

# **Self-Optimizing Human-Robot Systems for Search and Rescue in Disaster Scenarios**

***Ulf Witkowski, Stefan Herbrechtsmeier,  
Andry Tanoto, Mohamed El-Habbal***

*Heinz Nixdorf Institute, University of Paderborn*

*Fürstenallee 11, Germany*

*+495251 60 6352, fax +495251 60 6351*

*Witkowski@hni.upb.de*

***Lyuba Alboul, Jacques Penders***

*Materials and Engineering Research Institute, Sheffield Hallam University*

*City Campus S1 1WB, Sheffield, United Kingdom*

*+44114 225 3500, fax +44114 225 3501*

*L.Alboul@shu.ac.uk*

## **Summary**

The increasing capabilities of robot systems enable new fields of practical applications for individual robots as well as multi-robot systems. But for some application scenarios like a fire or earthquake disaster current robots are still too limited to act fully autonomously in the disaster area. To overcome these limitations we consider a heterogeneous team of humans and robots complementing each other. Core application considered in this paper is a large burning warehouse with smoke making it difficult for fire fighters to search the building and to orientate themselves inside the warehouse. Therefore, an assisting team of robots is surrounding the fire fighters searching the proximity, providing orientation data, and establishing a wireless communication infrastructure on a basis of a mobile ad-hoc network. The adaptation of the robots is achieved by applying principles of self-optimization on different levels of the human-robot system.

In this paper, we are considering self-optimization inside an individual robot to optimize its behaviour, within a group of robots, and in the entire system comprising of robots and humans. The focus of the optimization is the distribution of robots by applying swarming behaviour for forming a mobile ad-hoc communication network and performing map building.

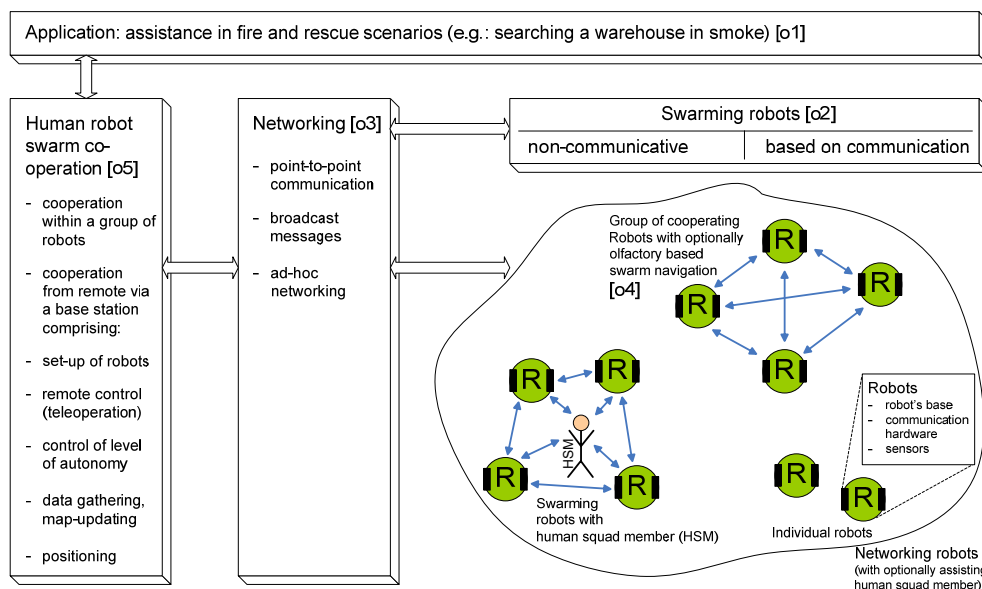
## **Keywords**

Multi-robot systems, self-optimization, adjustable autonomy, reconfiguration

# 1 Introduction

The increasing capability of robot systems enables new fields of practical applications for individual robots as well as multi-robot systems. But for some application scenarios like a fire or earthquake disaster nowadays, robots are still too limited to act fully autonomously in the disaster area. To overcome these limitations we consider a heterogeneous team of humans and robots complementing each other, as shown in image 1.

During such mission, the robots navigate the site autonomously and serve as a guide for a human squad-leader in finding the target location or in avoiding dangerous locations or objects. They connect to a wireless ad-hoc network and forward data to the squad-leader and the control station. The network, which is actually a chain of robots equipped with wireless communication modules, is self-optimizing, adapts to connection failures by modifying its connections from local up to central connections.



*Image 1: Simplified system structure of the human-robot system for disaster scenario applications: a group of robots is assisting human squad member (from [GUA+06]).*

The described and depicted scenario (image 1) is part of the GUARDIANS project that is funded by Sixth Framework Program of the European Union (no. 045269). The autonomous swarm operates in communicative and non-communicative mode. In communicative mode, automatic service discovery is applied: the robots find peers to help them. The wireless network also enables the robots to support a human squad-leader operating within close range. In the case of losing network signals, the robot swarm can still be functioning with non-communicative mode and continue serving the fire fighters.

Depending on the situation, the robots swarm can be deployed with or without a human. In no presence of human, they can search and navigate through the warehouse, maintain communication connections, designate one or more robots as positioning beacons, exchange position data with the control station, detect and possibly locate toxic agents, and possibly detect casualties. With human the robots swarm can navigate the human through the warehouse, exchange human's position data with the control station, warn for toxic agents, call the human's attention to objects of interest, and maintain the communication link between the humans (here fire fighters) and the control station. In some situation, a group of robots may be further split into several groups or individuals.

The above paragraph shows how complex and dynamic the situation is and that it requires an adaptive human-robot system. To adequately adapt the system behavior principles of self-optimization are used on various levels of the human-multi-robot system. This comprises self-optimization on single robots by using a combination of processor together with reconfigurable hardware. For the group of robot assisting the humans optimization methods are applied to form a swarming behavior to distribute the robots in the environment for optimal area coverage for a mobile ad-hoc network and robust mapping algorithms. On the level of human robot interaction the concept of adjustable autonomy is used to optimize interaction of humans and robots in a certain situation within a certain period of time. Thus, through its implementation, we can develop an adaptive and robust human-robotic system which can be deployed in various conditions.

This paper is organized as follows: In Section 2 the overall human-robot-system is discussed explaining the role of humans, robots, and the architecture of the robots. Furthermore, the two main tasks of the robots – these are networking and map building – are described. The underlying principles of optimization are presented in Section 3 and the self-optimization on robot level and on system level are discussed. Section 4 concludes the paper.

## **2 Human-Robot-System**

Scholtz in [S03] stated that the goal of research in human - robot interaction is to have an efficient and effective team consisting of human and robots and which can benefit from the skills of others. Humans are, on one hand, recognized as being a better problem solver in situations with unknowns through the use of intuition, hunch, etc. Robots are, on the other hand, known to be better in solving problems with repetitive nature due to its preciseness, speed, etc.

In critical tasks, such as search and rescue missions in disasters, a team consisting of humans and robots can provide more versatility and capability. In such missions, the environment is complex and hazardous, which render a lot of problems

to achieve the goal. It is most of the time risky to send humans inside the incident area. For example, during fire incidents in industrial warehouse or basement, fire, high temperature, toxic fumes, and possibility of explosions are factors that can prevent humans from entering the site. Hence, robots are assumed suitable for such missions [KTN+99, TKT+2000]. However, they are basically controlled by remote human operators because with our current technology, it is still impossible to have robots which can perform fully autonomously in the aforementioned environments. Moreover, such missions are too critical and risky that humans are still needed as decision makers.

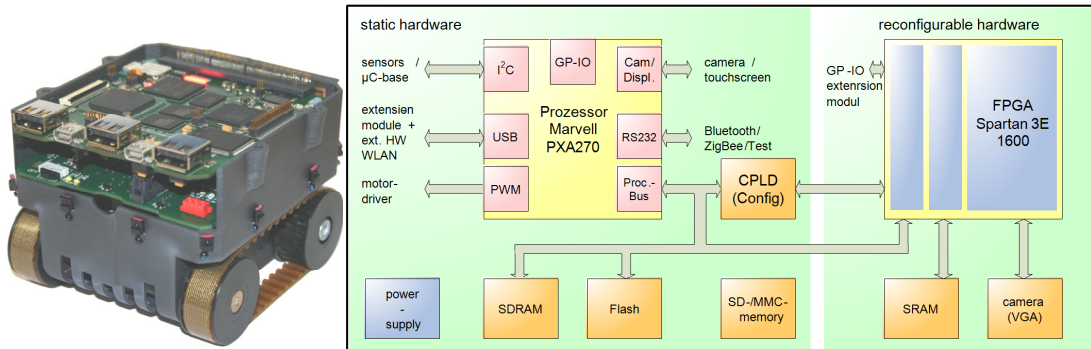
For supporting humans in the best way depending on the current situation we have developed a novel robot that can adapt its structure of the information processing hardware depending on the required task during runtime. Details are given in the next section.

## 2.1 Architecture of the robot

The robot platform used within the project for a downscaled or simplified real life scenario is a mini-robot offering a powerful information processing hardware. One of the main important features of the robot is the parallel use of a mobile processor and an FPGA (field programmable gate array) that enables hardware reconfiguration during runtime. The robot platform that has been developed in the Heinz Nixdorf Institute has a size of approximately 9 x 9 cm and a height of about 5 cm. It uses a chain drive to allow robust motion even on slightly rough ground. The case itself uses MID technology and has traces and electrical components directly on the surface. This allows the assembly of twenty infrared sensors directly on the outer side of the case and two microcontrollers for sensor processing inside [KTG+07].

The robot system has a modular structure and provides slots for two boards. The implementation of the basic functionality and power supply is done on a base board. An integrated microcontroller controls two motors and allows the implementation of simple algorithms. The module also contains a three axis acceleration sensors, a yaw rate gyroscope and a sensor for battery monitoring. The information processing is done on an extension board that is inserted into the upper slot of the robot. The board integrates a processor with 520 MHz, 64 MB main and flash memory. An FPGA (Xilinx Spartan 3E 1600) 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 WLAN offer communication with different bandwidth and power consumption. The board provides a variety of additional interfaces, like USB, MMC / SD card, audio, LCD and camera. The architecture of the information processing board with available IOs is depicted in image 2. The

software environment of the robot is a Linux operating system. This allows the use of any platform independent Linux software on the robot.



*Image 2: Photograph of the robot with processor and reconfigurable hardware (left) and architecture of the information processing board (right).*

The presented robot is used for experiments in a down scaled scenario as well as in a real world scenario (i.e. real dimensions of building), but without large obstacles on the floor. For experiments in real warehouses with fire a larger, more robust all-terrain robot is used that is developed by a GUARDIANS project partner (Robotnik, Spain). The information processing hardware of the small robot will be integrated into the large robot.

## 2.2 Networking, swarming and map building

In a large system with many mobile robots, it becomes difficult for all robots to exchange information at a time because of their limited communication capacities on one side. On the other side, after a disaster, fixed communication infrastructures may be destroyed. Accordingly, an ad-hoc network communication system is implemented, based on some of the mobile robots acting as communication nodes, offering a robust communication infrastructure.

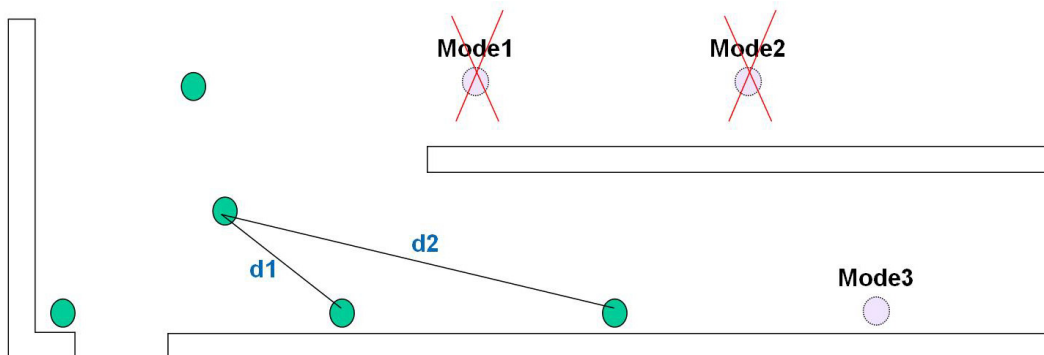
In addition to the communication capability, the ad-hoc network has to provide position data to support localization of the mobile robots and humans, which might be of great importance to guide the humans and robots to specific targets and locations or to quickly exit the search area. In outdoor applications the GPS system is one option to get position data. But finding the location of a communication node without the aid of GPS in each node of an ad hoc network is important in cases where GPS is not accessible, especially in indoor scenarios.

In our approach a cell based grid with master nodes in each cell forms the basic structure of the network. Some nodes formed by special robots act as beacons to uniformly span the network. These robots will act as reference points when posi-

tioning other mobile robots or humans and at the same time form the infrastructure to support communication all over the search area. A combination of distance and radio signal quality measurements as well as dedicated swarming behaviors of the robots ensure suitable distribution of the robots even in the presence of walls for example that are impervious to radio signals.

The main challenge is how to place the robot beacons in well-known positions in an unknown area, where only a rough basic map of the building is available, but with no prior knowledge on the real situation inside, taking into consideration all the damage and variations that would have occurred due to the fire. In our proposed approach, two systems are used for localization and measuring distances between communication nodes. The first system is the Nanotron communication system, which measures distances relying on the signal strength of radio links and time of flight of signals, with an accuracy of about 1 meter in indoor scenarios [NAN07]. The second system uses a LRF (Laser Range Finder), relying on a diffusion laser sensor that can detect objects within a range of up to 10 meters. Using the proper detectors like special photo transistors mounted on the robots, the laser beam can be detected and hence differentiate between robots and other obstacles.

To form the communication infra-structure, a mesh of equilateral triangles of beacons is implemented. The first robot enters the building and stand right next to the door, acting as the main reference point leading back to the exit after mission accomplishment. The second robot enters the building, moves along the wall for a pre-defined distance, which is considered to be the triangle side length, and then stops. Afterwards, each of the two nodes will lead the next robot to its proper position. In case of obstacles that hinder the robot from getting to its required place, several modes are used to re-calculate and guide the robot to its new position. The network topology can be reconfigured either autonomously by the robot beacons according to periodic link quality measurements, or manually by the base station to perform a certain task or achieve a special goal.



*Image 3: Placement modes to distribute communication nodes. Dots in general are symbolizing robots, dots with 'mode'-labels are new calculated robot positions depending on the placement mode.*

The movement of the robots within a group is considered as kind of swarm behavior. Depending on the presence of communication links we distinguish non-communicative and communicative swarming. In the basic mode the robots navigate on their own and do not communicate, but just react to each other's behavior, we call this non-communicative swarming. The communicative mode complements the basic non-communicative mode and allows 'higher' level cooperation, for instance coordinated navigation. The distinction between non-communicative and communicative mode is also referred to as between explicit and implicit communication [Pa00]. The communicative and non-communicative modes are quite distinct; however they are not mutual exclusive. The swarm is to be applied in industrial environments where the reception of wireless signals is very variable and communication failures are to be expected. The robot swarm brings its own wireless communication network and expands the network as required. We define this novel swarm behavior as the networking mode of the swarm, in this mode the robots build and maintain the wireless communication network. The robot swarm is to support rescue operations whilst the rescuing is done by a human being. Therefore the swarm has to assist and accompany a human being; in this novel assistive mode the swarming behavior is adapted to enable cooperation between the robot swarm and the human.

Map building is the mapping of environment data (e.g. obstacles, walls, open spaces) to an internal world representation inside the robot. In a disaster scenario a map increases safety for the fire fighters by being able to guide them out of the building in case of an emergency and to explore the mission area more efficiently in terms of time by using map data. One of the most important advantages of multi-robots teams is that multiple robots may produce more accurate maps, by reducing cumulative sensorial errors. The deployment of a swarm leads to further advantages of cost and time reduction, as data collecting is distributed among a large group of sensors with limited computer power. After the distribution of the robots in the environment their current positions may be used as initial information about the environment, and can be seen as an initial topological map. The network layout can indicate the boundaries of the environment as well as possible obstacles, which can lead to the initial navigation map. We briefly describe the basic ideas behind the so-called dynamic triangulation method which we are developing within the GUARDIANS project. More details on optimizing the placement of the robots based on the dynamic triangulation scheme are given in section 3.2.

### **3 Self-optimization principles**

Depending on the system complexity and the type of system realization self-optimization can take place on different levels of a system. In general, self-optimization is the process of adapting the system behavior autonomously. Fol-

lowing the definition in [GFS+06] self-optimization in technical systems always comprises the three main actions: (1) analysis of current situation and system status, (2) determination of (new) objectives, and (3) adaptation of system behavior. The new objectives can be chosen by selection from a list, by adaptation, or by generating new objectives using suitable methods. According to the framework for realization of self-optimizing systems in the SFB614 “Self-optimizing concepts and structures in mechanical engineering” [FGK+04], self-optimization takes place in sub-systems and in the overall system architecture of the human-robot system discussed in this paper.

We are considering self-optimization on robot level and on system level. On system level we have an optimization between several entities, which are the robots and the human squad members, and the operator monitoring the mission outside the burning warehouse. On system level, we discuss the optimization of robot movements within the group for establishing the communication network and for map building.

### **3.1 Self-optimization on robot level**

By introducing self-optimization on robot level the robots become more flexible and are able to offer that operation that is required for a specific task during runtime. Partly or fully autonomous robots (depending on the current level of autonomy) are able to act without external supervision. They perform three basic actions: sensing the environment, processing gathered information and deciding upon future actions with appropriate control of the system’s actuators. Self-optimization is required to provide autonomous systems with adaptability against internal or external changing conditions in an optimal way.

As introduced in section 2.1 we are using for the information processing a combination of processor and an FPGA that can be configured during runtime to run a task with optimal performance. The utilization of FPGAs alone or in combination with software architectures brings many advantages in contrast to pure software solutions. Our approach includes a hardware-software architecture, which takes advantage of dynamic reconfiguration of the FPGA to efficiently enhance the utilization of the available computational resources. Modern FPGAs are heterogeneous architectures constituted by programmable functional blocks and embedded application specific integrated hardware (e.g., embedded processors, SRAM memory, dedicated multipliers) interconnected by a reconfigurable network. The configuration and interconnection of the internal resources determine the functionality of the implemented design. For configuration, a partial bitstream, targeting a specific area of the FPGA is loaded (symbolized by the slots in image 3 in the FPGA area) while the rest of the FPGA can still operate without interruption. This process is known as dynamic reconfiguration. Dynamic reconfiguration can be



used to enhance the resource-utilization of an FPGA by time-sharing logical resources among different designs (event-driven reconfiguration) or by time-multiplexing a design requiring a bigger amount of resources than available (virtual hardware) [PCW+06]. Typical tasks of an individual robot in our scenario are

- scanning the environment for other robots and humans by using a radio based system (task t1) and a laser scanner (t2),
- position calculation based on scanning data (t3),
- driving the robot to required position to optimally cover the mission area for establishing the communication network (t4),
- reformation of the robots in case of bad or broken links to maintain communication (t5),
- updating robot's internal routing table with optimal routing path with respect to robustness (link quality, number of hops, latency, etc.) (t6),
- routing of data packets within the ad-hoc network (t7),
- providing orientation data for the humans in the team (t8),
- driving the robot within a swarm formation for example to rebuild a formation or to explore the environment (t9),
- performing a local environment mapping for updating robot's map (t10),
- image and sensor data preprocessing for sending it to the operator at the base station (t11).

Time critical tasks are intended to be executed on the FPGA in parallel to minimize latency and to increase robustness of the robot system in terms of safety issues for the fire fighters. The robots are providing a communication infrastructure and orientation data to guide the fire fighters out of the building. But usually it is not possible to have all tasks/algorithms implemented on the FPGA at the same time because of resource restrictions. Therefore, the tasks required at runtime are loaded into the FPGA dynamically. The decision of which tasks have to be loaded depends on a cost function. Input parameters are the current situation of the robot-human system, the individual robot (sensor measurements, internal state), and inputs from the fire fighters and the operator as well. Currently, this function is under development and is realized in the first version as a decision tree.

### **3.2 Self-optimization on system level**

The optimization on system level comprises the human-robot interaction, construction and maintenance of the communication network including the swarming behavior of the robots, and the map building based on both the gathered sensor data and information of the communication links. Here, we concentrate on the swarming task for the distribution of robots for robust networking and map building.

**Swarming and communication network construction and maintenance.** For the movements of the robots in the mission area and their distribution to span the communication network we consider communicative and non-communicative swarming modes. The swarm is to be applied in industrial environments where the reception of wireless signals is very variable and communication failures are to be expected. The robot swarm brings its own wireless communication network and expands the network as required.

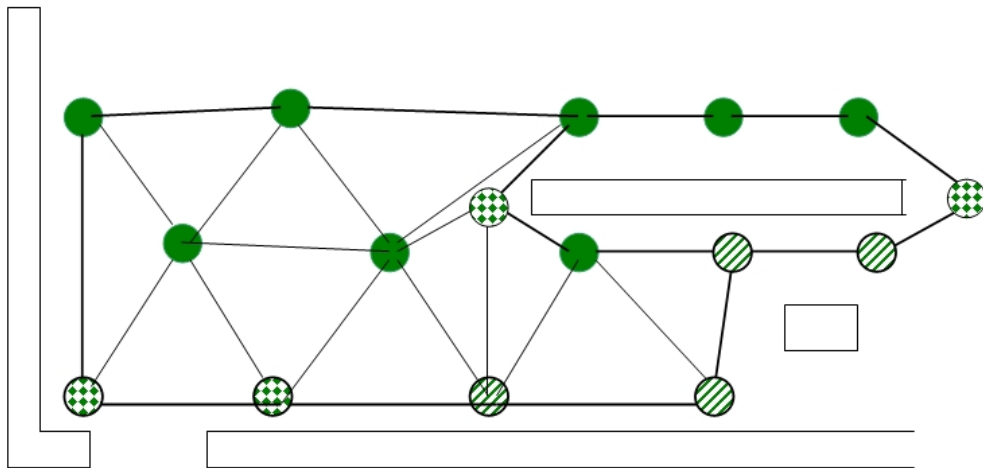
Non-communicative swarming has to be achieved without central or on-line control. In non-communicative mode the swarm consists of homogeneous but anonymous robots, the latter means that the robots are able to recognize another robot as a robot but they cannot identify other robots as a particular individual with a unique name. This approach allows for self-optimization as the applied algorithms must operate with any number of robots, thus the size of the group or swarm may vary considerably and the swarm is robust to failures of individuals. Obstacle avoidance, wall/track following and gradient following are autonomous behaviors of individual robots independent of being part of a swarm. Swarm control usually focuses on aggregation/dispersal, area coverage, search/exploration and moving in geometric formations. Autonomous navigation requires that the robots have some map of the environment available. Collective navigation in non-communicative mode is based on a combination of individual navigation and maintaining a particular geometric formation.

Communication improves the abilities for swarm control considerably. For communication based swarming several approaches can be found in the literature, with an abundance of multi-agent based approaches. The essences of a multi-agent system is the negotiation protocols and mechanisms. Obviously when the robots can communicate they may exchange information about their local environment, enabling better informed conclusions. In non-communicative mode the input values for a control model originate from the robot itself. In communicative mode the robots may use the information of all other robots. This global aspect allows for some control aiming at cooperative behaviors, such as cooperative Search/Exploration, cooperative Area Coverage, cooperative Gradient Following and cooperative Formation Control. The wireless communication technology also enables position detection. With positions known and the overall information available the swarm has the basic ingredients for map building, also some robots may act as temporary position beacons and one could even use the robot swarm to set out a complete triangulation of an area. By introducing negotiations the robots can further coordinate their actions, and for instance build up a division of labor.

The self-optimization of the swarm behavior differs depending on the presence of communication links. Without communication we apply the artificial potential force field method, introduced by Krogh [Kr84]. The sensor information is fed into a control model that governs the robots. Based on their observations, each robot

calculates a force, which is the generator of the new velocity vector of the robot. In its general form the control model depends on four terms: The first two terms represent the external influences (attraction of goal on robot and the repulsion caused by the obstacles). The second pair consists of the internal forces, which originate amongst the robots in the swarm (i.e. the attraction and repulsion between any swarm member and robot). Self-organization and self-optimization of the swarm behavior and shape is achieved by selecting particular combinations of the four mentioned terms. Usually, the functions for attraction and repulsion are chosen such that on large distances the attractions dominate ('goal seeking') while on short distances the repulsions dominate ('obstacle avoidance').

**Map building.** The map building is based on the dynamic triangulation method. Main goal is to deploy robots to provide largest area coverage. The robots should also be deployed in a sensible manner in order to facilitate communication and exploration of the environment. For example, some robots can be placed as beacons at the 'openings', which might be entrances, doors, beginnings of the passages; and/or at the 'junctions', which include the corners of obstacles. The aforementioned is illustrated in image 4. Here the robots are represented by circles, and communication links among them by line segments. The robots, which might be positioning as beacons are indicated with circles with a rhomboidal pattern. The robots, which are circles filled with lines, represent further possible beacons. The latter robots can be chosen as beacons to facilitate communications and indicate a safer and more robust path through the environment. The thicker solid lines indicate the boundary of the environment, covered by the local network built by the robots.



*Image 4: Sketch of the dynamic triangulation*

As one can see, the part of the environment where no visible obstacle is present represents a triangulation. As robots move autonomously from the previous posi-

tions to their present positions, and there are communication links between them, the only possible location for an 'unrecognised' obstacle is within a triangle formed by robots. Such obstacles can be detected by robots sensors thus enhancing the initial topological map by local metric information.

A larger obstacle might be detected already on the topological level by singling out areas where communication links are missing (holes in the triangulation, or cycles of  $r$  nodes in the local network, formed by the swarm, where  $r$  is larger than 3). In order that a hole in the local network indicates the presence of an obstacle with a sufficient probability, a robot should be allowed to move to its next location within the distance not larger than the half of the maximum distance by which they still can communicate. We can also assume that robots can estimate distances between themselves within their domain of visibility. This will provide an initial metric information about the environment, as the sensor network formed by robots can be seen as a discrete sampling of the underlying geometric environment. An estimation of the angle between two neighboring edges can contribute further to the map building process of the environment. The capacity to measure angles can also help with building a local network consisting of equilateral triangles whenever it is possible, which increases the robustness of wireless communication.

## 4 Conclusion

The successful interaction of humans and multiple robots in order to support the humans in a disaster scenario like the one considered in the GUARDIANS EU project with burning warehouses is a challenging task. By applying principles of self-optimization on different levels of the human-robot system it becomes more robust and easier to maintain. Additionally, we expect an increased safety for the fire fighters on the site. From our point of view there is a valuable potential for self-optimization on the following levels: On individual robot level this happens for the information processing by using a combination of a processor and a dynamically reconfigurable hardware on FPGA basis to optimize robot's skills during runtime. On system level, self-optimization can be used for the distribution of the robots in the mission area by dynamic swarming algorithms with and without communication. The optimal distribution of robots is recommended to maintain a robust ad-hoc network and to efficiently gather information from the environment for map building to increase the knowledge for the fire fighters. Another important area for optimization on system level is the human-robot interaction within the system. It requires flexibility and adaptiveness on the system to ensure the task can be done effectively and efficiently. With adjustable autonomy, we can optimize the performance of the human-robot system by combining the strength of humans and robots. The task that may look impossible for only robots or humans can be solved elegantly because it allows cooperation between humans and robots.

The discussed optimization approaches have been partly implemented on the presented mini-robot. In the next project phase we will also apply the considered concepts to larger robots used within the EU project.

## 5 Acknowledgements

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