPI, I2C, CAN). The SHT71 temperate and relative humidity sensor has also been included on the processor board. This allows automatic compensation for either temperature or humidity if required.

For simplicity a basic UART link provided the data communication between the sensor and the Korebot. The specifications for the data format and interpretation of the data string are given in deliverables D2.2.1 and D2.2.3. A player driver by has also been implemented by KTEAM to receive and process the incoming data on the korebot. This prototype was interfaced and integrated to several robots. The mountings on the sensor processing PCB have been designed to directly align with the Korebot. The interface board maps the I/O on the sensor to suitable ports on the Korebot and supplies power from the Khepera base to the sensor PCB and sensor processing PCB. The complete assembled sensor mounted on the Khepera is shown in Figure 13(b).

5 Swarm robotics

5.1 Brief overview of the state of the art

Swarm robotics is a relative new field of research building upon the pioneering work by Reynolds [58], 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 work is relevant for our work and is discussed below. Other approaches focuss on basically autonomous individuals that can physically connect together to form a larger 'organism', refer to the EU projects S-Bot or Replicator. 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 [40, 9], aiming at motion planning [38, 39] 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 inappropriate. 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 [57, 18, 27, 25, 26], virtual agents or virtual structures [7, 47], probabilistic robotics [60], and others [61]. Some approaches use optimisation criteria from game theory for navigation control [64] and robot distribution or area coverage [13]. There are also works dealing with improving system performance through adaptation and learning [51, 62, 5]. 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, 59, 37] and a web database on swarm robotics related literature has been compiled at swarm-robotics.org.

5.2 Swarming in the Guardians environment

The GUARDIANS swarm is intended to support search operations. 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 [23] and coordinated navigation. The distinction between non-communicative and communicative behaviours is also referred to as a distinction between explicit and implicit communication [48], 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 members will soon be found. For the first two options localisation and some mapping (SLAM) is a prerequisite and the map must be (relatively) reliable. Case (*i*), returning to a pre-defined position, requires reliable mapping while the revisiting problem must be solved (refer to [24]) which presupposes that the environment has not radically changed. Given the problems to be expected, we have designed algorithms (refer to section 7) 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 and the GUARDIANS approach adds to this human originating tactical planning.

Our approach differs from 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 [22]. 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, whereas in GUARDIANS the human beings cooperate with several robots. Several authors are developing remote interfaces for monitoring a swarm [14] or for monitoring and remote controlling [43] 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. [29] 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 built 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 6) 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 be occupied with maintaining the communication network; the networking behaviours, which are currently implemented on purpose built Bebots, are discussed in section 7.

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 - also provides a basis for localisation and mapping under harsh conditions. In section 7.5 we explain the information that can be retrieved from the networking behaviours and how additional sensor 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 unidirectional, 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 8.

6 Non-communicative swarming

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 meaning that the robots are able to recognise each other 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 active robots, 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 [35] and refined in [33], refer to [27] for a modern description. For biological simulations often *self-propelled particle* (SPP) models [11] are used, first introduced by Vicsek et al. [63] to simulate biological swarms. Whereas - as the name indicates - the potential fields methods originate from field descriptions, the SPP models focus on describing the behavior of the individual agent similar to the model in [56]. Basically the two approaches are equivalent and should be able to generate the same behaviours. The two approaches are sometimes referred to as Gaussian (integrative field based) and Lagrangian (individual based) [49]. 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 [57, 28] and [32]. 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 [52]. 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 [50].

6.1 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:

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

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 in 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 [57], as their combination induces coherence in the swarm. At a particular distance internal attraction and repulsion balance; this is called the *equilibrium distance* [57].

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 [56].

6.2 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 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 15 the *field of view* of each robot is 360 degrees, resulting in a *circular* visibility domain. In the demonstration with erratic robots in figure 16 the field of view 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 [46].

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 [21], 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 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

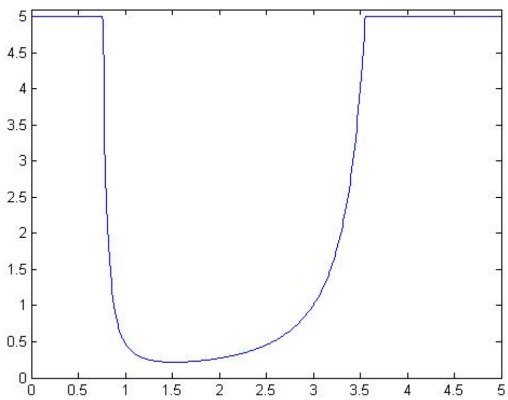
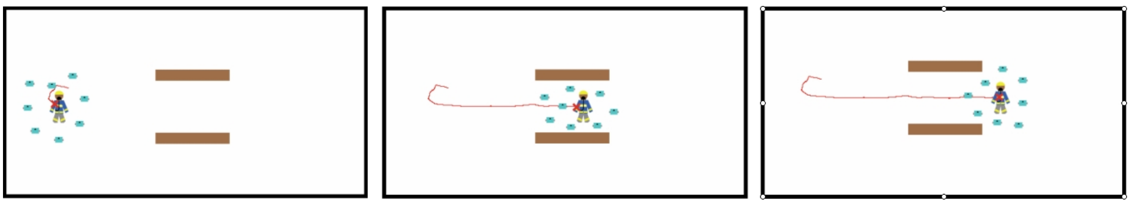


Figure 14: Example of the robot-human potential function; P_{Human} on the vertical axis, the distance d_r^H is on the horizontal axis.

H. The repulsive term prevents the robot from colliding with the human and the attractive term keeps the human within its visibility domain.

Figure 14 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 15 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 robots, which differs from the work of Gazi and Passino [28], where a predefined shape for a given number of robots is considered.



(a) (b) (c)

Figure 15: 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 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). 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.

Figure 16(b) shows the combination of software pieces that are used 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 JADE, making use of the JavaClient to access Player facilities.

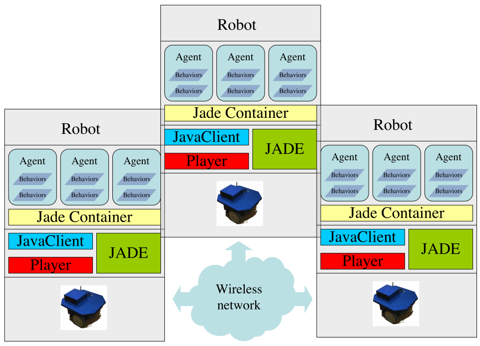
The implementations were demonstrated during the evaluation of the Guardians project's progress reviews in Brussels in January 2009, and January 2010 in Sheffield (UK) and were met enthusiastically by the audience. In Figure 16(a) video snapshots of the experiments on formation generation and keeping 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; figure 4(a) shows follow-up experiments with a human team member.

6.3 Olfactory Navigation

The Decentralized Asynchronous Particle Swarm Optimization (DAPSO) based high-level path planning is used as the basis for olfactory-based swarm navigation and search in an environment with real chemical (ethanol) gas. The objective is to build and visualize a real-time map of the chemical gas concentrations as well as determine high odour/chemical concentration. In order to improve the self-localization of the robots we have augmented the odometry of the robots

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

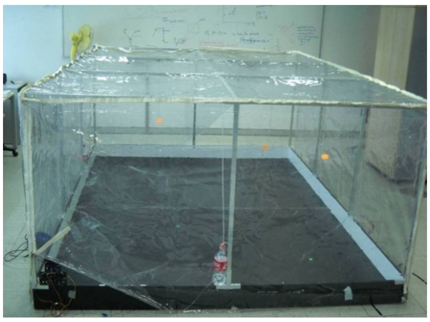
(a)



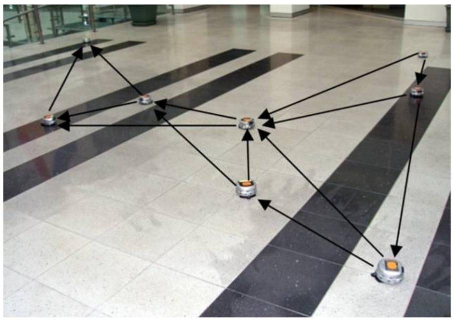
(b)

Figure 16: (a) Snapshot of formation generation Erratic robots around the leader in the middle; (b) Software packages applied in our team

with information from gyroscopes of Inertial Measurement Units (IMUs). Moreover, we have implemented a priority based robot-to-robot collision avoidance scheme. The navigation of the algorithms from one way-point to a next way point is based on potential functions.



(a)



(b)

Figure 17: (a) The experimental facility, Olfactory Arena; (b) Final robot positions in RSSI based triangulation.

The chemical sensor KheNose for the Khepera 3 robots was developed by UC-ISR. To achieve the main tasks substantial hardware and software integration and driver development (such as for example for the IMU devices to be used with the Khepera 3 robots) work was also performed. TCP and UDP communication routines between the robots and the robots and the main computer were also developed.

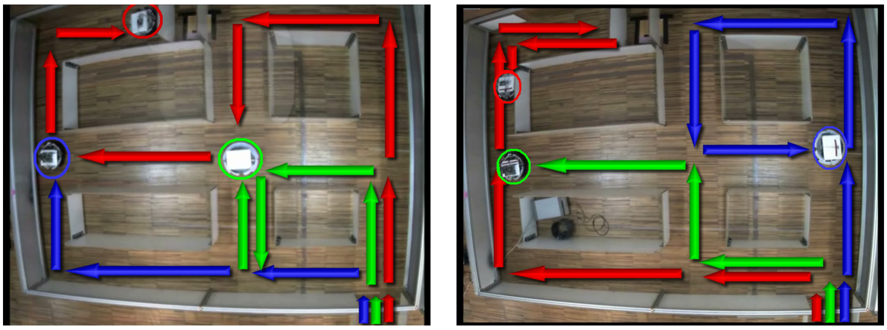
In addition to the Decentralized Asynchronous Particle Swarm Optimization (DAPSO) based search and olfactory swarm navigation we performed experimental work on RSSI signal strength based positioning and triangulation by a group of robots. In this experimental study the RSSI signal is viewed as a measure of the distance between robots and the robots try to position/triangulate themselves on an equal "RSSI distance" to the preceding two robots to form a regular triangular grid. We use a bacterial foraging inspired algorithm as a search strategy for positioning the robots. Moreover, in order to get better signal averaging we used three different strategies for getting the RSSI signal measurements and compare their performance. It is observed that the strategy in which the robots get several measurements on a circle with 25cm radius is fastest and results in a more regular metric grid. The motivation beyond this study is that in applications such as search in a warehouse on fire the communication distance (the RSSI distance in the study) might sometimes be more important than the metric distance between robots. Despite the noise and uncertainty in the signal measurements the robots were able to form an almost regular metric grid.

6.4 Sensor based exploration

The Guardians project aims to have two groups of robots; a group that explores the operative environment (unknown) based on the robots' sensors and helps the mission's supervisor to have a better knowledge of the building that is on fire; and another group entering latter that assists the firefighter, as it is explained in the previous sections. Since the first group is sent to the building before the firefighters, when the firefighters start operating, they will have more information about the environment's risks. The main task of the first group of robots is exploring the environment and generating the map of the building.

Exploration of an unknown environment is a fundamental issue in mobile robotics. Using multiple robot systems may potentially provide several advantages over single robot systems namely speed, accuracy, and fault tolerance. Cooperation, map merging, decision making, dealing with uncertainty in localization and reasoning, task sharing and navigation are the most significant research topics in multi-robot exploration. In [42] we have presented an approach for cooperative multi-robot exploration, fire searching and mapping in an unknown environment. The Method minimizes the overall exploration time, making it possible to localize fire sources in an efficient way. In order to achieve this goal, the robots must cooperate in an effective way, so they can individually and simultaneously explore different areas of the environment while they identify fire sources. The proposed approach employs a decentralized frontier based exploration method which evaluates the cost-gain ratio to navigate to target way-points. The target way-points are obtained by an A* search variant algorithm. The potential field method is used to control the robots motion while avoiding obstacles. When a robot detects a fire, it estimates the flame's position by triangulation. The communication between the robots is done in a decentralized control way where they share the necessary data to generate the map of the environment and to perform cooperative actions in a behavioral decision making way (details in [42]).

Figure 18(a) shows three robots exploring a small maze and finding an odor source. In this experiment there were no odor sources. All robots started from the same point but not at the same time. We intentionally ran the robots a few seconds after each other. The red footprint shows the first robot's path, the



(a) (b)

Figure 18: (a) Three robots exploring a gas free environment (b) Three robots exploring the environment and finding the odor sources.

blue footprint is related to the second robot and the green shows the footprint of the third robot. For an example of the coordination algorithm, when the second robot reached the junction it figured out that the path in the front was already explored and it chose the left path. The full algorithm is functional and it works in different maze structures and with different number of robots.

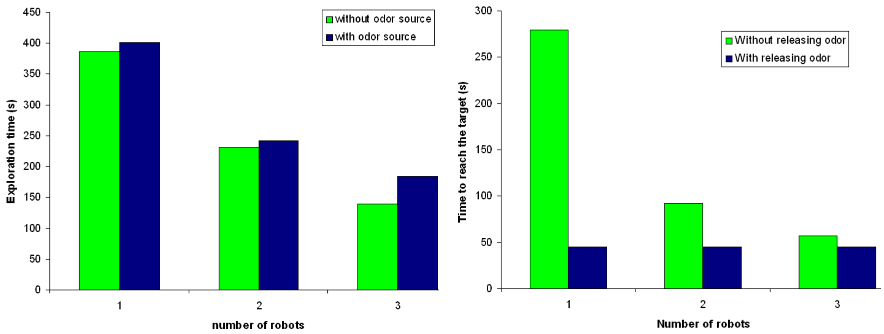
The same maze structure was tested with the same robots with adding an ethanol odor source in the left side of the environment. The results shows the effect of odor concentration on the behavior of the robots. Figure fig:realvisualISR(b) shows the path that robots took during exploring the environment. The first robot in the first branch made decision to go to the left-way because of a high clue of the odor and wind speed in that direction.

The most important parameter for evaluation of the method is the exploration time. The proposed method has been tested with a different number of robots in different mazes. The environment shown in figure 16 was tested by one, two and three Roomba robots separately, once without having any odor or gas source, and once with having an odor source releasing gas in the environment. figure **??** shows that the exploration time is a bit more, with having gas cues, however it is not a big difference and they are still comparable. figure **??** shows the time to reach the target (the location of the odor source) in these two scenarios. The chart shows that the robots reach the target much faster with having gas cues rather that without having it, that proves the functionality of the algorithm. Each result is the average of five similar tests. Different tests with constant conditions had similar results with about eight percent variance. The maximum speed of the robots were kept constant in all the tests.

Simulation

The search and exploration algorithm was tested in the real world and also in a simulation world.

The algorithm has been tested with different number of robots in specific mazes one with 34 nodes, one with 82 nodes and the last one with 135 nodes.



(a) (b)

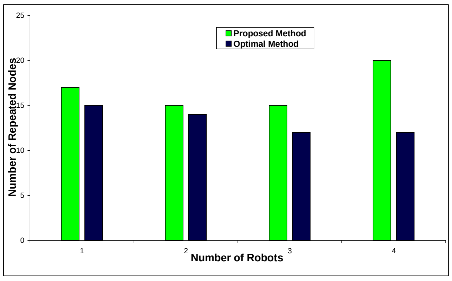
Figure 19: (a) TExploration time (b) reaching the target (the odor source).

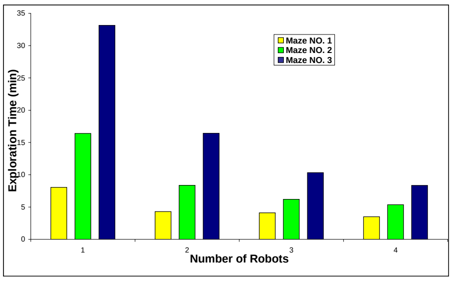
The models of those mazes are also given to the optimal method and then we compared the results of the proposed algorithm with the optimal results. Since the optimal method has the world's model but the proposed method is exploring the unknown world, it is obvious that the results of the proposed method are always worse than the optimal but this can be a good criteria for evaluating the method.

The number of repeated nodes during travel can be another good parameter for measuring the performance of the method. A repeated node is a node that robots pass more than once. Figure 20(a) shows the number of nodes that have been repeated more than once in the optimal method as well as in the proposed algorithm for the maze shown in figure 20. A good conclusion from the graph in figure 20(b) is that there is a trade-off between the number of robots and the size of the world. It shows that the proposed approach is acceptably comparable with the optimal method.

The mazes s have been tested separately with one, two, three and four robots and the results are shown in figure **??**. The graph shows the average of five tests for each data. The variance was less than one percent. It is obvious that the exploration time improves with higher number of robots. Another conclusion from the graph is that having more robots is more advantageous in a complex maze than in a simple maze. This also proves that the cooperation algorithm in this approach is efficiently functional. Since in the simulation there is no gas cues, the results of this part are very similar to our last presented paper [42].

In general terms, the proposed method for multi-robot odor source searching and unknown environment exploration has been implemented and experimented in realistic reduced scale scenarios. The exploration algorithm is modified by integrating odor sensing cues in the frontiers selection and has been tested in the real world. The robots navigate towards the odor sources and are able to localize them, cooperate and create a topological map of an unknown environment. The exploration algorithm has been tested against a large variety of configurations in Player/Stage simulation program. The effect of the number of the robots on exploration in different type of environment has been analyzed and discussed. The results show high efficiency and reliability of this method.





(a) (b)

Figure 20: (a) Number of repeated nodes, Comparing the results of the proposed method with optimal method (b) Test of various numbers of robots against complexity of the environment, 1: maze of 34, 2: maze of 82, 3: maze of 135 nodes.

The algorithm was tested in the real world with different configuration and different number of robots and the results show the effect of gas cues on the behavior of the robots and it proves that based on the proposed algorithm, robots first explore the area with higher probability of existence of odor sources.

7 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 or solid concrete present 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 (coarse) fall back.

7.1 Communication Infrastructure

A wireless communication network usually consists of access points and clients. The robots in the GUARDIANS swarm can act both as clients and as access points, i.e. all robots are equipped with a communication module that provides routing functionalities for forwarding messages but which may also 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 assignment of certain robots as access points 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 [6]. 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. More details on ad-hoc networking in multi-robot scenarios have been presented in [67] and [69].

Hardware platform

The physical communication device has been realized as a gateway module. The gateway manages all required functionality for operating a 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 dormant hardware components including wireless communication processing. Therefore the gateway is equipped with Texas Instrument's (TI) new OMAP 3 processor. The memory is implemented by a package on package solution on top of the processor. The integration of a commonly used Bluetooth and ultra low-power Wi-Fi single chip 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 technical implementation is described in Deliverable D3.5.

Software environment

The software environment for the gateway is automatically generated via Open-Robotix ([1]). OpenRobotix is an extension of the OpenEmbedded development environment and the Angstrom distribution to meet the needs of miniature (mobile) devices including robots. 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 and gives the robot the possibility to detect connection loss so that it can automatically switch to non-communicative swarming. The modular software and hardware environment allows attaching additional hardware to the gateway and simplifies its integration with 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) Ethernet 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

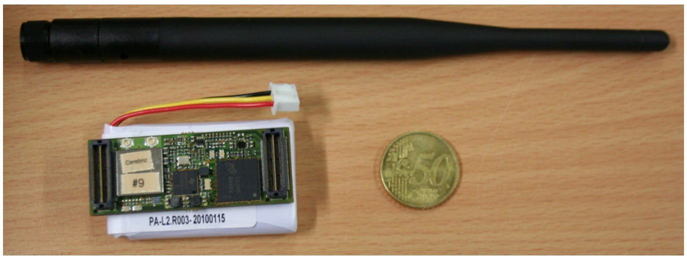


Figure 21: Separate parts (PCB, battery, and antenna) of the Gateway module and their size compared to a coin

and allows a simple identification of 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 this enables a standard network communication suite (TCP/IP) based network communication between the gateway and client as well as client and other clients in the network. 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.

Overall System

The whole communication gateway (excluding the antenna) is smaller than a mobile phone whereas the biggest part is the battery pack (figure 21). The big antenna is used to ensure good communication ranges even in hazard environments. The maximal power consumption of the gateway is approximately 2.3W which allows the system to operate for more than 3 hours from a 3.7V battery pack with a capacity of 1950mAh. The runtime can be extended by using a bigger battery. Furthermore the operating system of the system is not optimized regarding power saving at the moment but there is good potential to reduce the average power consumption below 2W. The price for the gateway in low volume production is expected to be around 250 Euro. Compared to mass produced standard router the price is higher but our gateway offers energy efficiency, multi standard communication, a USB interface which allowing easy integration and expansion with additional devices, actors or sensors (temperature and chemical sensors or servo and camera devices). The functionality of the device was shown during different tests and in the final demonstration in a real environments, standard offices as well hazardous parking garage. The gateway has been successfully tested in different environments and network configurations. Details have been presented in [31] and are documented in deliverable D.3.5.

Small size but versatile robots called Bebots [30, 68] have been used for implementing mobile ad hoc networking, refer to figure **??**. The robots support

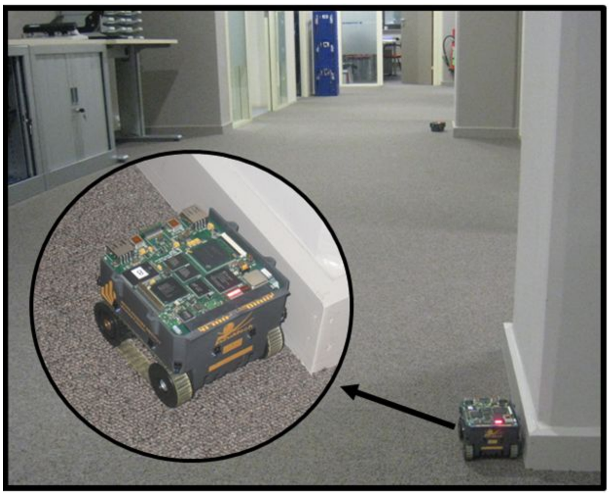


Figure 22: The Bebot robots forming a chain of communication nodes. Long distance communication is realized via multi-hop transmission.

the standards Wi-Fi, Bluetooth and ZigBee. Compared to Bluetooth, ZigBee provides slight power consumption savings, however ZigBee was omitted to ease design complexity. In our case Bluetooth is used to form a local network to avoid large latencies. But as shown in [17] it is possible to form large Bluetooth networks, called scatternets. 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.

7.2 Topology and routing

The routing protocol has to find valid routes between the source node and the destination node. Special for the Guardians application is that nodes may fail due to the harsh conditions (local fire or collapse of parts of the building). Nevertheless the choice of a communication routing protocol depends on many factors, like interior structure of the scenario area, complexity of network, number of nodes, route establishment time, maximum allowable message forwarding time, etc. An approach for large scale mobile ad-hoc networks has been discussed in [20]. But in the Guardians scenario, having an intermediate number of nodes in our network, and harsh conditions with areas full of metal obstacles, we choose the most reliable pro-active routing protocol. The newest pro-active routing protocols were found to be categorized under the name "Link State Routing Protocols". This kind of routing had the advantage over its former category, named "Distance Vector based routing protocols" that it does not rely for routing only on the shortest path between nodes, but also on the most reliable link (that is least likely to fail) and also the highest quality link (providing least number of packet losses). Combining all these parameters, a

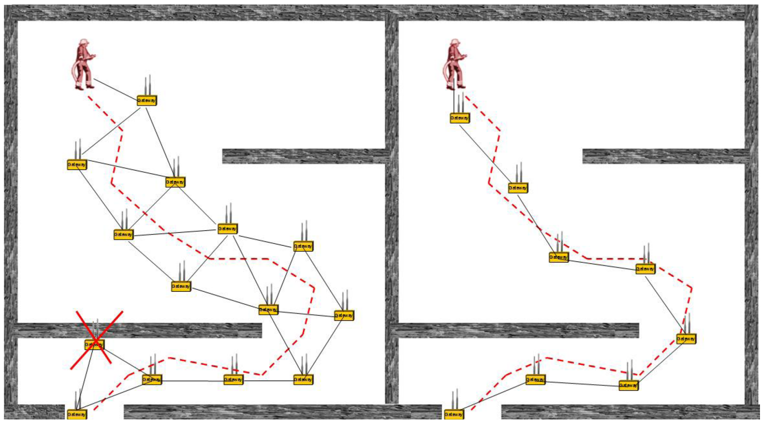


Figure 23: Considered options for spanning a network: multiple triangles (left) and line topology (right).

link state routing protocol chooses the best reliable routes to guarantee establishing very robust reliable connections within the network. The famous three link state routing protocols are GSR (Global State Routing), OLSR (Optimized Link State Routing) and FSR (Fish-eye State Routing). FSR is better suited for large networks, since it tries to reduce number of updates for far placed nodes than nearer ones. GSR and OLSR were found to be quite suitable for our scenario case, so we have chosen OLSR, which is supported using the OLSRD daemon firmware. More details about the chosen routing protocols can be found in deliverable D3.3.

In the Guardians project several topological distributions of robots were proposed by HNI-UPB and SHU, like forming triangulations or following in a line. We merged the two topologies together to form an adaptive topology, the first trial presented by HNI-UPB in RISE09 workshop followed by SHU in RISE10, The idea of the adaptive triangular distribution is shown in figure 23. In the figure, we can see the fire fighter moving in a narrow corridor at the bottom left of the figure. Here each two nodes try to guide the next node where to be placed to form the triangulation. In case of corridors, the robots switch to forming a line when a triangle cannot be formed, as shown by the discarded node crossed with red colour. After reaching a larger space the dynamic triangulation can once again take place, as shown in the figure while the fire fighter continues roaming to the upper left corner. On the right side of the figure the distribution of nodes is shown but forming a line only, as presented in HNI-UPB demo scenario 2.

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 8 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 22 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.

7.3 Novelty of the communication system

The main objective of the communication research in the GUARDIANS project, part was the development of a wireless system that is able to provide robust connectivity to the robots, the fire fighters and the base station. Robustness in this context means that in case of a failure of a communication node or a single link connectivity is not completely lost. In order to achieve this kind of robustness several options have been considered, like inherent redundancy (a), modulation and carrier change (b), node replacement (c), network shrinkage (d), role changing (e), non-communicative swarming (f). Details of the six mentioned methods are discussed in sections 7.2 and 7.1. 'Approaches and algorithms'. Important is that the network maintenance, node discovery, routing, message forwarding via multiple hops, selection of the underlying wireless technology is done automatically as core function of the communication devices. Thus, from the application point of view there is no need to have special knowledge on wireless networking. To achieve this, it is required to integrate and to encapsulate RF-processing including the physical layer, base band processing, and networking on an optimized processing hardware that offers high performance at low power consumption and small size. The developed gateway module is depicted in figure 21.

The minimum requirement for actively adjusting the network is information on link qualities between nodes. In our case the link quality is based on packet loss rate and received signal strength. The initial placement of nodes is based on a line of sight strategy. After entering the building robots are spreading out to form a communication line as a minimum communication infrastructure. The maximum distance between two adjacent nodes is chosen to have not only a link to the next node but also to the second next node (second neighbour). This enables redundant links, i.e., there can be a communication along the chain of nodes even in a failure of single nodes. To have a more robust network our favourite is to span a network of triangles along the walking line of the fire fighters or a leading robot. In this case every time there is more than one route available between a source and a destination. Special to our approach is not to depend on the packet loss rate and the signal strength only, but also on the distance measurement between nodes. Because laser based measurements can fail in case of smoke we have integrated a distance measurements system that is based on time of flight measurements. Technological basis are specialized hardware devices of the Nanotron company. Again, the required functionality is encapsulated in the communication device. But there is some optional feedback to the robot to be able to use measurement data for the adaptation of the robot's swarming behaviour.

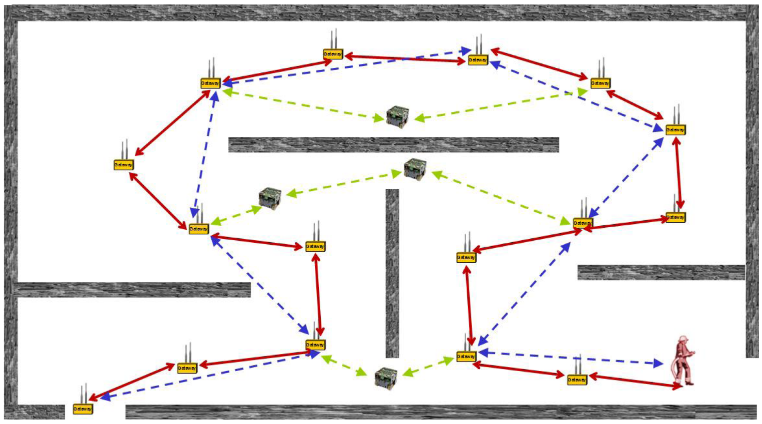


Figure 24: Example communication network with redundant routes.

Placement of relay nodes to guarantee end-to-end communication or quality of service

Another novelty point was the real implementation and testing of the communication protocol, including relay nodes placement. Building up a chain of relay nodes has been used and implemented in many projects before, but most of them used object recognition using cameras, and sometimes with the aid of laser sensors for more accurate distance estimations. In the Guardians project we tested various methods and sensors to support the fire fighter / robot following feature, which is part of the relay node placement. Here we tested and compared between ultrasonic, Laser, MMW-RADAR and the radio-based Nanotron sensors for distance estimation, besides testing of various robot recognition methods, via special pattern recognition or via detection of rays, etc. All details on this part are to be found in deliverable D3.5. In the node placement demo, robots perform fire fighter/robot following, and then when distances between them exceed the communication threshold, they change their role and act as relay nodes, to support multi-hop forwarding. This communication threshold can be either measured by the Nanotron system or using the RSSI of Wi-Fi. It is better to use a distance estimator relying on radio quality / quality like these two, and adjust the threshold to at maximum half the quality. This is to ensure that each node can reach at least its second (or maybe higher) neighbour, in case its direct neighbour was damaged or out of order. This is shown in figure 24, where the red links connect between direct neighbours, while the blue links are between second neighbours. Green links are additional links that are supported by other robots from the swarming team in case many of the relay nodes are damaged in one area. More details have been presented in section 7.2.

7.4 Recovery from failures of individual nodes

The wireless communication system must be robust in terms of availability of communication links and be able to recover from failures of individual nodes. Below six possible methods are discussed. We distinguish between infrastructure nodes and additional communication nodes that are part of robots or other

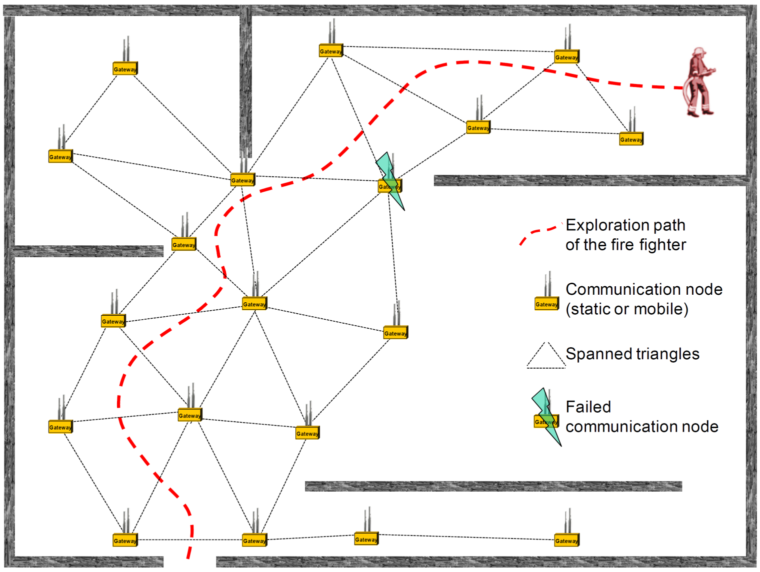


Figure 25: Network recovery in case of node failures is inherently done by placing nodes in triangular shape. Every node has as minimum two neighbouring nodes. In the case of a node failure links are still available and a route between two arbitrary nodes can be found.

devices that are not primarily intended to act as infrastructure nodes. The infrastructure nodes are used to form the robust communication network. These nodes are placed in the beginning of an operation to cover the operational area or as a minimum the path of the fire fighter. All nodes depicted as gateways in the following figures are considered to be infrastructure nodes. Without a network failure they are static with the option of movements in case of node of link failures. Robots that are equipped with communications devices being not part of the infrastructure system are denoted as clients using the infrastructure for communication. The different movement options and behaviours in case of failures are discussed in the following paragraphs.

Inherent redundancy (a)

For the approach of 'inherent redundancy' as many nodes as required are used to fully cover the operational area. During the initial placement of communication nodes care has to be taken that a node is able to communicate to two other nodes as a minimum redundancy. In case of a node failure other nodes in the vicinity are able to compensate the node loss, see figure 25. The consequence can be a slightly degraded performance of the network, i.e., reduced throughput and increased latency because of additional interference between the nodes. In order to fully compensate the node failure one option is to replace nodes in the vicinity of the failed node or to guide a new robot into the area of the failed node as a replacement.

Modulation and carrier change (b)

If a broken link or failed node has been detected communications nodes in the vicinity can change their modulation. The important factor for the correct demodulation of a signal is the receive signal strength to noise ratio (SNR). Higher modulation bit rates need increasing SNRs because of the higher symbol rates and thereby lower distances between each symbol. As the signal strength and thereby the SNR decreases with the communication range also the communication range decreases with the higher modulation bit rates. Additionally different modulation schemes show different maximal ranges. We use this fact to adapt the communication range. At default the Wi-Fi communication in our setup uses the orthogonal frequency-division multiplexing (OFDM) modulation with a bit rate of 36Mbps. This allows a high throughput medium range communication. By reducing the bit rate to 11Mbps and changing the modulation to complementary code keying (CCK) the range can be significantly increased. As a result the throughput is decreased but a node is usually able to establish links that are more far away than the original one that is failed. Another option is to temporarily switch to another communication technology by activating another physical layer including necessary software stack. Our approach is to activate a communication technology in the area of the broken node that uses another carrier, i.e. another frequency band and modulation technique. At this fall back frequency the communication range is larger than one available at the default frequency. The drawback is the reduced throughput. As a consequence the transmission of live video signal becomes impossible, but status data can still be transmitted until nodes have been rearranged or a new node has been integrated into the network to replace the broken one. In our case the fall back frequency band is in the Sub-1-GHz domain at 915 MHz, that supports a data rate of up to 500 kbps over several tens of meters.

Node replacement (c)

In case a single communication line connects the furthermost robot to the base station the failure of a single node may disrupt the communication to the base station, see figure 26. Both separated networks are still able to operate independently, but effort has to be made to reconnect both networks. Our approach is to jointly move all robots that are part of the network being closer to the entry into the direction of the failed node. A new node will join this network to close the accruing gap.

If in figure 26 node N2 fails the nodes N3, N4, and N5 will jointly move in the direction of N2 until the connection to the second network built of nodes N1 and N0 is re-established. A new node from the pool of robots will enter the operational area to replace N5 at the entry. During the initial placement strategy every node has been placed that way that a minimum deviation from the line of sight condition is ensured. This strategy enables the moving robots N3 to N5 to drive into the direction of node N2 by using local odometry only. No global view is required.

Network shrinkage (d)

If enough communication nodes are available in the operational area a node failure can be compensated by readjusting the remaining nodes. Strategy is to

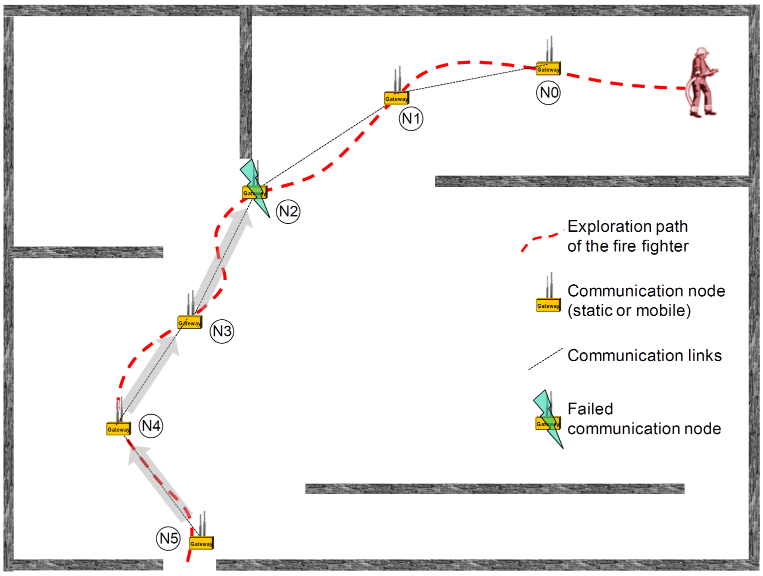


Figure 26: Node replacement by jointly moving of nodes N3, N4, and N5 to replace N2.

recover the network by minor positional changes of all nodes as depicted in figure 27. Nodes in the proximity of the failed node have to travel a larger distance than nodes that are further away. In total the topology of the network is kept similar to the initial one and big reconstruction is required thus minimizing the movements.

For doing appropriate network shrinkage a failed node can be theoretically compensated by the described node displacement scheme. The problem of this approach is to correctly know the direction of movement. It is assumed that the robots neither have a map of the environment nor their absolute positions. Only a topological map of the network without metric information and the link quality is known. As a consequence it is important to combine this network shrinkage approach with map building.

Role changing (e)

If an infrastructure node fails and some other swarm robots are close to the area with the failed robot a robot of the swarm can take over the infrastructure role of the failed robot. This means that the robot will stop moving, .i.e. swarming, and it will no longer assist the swarm in its former function. The advantage of the role change is that the network has some self healing properties, but the disadvantage is that the swarm algorithms have to deal with the loss of robots that should not be a problem if enough robots are available. Special care must be taken towards the delay between the role changes and the different thresholds otherwise the robots can start oscillating between the roles.

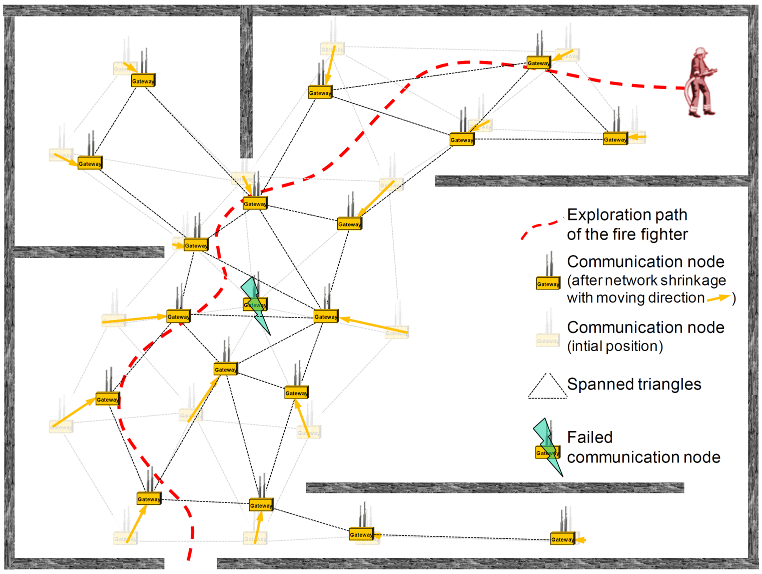


Figure 27: The broken communication node is compensated by network shrinkage. Mostly all nodes adjust their positions to re-establish similar signal quality as it was available before the node failure.

Non-communicative swarming (f)

This is the simplest approach to cope with network failures, because the idea is to passively replace failed nodes by a swarming behaviour. The initial idea of GUARDIANS as proposed in annex 1 is to have both communicative and non-communicative swarming behaviour. Non-communicative swarming has been considered as a fall back option if communication is lost. Robots being members of the robot swarm switch to a non-communication behaviour to be able to continue the operation. Assuming ongoing movements of the swarm performing environment exploration it may happen after a while that one or more robots of the swarm are able to connect to a node of the wireless network. If a communication signal is detected the swarm can try to move into the direction of increasing signal strength until a minimum strength has been reached. Now one robot of the swarm can change its role to act as an infrastructure node to extend the wireless network into the direction of the swarm. At this point the proposed approach is similar to the last one. The approach is depicted in figure 28.

A large portion of the operational area has already been covered by infrastructure communication nodes. A swarming team of robots is connected to the infrastructure nodes and it is able to send data to the base station as an application example. At the arbitrary time t1 four nodes of the network fail and the swarm is disconnected. As a consequence the swarm switches to non-communicative swarming. After a while one robot of swarm has reconnected to gateway G. Now one robot of the swarm can change its role to act as an infrastructure node and the network is party recovered. Drawback of this method is that it is not based on a goal-specific behaviour of the swarm. Therefore it may

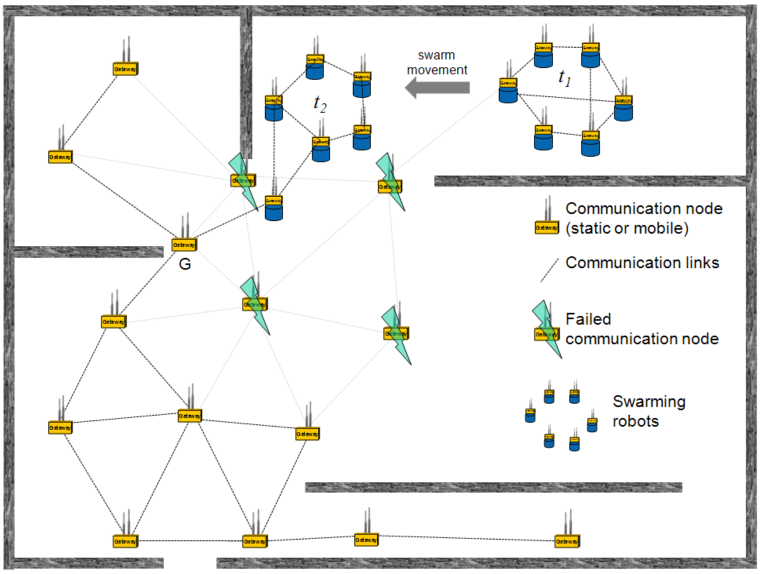


Figure 28: Passive network recovery by non-communicative swarming.

take some time before the swarm is reconnected to the rest of the network.

Conclusion

Taking all presented options for network recovery into account our current favourite is the inherent redundancy that is achieved by placing as many nodes as required to cover the operational area during an initial placement scheme in the beginning of an operation. After infrastructure nodes have been placed no major change in the node placement is foreseen. If it becomes necessary new nodes may enter the area to cover incrementally larger areas. A concept of goal-oriented replacement of communication nodes requires simple maps and better options for localizations as are currently available in the Guardians project. At this point future research is required to cope with non-visual conditions. The concept of inherent redundancy is able to cope with single node failures without large delays for network recovery that is an important aspect if humans - in Guardians fire fighters - are involved. As an additional concept to increase safety the gateways are optionally equipped with a complement wireless communication technology as described as method (b) 'modulation and carrier change'.

7.5 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 robot movements, 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 [66].

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 [66]. 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. To avoid disconnections, each robot has to check the strength of the wireless signal frequently (RSSI) and when applicable search for a (better) signal. In case of periodic data transmission the packet loss rate is used as an additional measure for the connection quality.

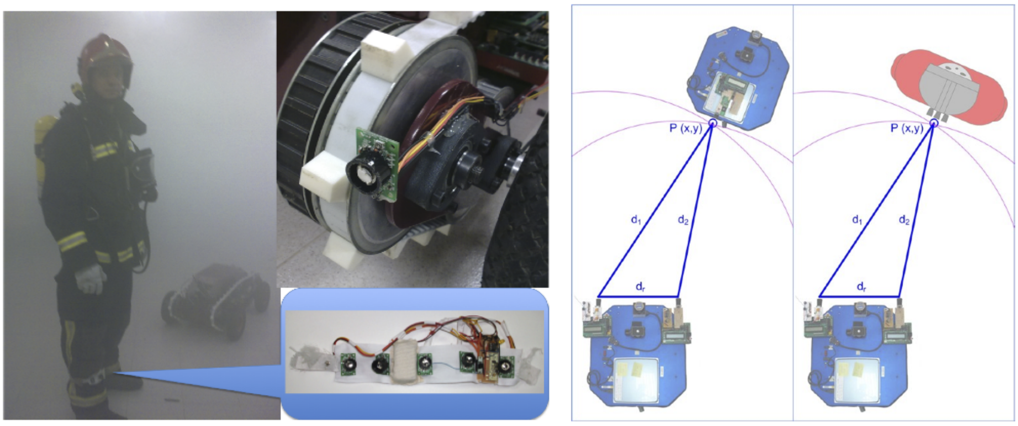
To aid localisation a beacon structure forming mesh of (nearly) equilateral triangles of beacons is preferred. Our procedure for (*dynamic triangulation*) [65] is as follows. The first robot enters the building and stands right next to the door. This robot will remain there throughout as the main reference 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 reconfigures autonomously. Figure 30 depicts a developing network and shows the triangles of nodes and the communication lines between relay nodes.

The robots are to operate in smoke and measuring distances for the (temporary) placement of communication nodes might not be straight forward. We apply three 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 [19, 45]. In the second and parallel approach we use a laser range finder (LRF), to obtain whenever possible more accurate data.

The third approach combines ultrasound and radio signals, in order to cope with smoke. Figure 4 shows a team of mobile robots accompanying a human firefighter. The team of robots maintains a flexible formation around the firefighter and follows him, while sending sensors data to the base station. Moreover, figure (6 shows the Guardian 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 figure 29a, the firefighter wears a radio/sonar transmitter around his leg (detailed under figure 29(b) , which enables calculating the distance and the orientation of the robot respect to the firefighter, with an accuracy of 1 centimeter. In figure 29b we can see the Person Following Behaviour in very dense 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.

Using two receivers mounted in front of each robot (see figure 29(b)) and separated by a known distance of dr, we can measure the distances from an emitter located at point P (refer to figure 29c). The point P is the position of the object that we want to locate (i.e. a robot or a fire-fighter).



(a) (b) (c)

Figure 29: Experiments with localisation in smoke(a)Firefighter interacting with the Guardian robot using a Radio/Sonar transmitter in his leg ; (b)Radio/Sonar firefighter localization and following in smoke using radio/sonar TDoA; (c) Localisation of a robot or firefighter by trilateration.

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 showed good performance when trying to follow a firefighter even in very dense smoke, and provide localisation data to the base station.

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 for a full map. A rough map of the building is available, refer to section 3, and a coarse indication of the position of the fire fighter and the robots on the map is sufficient.

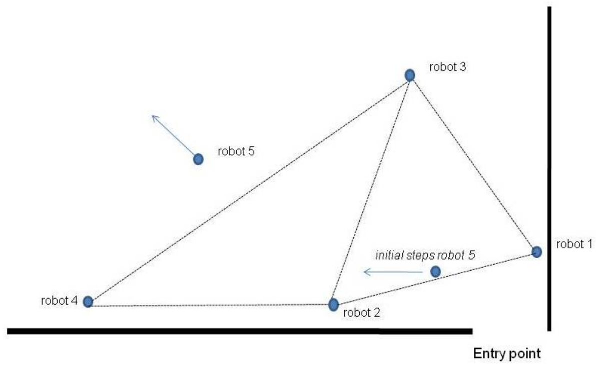


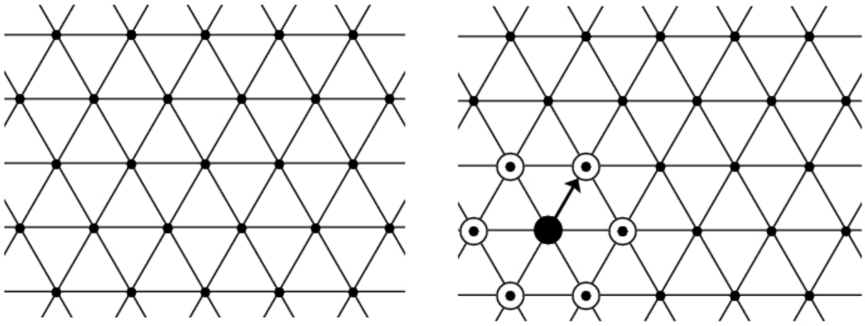
Figure 30: Distribution of infrastructure nodes. Dots symbolize robots, robot 5 has entered and is extending the covered area.

The communication backbone is a dynamically evolving graph which also provides a basis for relative position determination of the swarm members [34, 4]. 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.

Basic Concept The idea to use the robots as the nodes of the graph has lead to the following strategy. The (unknown) site is initially covered by a virtual triangular grid (triangular tiling), depicted in figure 31(a). The grid can be seen as infinitely spanning all directions, and the robots, while exploring, will take positions on the grid and make it 'real'.

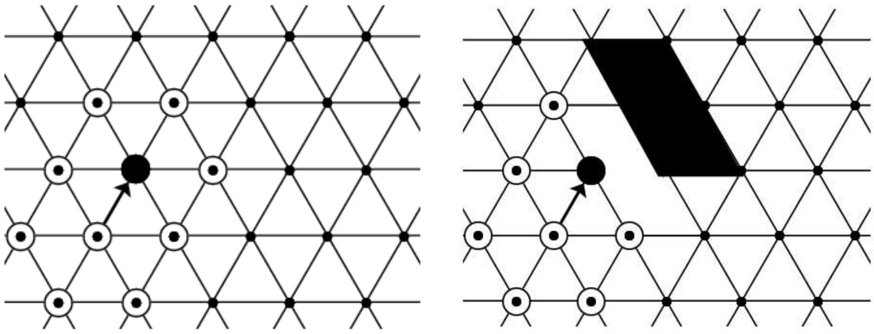
Each robot forms an attainable visibility domain (AVD), determined *a priori*. The radius of this domain is at most half of the sensing range of the sensor used. As figure 31(b) shows, the domain has the form of a hexagon; the black node indicates the robot, and white dots are nodes that the robot can 'see'; they are also the grid nodes to which the robot can move. The robot moves along the edges of the grid to available nodes, and while it moves the part of the environment visited transforms into a (topological) graph referred to as the *initial topological sub-map of the environment* or ITSM (see figure 32(a)). The robot is indicated by the black disk, and the explored (either 'sensed' or visited) nodes are indicated as white circles with a black dot inside.

The ITSM is being expanded while the robot moves. If the robot encounters an obstacle, then all the incident edges of the node whose location 'falls' on the obstacle, are removed. However the node itself is kept as it may happen that its position will be 'behind' the obstacle and therefore can be explored later on. However, if the node as it will turn out later during the process of exploration



(a) (b)

Figure 31: Triangulation (a) Virtual triangular grid. (b) Visability Domain of a robot



(a) (b)

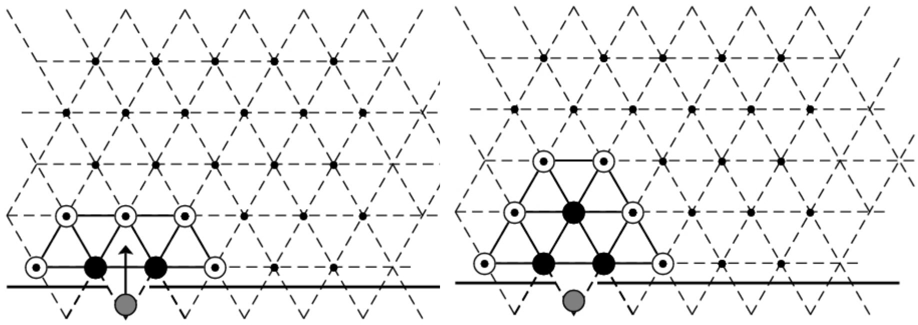
Figure 32: Triangulation (a) Explored part of the site; (b) Explored part of the site with an obstacle present.

, is really 'within' the obstacle it will also be removed from the AVD and from the ITSM (figure 32(b)).

As robots move around the virtual point lattice they extend the real graph. Importantly, when the robots detect obstructions they remove edges between vertices to indicate that robots cannot move to adjoining vertices. This is the main structure and principle governing the manoeuvrability of the collective.

Step-wise distribution and positioning We upgrade the strategy to a group of robots that additionally allows for accurate robot positioning and localisation. The main step is depicted in figure 33(a).

The first two robots (black discs), take the initial positions by the entrance to the site. The distance between robots is predefined (the radius of the AVD). The third (anonymous) robot (depicted as the grey disc) enters the site and moves to the apex of the equilateral triangle, the base of which is formed by the first two robots. The first two robots are stationary and referred to ibelow as *sentinels*.

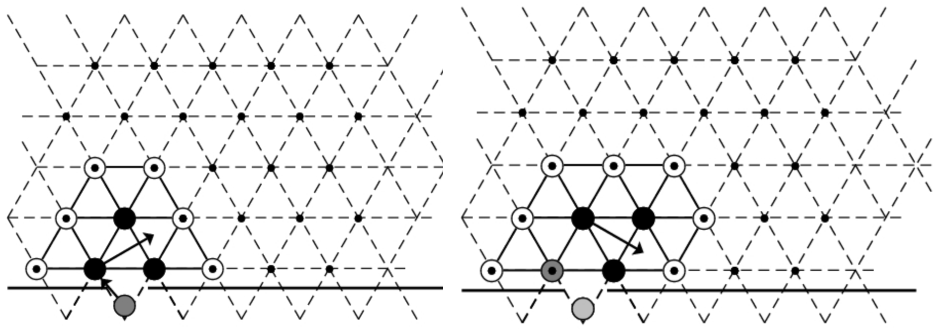


(a) (b)

Figure 33: Triangulation (a) Robots guided distribution, initial step; (b) Robots guided distribution. Forming a triangular cell.

Recognition of the anonymous robot is carried out by the two sentinels, following which the new robot is informed of its position (calculated relative to the sentinels), and the new robot is instructed to manoeuvre to its new position, periodically requesting laser data from the sentinels as required. The whole process operates over wireless TCP/IP communication. The robots finally form a triangular cell, and their AVD are fused, as in figure 33).

The next step is similar in that one of the base robots will move, initially on command of the new sentinels, and then autonomously on its own (requesting sentinel laser data when necessary as before). Decision over which sentinel will move next depends on collision information gathered by the sentinels. Suppose it is the left sentinel. Now the previous right sentinel and the apex robot become the new sentinels and the procedure regarding the movement of the (previous) sentinel is identical to the initial step. A new anonymous (fourth) robot assumes position of the left sentinel. This is depicted in figure 34(a).

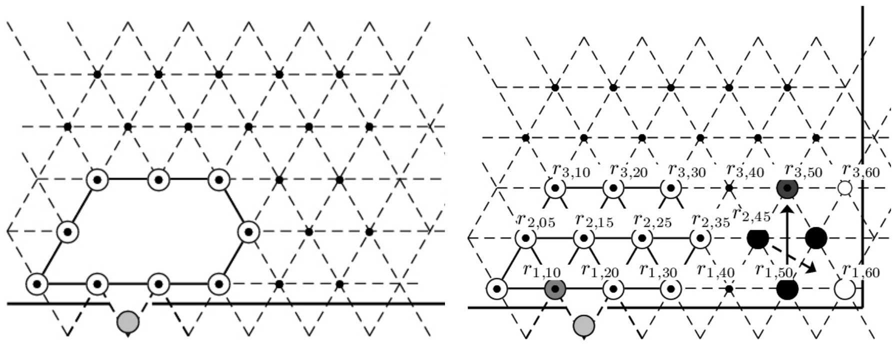


(a) (b)

Figure 34: Triangulation (a) Robots guided distribution, next step; (b) Robots guided distribution, moving around.

The procedure is now as follows. The robots will explore the environment by propagating the triangular cell formed by three robots either to the right, or up, depending on the structure of the environment. When the possibility to move to the right is exhausted, the robots first move up and then again, depending on the 'sensed' environment, will move again right, or go to the left. The fourth robot stays as the beacon for maintaining the wireless communication. The fifth robot can enter the site and take the initial position of the second robot. As we see the three robots can move in the described manner and 'swipe' the site while our set up ensures accuracy in robot localisation (see figure 34(b).

The map of the environment is formed by the boundary nodes of the fused AVD of the robots. If there is no obstacle, the map will represent a simple polygon. An example is given in figure 35(a).



(a) (b)

Figure 35: Triangulation (a) An example of the topological map, built by the robots; (b) Grid with coordinates and corner strategy.

The proposed triangular grid provides us also with a nice coordinate system. Each node can be addressed by two numbers: (i) the number of the horizontal line where the node is situated, and (ii) the number of the position of the node in the line. Both numbers can be negative as well. An example of labelling is given in figure 35(b). This figure also depicts the strategy when robots encounter a corner, for example. An obstruction arises when a robots laser range identifies a collision in a direction (and distance) known not to correspond to a robot within the graph. In such circumstances, the edge connecting the robots real node with the virtual node is removed. Thus, that area of the graph is no longer navigable from the robots current position (or by any other robot finding itself in that position). On encountering a corner, the robot collective co-operate to propagate upwards, until they are able to move left again. This results in a snaking movement of the robots which is dependent upon the obstacles within the environment.

The general strategy for graph construction is to remove edges from the graph where collisions occur in directions known not to contain robots. Robots examine a pre-defined small range of laser data in the directions of the graph edges (where the laser range allows) in order to do this. This approach allows new robots to construct the correct graph which later robots can use to successfully navigate the environment. The algorithm has been implemented in the

Stage environment and also first experiments were carried out using Khepera III robots. The practical aspects of the implementation are described in Deliverable 6.2.3/2.

8 Assistive Swarming

The aim of assitive robot swarming is to support human led rescue operations. In section 6.2 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 warehouse, 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 3 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 of chemicals. The tasks of maintaining connectivity and warning of 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.

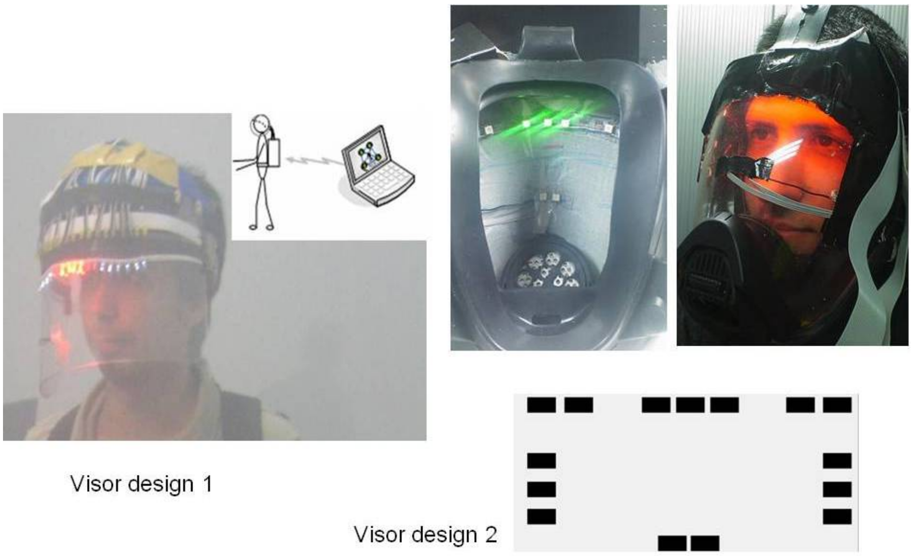


Figure 36: Left: the first prototype array visor with LEDs; Right: version 2 of the array visor with LEDs .

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 6.2, this requires no additional effort from the human. Regarding feedback from the robots to the human being, the environmental conditions restrain 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 36, 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

Figure 37: Searching fire fighters in a trial of the second version visor

fire search where colleagues continuously report verbally to one another about 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.

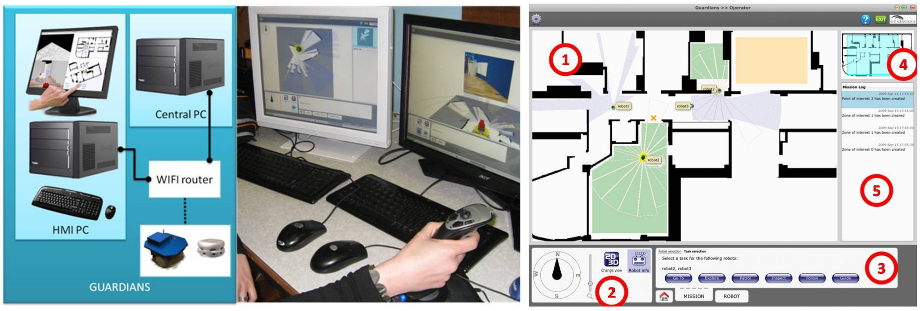
The second version of the Light Array Visor was developed using a real operational fire fighting helmet. The style of the interfaces is adapted and consists of RGB LEDs positioned in a logical layout, refer to figure 36, photograph on the right. In the second design an internal measurement unit (IMU) 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 were 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 times 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 37.

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.

9 Base station, baseline concept

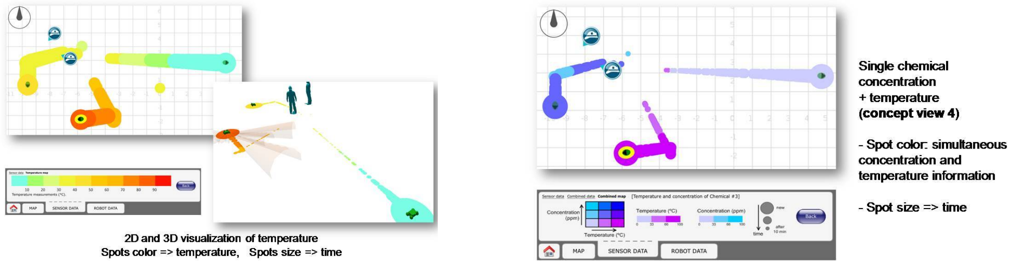
The Guardians robotic system as a whole is to be incorporated within fire-fighters intervention organizations as a specific appliance. It would typically come in support to, or in coordination with other firefighting appliances, like e.g. hazardous material dispersion (aka. HAZMAT). The base station itself is located inside an advanced outpost, close to the intervention site. A Guardians appliance typically comes as a payload of a firefighting truck carrying the base station, the equipped robots swarm, the communication means (e.g. communication antennas for the robots, organization dedicated communication means) and the base station firefighter team. Once on site, the robots and communication means are deployed and the mission starts. Several categories of base station users, with different operational / analytical skills, have to cooperate during missions. For that purpose three roles have been identified: (1) Robots Operators (RO) are in charge of supervising the robots swarm, through group of robots monitoring and control functions. (2) Sensor Data Specialists (SDS) are in charge of supporting decision making through monitoring of science data (and in particular assessing chemical hazards). (3) 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. In particular, it is foreseen that most of the operator's time will be dedicated to monitoring robots activities and this will mean there is a rather low frequency of user inputs. It has been considered that sporadic interaction was well suited to the nature of touch screen interaction. In addition, and for the sake of consistency with keyboard less interface, users connect to the base station with a fingerprint reader. Once recognized by the system, the user is logged in and accesses the user interface according to his or her role.



(a) (b) (c)

Figure 38: Base station (a) main connections; (b) screens and joystick; (c) GUI, numbers explained in the text

As a demonstration setup for Guardians, the base station physically consists of (1) a Linux PC running essentially the Base Station Core (BSC), a Mission Data Recorder and Dispatcher (MDRD) and the Player interface to the robots swarms and firefighters proxies, and (2) several Windows ones running the HMI clients for the different end users. 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 above. Several areas can be identified: (1) The main visualization zone, filling the largest screen space. It provides with an overall, immediate understanding of the global situation. Robots are represented in their (known) environment. (2) Viewport navigation: it allows the user controlling different parameters of the main view, including zoom, rotation, camera heading (in 3D only), 2D/3D mode and textual information display. (3) Operator actions area: this area gathers a number of buttons allowing swarm level control of the robots. (4) Overall map view: it helps understanding where in the overall space is situated the currently observed area. The highlighted area represents the field of view appearing in the area (1). (5) Mission log: this area 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 interpretation, and in particular temperature and chemical data interpretation. A couple of such concept views are illustrated in figure 39



(a) (b)

Figure 39: Base station: sensor specialist views

Concepts are to be further tested with end users, to identify most appropriate concepts, i.e. those being the most suitable for efficiently conveying important information and thus supporting local decision making.

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 end-user community of both Guardians and View-Finder. The focus of the evaluation so far has been on the operator role, and especially on robots telemetry and video images visualization in one hand (i.e. perception types of tasks), and robots navigation and control in the other hand (i.e. navigation types of tasks). Three steps in the evaluation process have been carried out: they are wholly reported in D7.2.1(d), were details about the process and overall results are provided.

1. First step was an early protoype end-user test trial to gather qualitative user feedback. It took place to the SyFire brigade, Sheffield, UK. 2 firefighters participated. They were observed (and camera recorded) while executing a set of 5 tasks covering both perception and navigation issues, in a simulation setup (using the PlayerStage framework [Player-09]). 3 trials were requested for each task.

2. Second step was an expert evaluation. We performed an heuristic evaluation [Nielsen-94] with a group of 3 experts who examined the interfaces. Typically, a demonstration of features was done through a number of tasks by a user familiar with the base station. The 8 heuristics developed by Clarkson and Arkin (2007) [Clarkson-07] have been used for that purpose.

3. Third step was a formal end user usability evaluation session. The tests participants were observed (and camera recorded) while executing a set of 6 defined tasks through the base station. 2 trials were requested for each task. The physical setup consisted of the base station controlling either simulated robots and firefighter (using the PlayerStage framework) or a DrRobot X80 mobile robot. Evaluations took place at the DOVO (Belgian demining service) (first group, 3 users) and at the Antwerp fire brigade, Belgium (second group, 3 users too). The former group was rather representative of View-Finder users, while

the latter group was rather representative of Guardians users. In addition, we shall mention that DOVO users were already acquainted with bomb disposal mobile robots technologies, while firefighters were totally novice to robot teleoperation. Each participant filled a post-test questionnaire. During this test session, both qualitative and quantitative user information have been collected.

Evaluation criteria have been formulated, focusing on different aspects of the usability aspects of the user interface. They are based on Scholtz' six evaluation guidelines [Scholtz-02]. Effectiveness, efficiency and user satisfaction metrics have been used in the evaluation process. Results from the successive usability evaluations confirmed a number of our design choices and helped fixing most shortcomings. In terms of the evaluation criteria introduced above (in the evaluation setup description), i.e. effectiveness, efficiency and user satisfaction, results looked promising. It shall be mentioned that additional usability evaluation sessions (in particular with a multi-users setup) are planned as a follow-up of the Guardians base station design and development efforts. Besides HMI aspects, work has also been carried in WP6.3 for investigating possible tools supporting mission planning for the Coordinator role. Prototype Mission Planning, Scheduling and Execution Monitoring (MPSEM) component has been developed and integrated to the base station, though rather targeting individual robots actions: the nature of swarms makes it less relevant to anticipate on individual robots plans and actions than in a context where only one or a few robots shall be individually controlled (like in View-Finders). Nevertheless, group robot behavior planning can in some extent be considered in the task planning approach we introduced, relying on the Hierarchical Task Planning (HTN) based planning engine Shop2 (open source, from the University of Maryland [44]. It allows breaking down high level tasks into elementary actions (typically motion or perception oriented), taking into account available resources and time. It is able to call for specialized planners providing (e.g. path planning or perception planning capabilities) during planning, relying on the latest available world representation (e.g. environment Digital Elevation Map, robots and sensors health, status, availability) as well as mission constraints (area scope / limitation, available time, etc). Specific modeling and consideration of swarm behaviors in the planning aspects will be further considered in upcoming base station development plans.

Comparison to work done in other related EU projects Compared to previous EU project such as FP5-Pelote [Pelote-09], the MPSEM introduces autonomous task planning capabilities in support to operations coordination, which is a concept going much further than path planning (for example, in Pelote: Traveler Salesman Problem / TSP, Shortest path planning, etc.). Telepresence / user interface prototype developed in FP5-Pelote allows robots and firefighters visualization on a 2D layer, with complementary numerical information on e.g. robots position. Video camera feedback is provided too. Although the presented information are useful ones, the base station layout and overall HMI goes much further in the integration of the HMI components and the navigation in the world in 2D and 3D, supported by the touch-screen priviledged interaction mode. In other projects such as FP6-COMETS, the base station controlling the UAVs only provides mission support tools to monitor UAVs paths and activities and support path pre-planning, whereas no task planning aspect is tackled from a central perspective (although in some extent considered in a distributed fashion). In the FP6-AWARE project, although remote overall system monitoring and control was not the main focus, the developed monitoring and control tools are rather conventional, displaying tables of numerical values aside with a 2D simplified representation of the environment, trajectories, etc. Video feedback is provided aside. Usability issues were seemingly not explicitly considered here. In the FP6-URUS project, remote monitoring and control was essentially based on 2D and 3D map visualization, without explicitly considering an overall consistent interface to handle the robot system and capabilities. To our knowledge, usability issues barely been addressed either. In the FP6-RESCUER project, the remote monitoring and control of the mobile robotic platform is developed in the scope of a component named ERRMA, featuring interfaces for the teleoperator. It considers and in some extent implements interfaces with e.g. Head Mounted Display for stereovision feedback, and force feedback device for the robot's arm control. However as far as the ERRMA's graphical user interface is concerned, it relies on rather conventional gauges and multi-view screens, thus does not address user's cognitive load balance, neither intuitiveness (aka. "learning curve"), which are strong assets of our approach (as validated during usability study). Moreover the proposed ERRMA interface fits well the control of a single robot for a single operator, but according to us would likely not properly scale to multiple robots and multiple users, contrary to the base station developed in Guardians.

10 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

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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