Ad-hoc network communication infrastructure for multi-robot systems in disaster scenarios

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Abstract

Mobile ad-hoc networks (MANETs) are communication networks that do not rely on fixed, preinstalled communication devices like base stations or predefined communication cells. MANETs are wireless networks consisting of mobile nodes which are characterized by their decentralized organization and the potentially high dynamics of the network structure. Therefore, MANETs are ideally suitable for applications with multi-robot systems. One of the most promising applications of a multi-robot system is to assist humans in urban search and rescue (USAR) scenarios in the aftermath of natural or man-made disasters. We are focusing on an ad-hoc network communication system with the mobile robots being communication nodes offering a robust communication infrastructure. Main disaster scenario covered by our system is a large industrial warehouse in fire, described in the GUARDIANS project funded by the European Union. In this scenario, black smoke may fill large space of the warehouse that makes it very difficult for the firefighters to orientate themselves in the building which in turn will usually limit the action space of the firefighters. In order to increase the coverage area of the fire fighters 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 our proposed approach a cell-based network with master nodes in each cell forms the basic structure of the network. Some nodes formed by specially-equipped robots act as beacons to uniformly span the network. These robots have a role as reference points when positioning 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 are capable of maintaining

suitable distribution of the robots even in the presence of walls that obstruct the radio signals.

Communications standards considered for the ad-hoc network are Wireless LAN, Bluetooth and ZigBee. All are integrated on a miniature robot for real experiments. The features of the network are studied analytically, in simulations as well as in experiments to verify the results. Furthermore, frequency and power managements are also taken into consideration to ensure robustness of communication in the network.

1 Introduction

Communications and communication protocols play an important role in mobile robot systems, especially in multi-robot systems that are optionally enhanced by humans to complement individual skills. One of the most promising applications of a multi-robot system is to assist humans in urban search and rescue (USAR) scenarios in the aftermath of natural or man-made disasters. The main disaster scenario covered by our system is a large industrial warehouse in fire, described in the GUARDIANS project funded by the European Union 6th Framework Program (project no: 045269). In this scenario, black smoke may fill large space of the warehouse that makes it very difficult for the firefighters to orientate themselves in the building.

During such mission, the robots navigate the site autonomously and serve as a guide for firefighters in finding the target location or in avoiding dangerous locations or objects. They communicate to each other or with the firefighters implicitly through stigmergy and explicitly through wireless communication. Also, they communicate with humans at the base station through wireless communication, forwarding data to the squad-leader and the control station. 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 loosing network signals, the robot swarm can still be functioning with non-communicative mode and continue serving the fire fighters.

In the environment where the operation takes place, there are a lot of disturbances and noises which make it difficult to communicate. Debris, smokes, and obstacles may obstruct the line of sight which may hinder them to sense the present of firefighters or other robots, thus stigmergy may be difficult to achieve. Metals in the warehouse, which are commonly found, greatly affect the quality of wireless communication links. Moreover, after a disaster, the fixed communication infrastructure may be destroyed.

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. However, GPS is not accessible for indoor application. Thus, for such application, each node of an ad-hoc network must know its location autonomously.

An ad-hoc network communication system based on the mobile robots as communication nodes is deemed suitable because it can offer a robust communication infrastructure. In this paper we present a mobile ad-hoc network being able to be used in large burning industrial warehouses. The network has to support the fire fighters and the assisting group of robots with a communication infrastructure as well as position data. One of the most important features of the network is its robustness in terms of available communication links and position data to maximize safety for fire fighters.

The paper is organized as follows: In Section 2 the overall communication system is described. First, details of the infrastructure used are presented. In the second part the coverage of the operation area with communication nodes by using swarming behavior is reported. In addition, a scheme for building a dynamic triangular network is presented. Section 3 gives an overview on the robots that are used for experiments to evaluate the communication network. In addition, experiments are presented. Section 4 concludes this paper.

2 Communication System

The main objective of the communication system is to provide the team of robots and humans inside a building full of smoke with robust communications links. The idea is to establish an ad-hoc network with mobile nodes that provides the fire fighters as well the robots with both a communication infrastructure and position data. As depicted in figure 1 the robots span a mesh of nearly equilateral triangles. Between the robots and humans and among neighboring robots there is short-range communication. A long range communication link, which is realized by multi-hop connections, takes place between the base/control station and the team on site. Such a link is used to exchange data mainly for monitoring the operation.

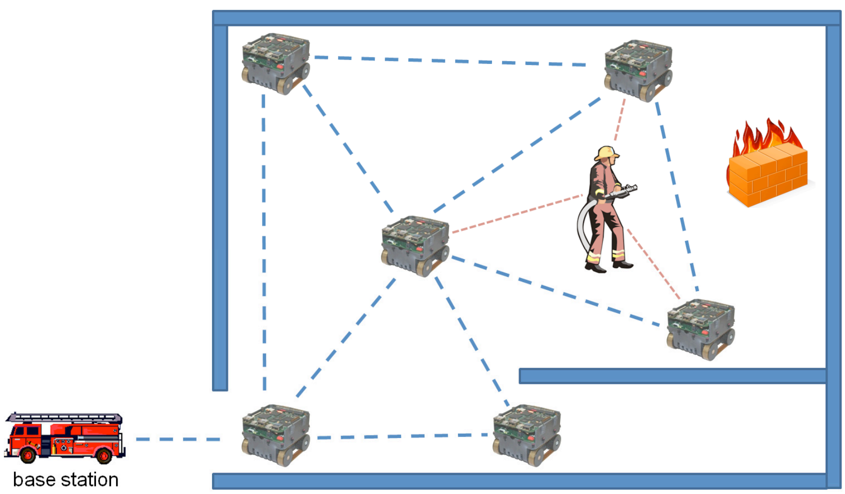

Figure 1: Mobile ad-hoc communication network with integrated human team member and link to base station for monitoring the operation

Service Discovery In order to optimally support the humans in the team a service discovery approach is implemented. If robots are deployed together with the human squad members in a disaster scenario, the ability to discover resources and exchange generic services with other robots in an open, heterogeneous network will be essential for a successful operation. By using a discovery protocol the robots will be able to efficiently locate resources and services available in the networks. The protocol exploits the position data of the robots to increase scalability and efficiency. Using the cell-based approach, each master node (or mobile beacon) has its own service list where all services offered by robots within its cell or operating range are listed. The service list of each cell is updated each time a robot enters or leaves the cell. If a robot needs and searches for a service provided by another robot, it sends the request to the nearest master node, which forwards the request to other master nodes via the master nodes communication hierarchal level. Each master node receiving the request searches for the required service in its service list and continues forwarding the request if the service is not found in its list. Once a master node finds the service in its service list, it sends the request to the robot offering the service and hence establishes a connection between the source and destination robots.

Routing Another essential part of the ad-hoc communication network is the routing algorithms. Appropriate routing ensures the robustness of communication in case of node failures by delivering messages to its destination via different routing paths. Traditional protocols like proactive, reactive and hybrid protocols use the available robots existing in the path to the destination to route messages. Our cell-based approach uses only special nodes, which are mainly the robot beacons, to route messages to its destination. These beacons are equipped with communication modules that support wider transmission ranges than the other robots and also have dedicated channels for routing on their hierarchal level. Routing over fewer nodes offers the advantage of reducing the transmission time, saving power for other robots and reducing interference and collisions that would occur if normal robots were used for routing. Additionally, the uniform distribution of the beacons all over the search area ensures full coverage of the area and makes it possible to deliver messages to all robots even in the presence of gaps where no robots are available between the source and destination of the message.

Positioning 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. The robot beacons will act as reference points when positioning 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. For swarming, the robots will have different modes of operation and they will switch between these modes based on the environmental cues and some predefined algorithms. For example, once a sub-group of robots reaches the edge of communication with the rest of the network, one of the robots will change its behavior from the current mode (e.g., search mode) to act as beacon/router mode so that the rest of the robots continue their task further. The robots will seek to swarm and position themselves so that there are always at least two beacons/stationary routers in the line of sight/communication range. An algorithm based on distributing robots using equilateral triangles is explained in more detail below.

2.1 Communication infrastructure

The team of robots and humans consists of a number of mobile nodes which needs ad-hoc wireless communication with different requirements for power consumption and data rates. The adaption to the different requirements will be achieved by using three wireless communications standards. All of them use the 2.4 GHz industrial, scientific and medical (ISM) unlicensed radio band.

The common type for wireless local area networks (WLAN) is the standard 802.11g of the Institute of Electrical and Electronics Engineers (IEEE). This allows data rates up to 54 Mbps and range up to 100m, but has high energy consumption. Networks can build ad-hoc or by infrastructure. The WLAN standard is mostly used for web, email and video applications. A widespread standard for low power cable replacement is Bluetooth (IEEE 802.15.1). It uses a frequency hopping spread spectrum for data transmission and can reach data rates of 721 kbps. Version 2.0 of the standard introduced the enhanced data rate which allows transmissions with 2.1 Mbps. Bluetooth devices are divided in three power classes with ranges of 1/10/100 m. A group of Bluetooth devices is combined in a so called piconet. The whole piconet is synchronized to one master and uses a specific frequency hopping pattern. One network can consist of up to seven active and 255 inactive or parked devices. In order to build larger networks (scatternet) several piconets are combined by devices acting as bridge between them. A wireless communication standard with low power consumption and optimized for timing-critical applications is ZigBee (IEEE 802.15.4). It has a data rate of 250 kbps and allows ranges from 10 to 100m. This standard divides the band in 16 separate channels and transfers the data with the direct-sequence spread spectrum modulation. One network can have up to 65,536 nodes with full mesh networking.

The main disparity of the three wireless standards besides the bandwidth is the energy consumption. This demonstrates how important the use of different wireless communication standards for changing requirements is. The system offers adaption to the needed requirements like network size, connection latency, bandwidth, and power consumption. WLAN can be used in high bandwidth applications like video streaming. Bluetooth allows continual low power communication. ZigBee offers the possibility of very low power communication for applications with short connection time through short network connection latency. Later on a good solution for mobile ad-hoc communication and localization can be the currently developed low data rate impulse radio ultra-wideband (IR-UWB). It uses a large portion of the radio spectrum and transmits information by generating extremely short pulses. This technique support low data rate for large distances with the ability to determine “time of flight” of the direct path of the radio transmission. The combination of low power and distances measurement will be a good solution for mobile ad-hoc communication and localization. But this can only be evaluated when the hardware is available.

2.2 Distribution of robots by applying swarming algorithms

As already mentioned in the introduction of section 2, the robots have to be distributed in the operation area in such a way that the communication network can robustly operate and that position data can be provided. We propose an equi-triangular distribution of the robots being equipped with communication modules as depicted in figure 2. To achieve this goal, we are investigating swarming algorithms working with and without explicit communication. Details of the swarming are discussed in the next two subsections. The dynamic triangulation method to span the robot mesh is presented in section 2.2.3.

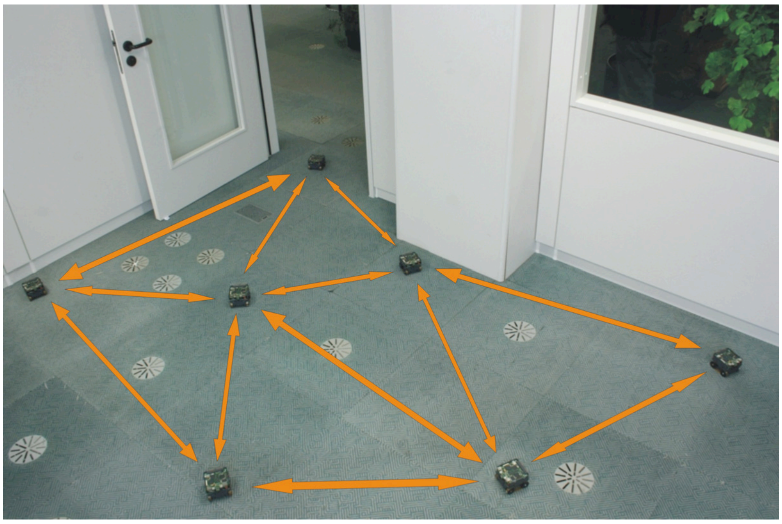

Figure 2: Robots are spanning a communication network with equilateral triangles after they drove into a room (downscaled scenario)

2.2.1 Non-communicative swarming

Non-communicative swarming is considered as a backup for the case in which the communication links are lost. The robots should be able to autonomously navigate in the environment and perform basic behaviors such as aggregation, dispersal, obstacle/robot/fireman avoidance, wall following, robot/fireman following, search (for objects, chemicals, fireman, other robots, exits, communication signals), track gradients, localize themselves, and extract the map of the environment using its on-board sensors (such as infrared/ultrasonic/laser range finders, camera, IMUs, compass, GPS etc.). There are various methods/approaches for achieving these behaviors. Our approach for obstacle avoidance/navigation here will be based on methods such as potential fields [K86, RK92] and Visual Field Histograms (VFHs). Nonlinear control methods (such as sliding mode control [G05], feedback linearization [LBY03]) and intelligent methods (neural, fuzzy) can also be applied. If a map of the environment is available a priori, then higher level path planning for determining a sequence of destinations (way points) to visit (or areas to search) can be determined using efficient search algorithms such as the A* algorithm [HA05]. Then lower-level control algorithms (based on potential functions or other methods) can be used for collision-free navigation between two consecutive way-points.

An important problem in a mobile robotic system is the localization of the robots with respect to the map of the environment or relative to some landmarks. In unknown environments the localization problem is usually also combined with the map building (a problem called simultaneous localization and mapping or shortly SLAM) [DB06, BD06]. In the GUARDIANS system it is highly unlikely that a map of the environment is available a priori. Therefore, the robots should be able to concurrently build a map of the environment and localize themselves within that map and also relative to other robots, the fireman, beacons, landmarks, entrances/exits. The robots have to know the exit path and guide the firemen towards it in case of emergency. This behavior should be successfully performed even in the case of lost communication. Map building (of the environment) is needed not only for localization purposes but also for the objectives of efficient search/exploration and transmitting the data to the base station (when communication is available). The practical implementation of these behaviors will depend on the on-board sensors available on the robots. Inertial measurement unit (IMUs), compass, GPS, vision, infrared, ultrasonic, and laser range finders, can all be useful not only for navigation but also for localization and mapping purposes. There are various studies in the literature for localization and map building using the above mentioned sensors. However, in a smoke situation, some of them (e.g., vision, IR, laser) may not be very reliable and algorithms based on a combination of them or based solely on the most reliable sensors (in the worst case the ultrasonic sensors) is planned to be achieved. Different methods such as occupancy grids, probabilistic (Bayesian) estimation, state/Kalman/particle filters, neural/fuzzy approaches, manifold representation for these purposes are already available in the literature.

Search (for objects, victims, chemical or fire sources, landmarks, beacons or communication signals) and exploration and effective coverage [CMK+04] area are basic desired properties/behaviors the GUARDIANS swarm should possess. Provided that inter-robot communications are available these tasks can be performed cooperatively. However, in the case in which the communications are lost (for one reason or another) search and exploration behavior and sufficient coverage should be achieved without communication (or with very limited communication). The most basic non-communicative search behavior that could be implemented could be random walk, wall following, sweeping, and spiral search. These combined with other behaviors may lead to sufficient exploration and coverage. For example, artificial repulsion of the robots from each other and the obstacles and walls combined with local search may lead to dispersion of the robots and result in search by the individual robots in different sub-areas, artificial attraction/repulsion and formation acquisition/keeping combined with the sweeping behavior may lead to faster exploration. Other more efficient methods will also be investigated.

2.2.2 Communicative swarming

In the case where communications are available the swarm of robots can cooperatively perform most of the swarming tasks more efficiently. For example cooperative parallel search and exploration will be much faster than individual based search [FKL+06]. For this case cooperative algorithms such as cooperative parallel sweeping, PSO (or bio) inspired search are techniques that could be implemented. Techniques for multi-robot cooperative decentralized/distributed simultaneous localization and mapping (SLAM) [RB02, MR06, HSM06] (such as set membership approach, cooperatively merging occupancy grids), area coverage (using Voronoi partitions and probability maps), cooperative swarm plume tracking (gradient following) and source localization [ZSS05] could also be implemented for more efficient and reliable performance. The communication signal can be used not only for information exchange but also its strength can provide valuable information for relative distance and even relative position (provided that appropriate hardware is available for that purpose.) Such information can be used not only for localization purposes, but also for switching from one behavior to another. For example, if the power of a stationary beacon/router is very low, the robot may decide to abort its current task and to become a stationary beacon/router itself.

The basic behaviors developed for non-communicative swarming will constitute the base for the cooperative algorithms to be deployed for communicative swarming. Leader-follower based approach and robot task assignment based on priorities and/or ranking among the robots or through negotiation between the robots can also be investigated (provided that time permits). Potentially useful techniques in developing the communicative swarming algorithms may include Kalman filtering techniques, intelligent (neural/fuzzy) methods, and probabilistic approaches.

Communication and service discovery constitute important utilities for more efficient cooperation between the robots and improved robust performance. Since the swarm will be a heterogeneous one (i.e., there will be different type of robots with different on-board hardware and different capabilities in the swarm), some robots may need to request tasks that they cannot perform from other robots which have that capability. For example, a small robot which has encountered a small obstacle and is unable to overpass it may request a larger robot to continue on its path (to search) or to clear the path (by pushing the small obstacle). Alternatively, a larger robot may request a smaller one to enter a narrow region that it has encountered and cannot go within. Similarly some robots may be equipped with sensors that other robots do not have and could share the information obtained from these sensors with the other robots. Appropriate techniques for robot cooperative control (in addition to the routing and service discovery protocols) may need to be developed for such scenarios.

2.2.3 Dynamic Triangulation Method

We refer to the set of swarming algorithms related to the distribution of robots in the site to be developed within the GUARDIANS project, as to the *dynamic triangulation method.*

The main goal of the dynamic triangulation method is to deploy robots on the site in such a way as to provide its largest coverage. The robots should also be deployed in a sensible manner in order to facilitate communication and exploration of the environment. The dynamic triangulation method should provide, for example, positioning of beacons used as reference points at the vertices of equilateral or nearly equilateral triangles. As the geometry of the environment might be very complex, 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 might include the corners of obstacles. Other robots might be distributed as uniformly as possible in order to gather reliable information about the environment. The robots will form a partition of the environment, separating it in regions, which will represent a triangulation in the absence of obstacles. This partition should adjustable due to the movements of the robots, to accommodate the appearance of new robots, or the loss of some robots, and to reflect the exchange of the roles between mobile robots and beacons. Therefore we call the method the ‘dynamic triangulation’.

The fulfilment of the method represents a challenge for the design of swarming algorithms as the dynamic triangulation is a complex behavior that has to emerge from relatively simple behaviors. The method will also incorporate both non-communicative and communicative swarm modes. All the algorithms and methods presented in the previous subsections will be explored. Essentially, the method will develop a new self-organizing system, which will be a hybrid of a (heterogeneous) swarm, and a mobile ad-hoc network. Such a system will pose new problems and new opportunities.

Among problems addressed we can distinguish the problems of self-localization and morphology of the sensor field. The self-localization problem means that the nodes of the network by using, for example, some ranging devices, estimate distances (and angles) between the neighboring nodes and then on the basis of these measurements derive their global positions. All nodes are formed by mobile robots and each robot has its local communication domain, which includes the node corresponding to a robot together with adjacent edges corresponding to the communication links of individual robot (individual network). Each robot possesses also the sensory information about the surrounding environment, which can be referred to as its domain of sensor visibility. Individual networks form a local network that comprises several robots together with their communication links in such a way that there is a path from a robot $\boldsymbol{r_i}$ to a robot $\boldsymbol{r_j}$ along the edges of the network. So, a local network is a connected graph. A local network becomes a global network if all robots of the swarm are in it, otherwise the swarm may form several local networks. The topology of a local network provides us an initial information about the environment, and can be also seen 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.

Figure 3 shows a sketch of an environment, covered by the ad-hoc local network build by robots. Robots are represented as circles, and the communication links among them are indicated by dashed line segments. Two white circles represent the beacons positioned as the entrance to the site. Whereas other beacons can change their positions, these two positions might be preserved, as beacons at these positions can have several missions. They will provide communication between the swarm and the external facilities; serve as absolute reference points for localisation of other robots and assist robots and humans in the ‘entrance-exit’ procedures. However, it is not necessary that the same robots will act as the ‘entrance beacons'; while the swarm evolves new robots can replace the acting beacons whereas the previous beacons will take part in the swarm.

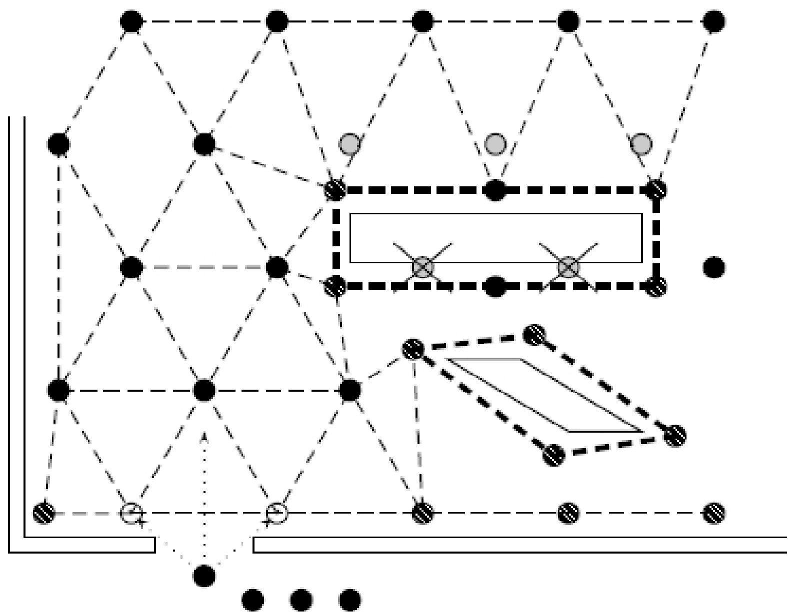

Figure 3: Dynamic triangular network schema

The robots, which might be further positioned as beacons are indicated with rendered circles. These positions might be chosen to facilitate communication (beacons along the wall), indicate obstacles and passages, which in turn will help in map building of the environment and path planning for the human squad.

The thicker dashed lines indicate the obstacles in the environment. The part of the environment with no visible obstacles represents a triangulation. The 'grey' circles indicates the positions of the robots in the case if the environment had no obstacles, in which case an equilateral triangular grid would be preserved. Some of these positions are still possible, but not necessary, as the communication network can function without them. Some positions indicated by 'crossed' grey circles are simply impossible. The challenge here is to keep an 'optimal' network, i.e. such one that provides a good communication but not 'overcrowded' by robots, whose presence enhance neither communication nor the understanding of the environment.

When new robots enter the site, they do not need to go through the whole mesh of the robots to take their positions, but take the positions of the nearest robots, which in turn, will replace some of the robots nearest to them, thus expanding the network by local replacements of nodes. In the figure three possible positions where an entering robot can move, are indicated by dotted arrows.

As robots move autonomously from the previous positions to their present positions, and there are communication links between them, the only possible locations for 'unrecognised' obstacles are within triangles formed by robots. Such obstacles can be detected by robots sensors thus enhancing the initial topological map by local metric information. Therefore, the dynamic triangulation method is the 'alloy' of swarming algorithms, networking protocols and map building.

2.3 Routing and protocols for mobile ad-hoc networks

Wireless mobile networks can be very dynamic. Nodes are mobile and may enter and leave the communication range of other nodes or even the network at any time. Communication over long distances is based on multi-hop connections where nodes on the path between source and destination act as routers and forward messages. Various routing protocols have been developed and proposed for such networks, which can be classified in reactive, proactive and hybrid protocols. Proactive protocols build up routes in advance, whereas route finding in reactive protocols is on-demand and only initiated when data actually has to be sent.

Proactive protocols can offer low latencies as the routes are already available when needed. Destination-Sequenced Distance-Vector Routing (DSDV) is a typical example for a proactive routing algorithm [PB94]. Every node knows its direct neighbors and uses regular messages to maintain the connection to those neighbors. Each node in the network constructs its routing table by exchanging shortest path information with its neighbors. The constructed routing tables contain the address of every node in the network and an optimal route (based on some metrics, e.g. number of hops) to those nodes.

One disadvantage of proactive protocols is usually that traffic is required to maintain the routing tables even when no user data is being sent. However, in master-slave architecture, the neighbors of a node are usually always known. As this neighborhood information can be used by the routing protocol at no cost, a proactive protocol can be implemented without having to exchange messages for neighborhood detection. Therefore, we are going to implement such a slightly modified DSDV protocol. Only in the case of topology changes (new nodes, lost nodes) traffic is generated by the routing protocol for propagating routing information through the network. This solution guarantees low latencies and almost up-to-date routing tables.

3 Experiments and Results

In this section, two experiments are presented. The first experiment aims at measuring the signal quality of WLAN and Bluetooth communication nodes in indoor environments with different kind of wall materials. The second experiment deals with radio based positioning of robots in dynamic environment. Before discussion of the experiments the platform is presented.

3.1 Robot platform

Main robot platform for the real application of an acting team together with fire fighters are to be developed by the Spanish project partner Robotnik. These robots will be equipped with the communication system developed within the project by partner from the University of Paderborn. For the evaluations of the proposed methods and the characterization of the communication devices we are using small scale robots. For a down-scaled scenario the KheperaIII robot from K-Team is used [KT+07]. A robot that has been developed by the Heinz Nixdorf Institute

(HNI) is used to perform indoor experiments with real size of environment. This robot is characterized by its robust chain drive, the modular structure and ideal expandability in terms of sensor systems, communication devices, information processing capabilities, and electromechanical components. This robot is used for the two experiments described in this section.

The HNI-robot platform has been developed in the Heinz Nixdorf Institute. It is designed for experiments with downscaled or simplified real life scenarios and offers a powerful information processing hardware on the robot. One of the main important features of the robot is the parallel use of a powerful mobile processor and an FPGA (field programmable gate array) that enables hardware reconfiguration during runtime and therefore optimal utilization of available hardware resources [KKK+05]. The robot platform has a size of approximately 9cm × 9cm 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 the case [KKG+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 behavior algorithms. The module also contains a three axis acceleration sensor, a yaw rate gyroscope and a sensor for battery charge condition and temperature monitoring. The information processing is done on an extension board that is inserted into the upper slot of the robot. The architecture of the board is shown in figure 4. The board integrates a processor clocked with 520 MHz, 64 MB main and 64 MB flash memory. An FPGA (Xilinx Spartan 3E 1600) enables the use of reconfiguration on hardware level. This allows the computation of complex algorithms by using the FPGA as a dynamic coprocessor.

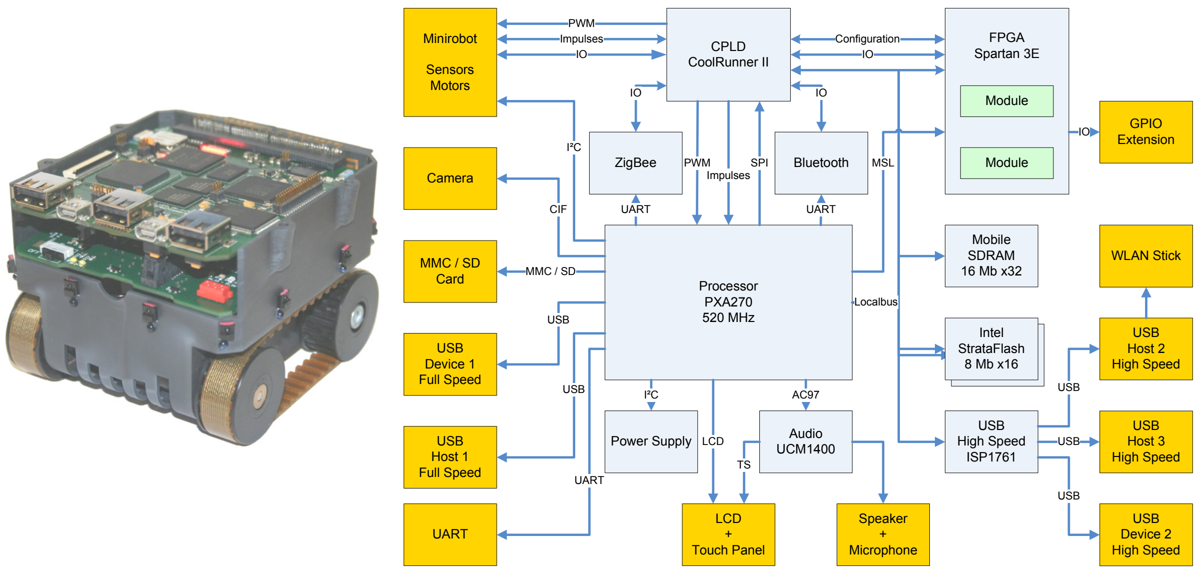

Figure 4: Photograph of the robot used for the presented experiments and architecture of the information processing board

The integrated wireless communication standards ZigBee and Bluetooth offer communication with low bandwidth and low power consumption. High bandwidth communication can be achieved by connecting standard WLAN USB-sticks to the board. 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 4. The software environment of the robot is a Linux (kernel 2.6.22) operating system. This allows the use of any platform independent Linux software on the robot.

3.2 Signal quality evaluation

Several experiments were done for measuring the link quality of both WLAN and Bluetooth standards. For evaluating the Bluetooth standard two experiments were done. The first experiment is to observe the robustness of the communication link between the robots and the communication beacons, and to know the maximum coverage distance that can be supported between them. Here the robots were equipped with Bluetooth class-2 modules while the beacons were equipped with class-1 modules. The second experiment is to observe the maximum coverage distance that can be supported between the beacons, all having the Bluetooth class-1 module.

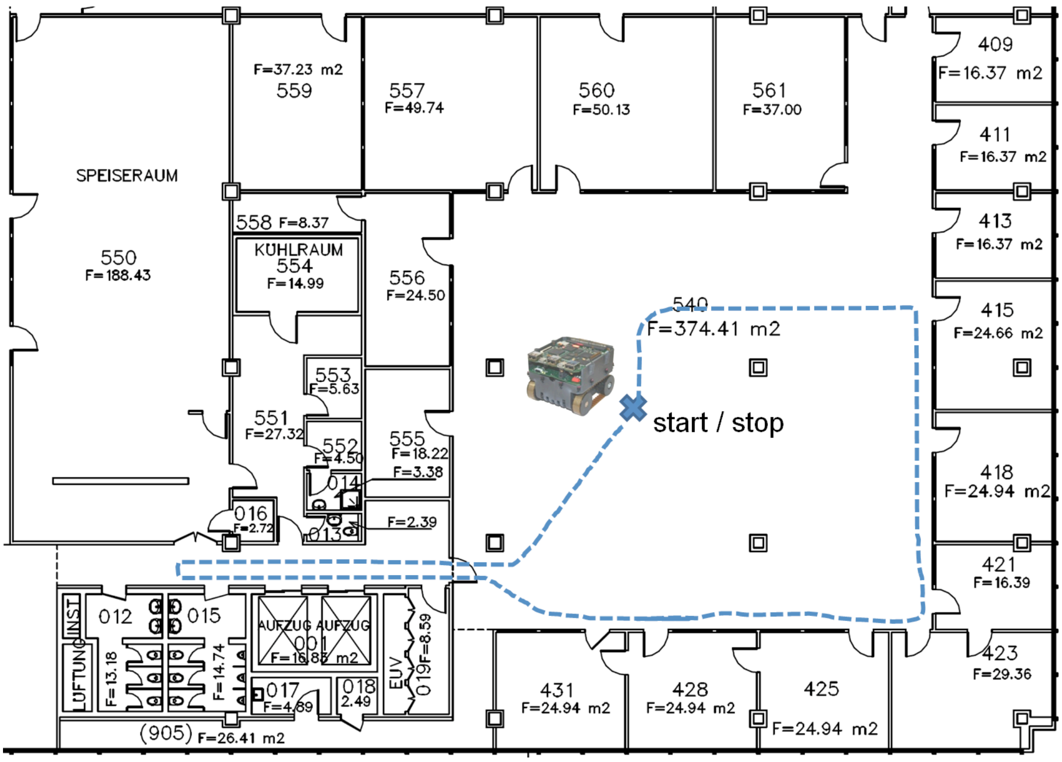

Figure 5: Set-up for the experiment to evaluate the signal quality; The robot was guided along the dashed path, area size: 30m by 15m, path length approx. 90m

In both experiments, the robots were controlled to move in large areas and also inside rooms to monitor the effect of walls and obstacles on the link quality, cf. example in figure 6. A third experiment was done to perform the same measurements but using the WLAN module, first results are depicted in figure 6. Further experiments are planned to be done by navigating the robots using the camera module integrated on the robot's platform to move the robot in corridors and narrow places for a better monitoring of the signal's quality in possibly various conditions. Furthermore, both standards will be tested in smoky environments to simulate real conditions faced in real scenarios.

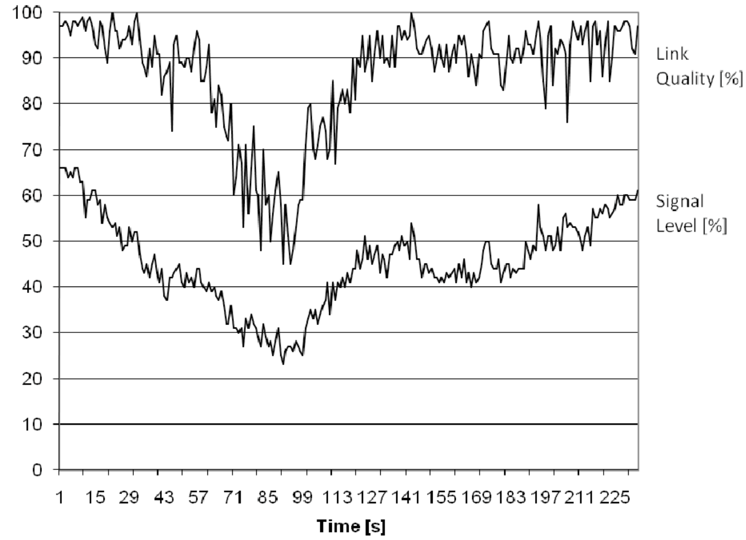

Figure 6: Example link quality and signal level measurement for a WLAN network in indoor environment with respect to figure 5

3.3 Demo scenario

A first demo was done to initially span the network uniformly using equi-lateral triangular distribution, see figure 2. In this demo, a robot placed in a random place is being guided using two beacons to reach the required position to complete the equi-lateral triangle. Both the robot and the two beacons have Bluetooth modules installed to exchange data. The robot is equipped with a laser sensor that can measure distances up to 10 meters, which can rotate to scan the surrounding area with the aid of a stepper motor. The two beacons are equipped with special photo transistors to detect the incident laser beam. The robot starts establishing a wireless connection with the two beacons informing them that it will start the scan process. After connection establishment, the robot starts scanning by rotating the laser scanner while waiting for a response from the beacons. As the laser beam hits the first detector attached to the first beacon, the beacon sends a message to the robot, which acquires the distance between them.

The same process is done with the second beacon. If the angle between the robot and the two beacons is required to be measured, it can be calculated in terms of the steps turned by the stepper motor. Using these data, the required angle to be rotated and distance to be moved to reach the goal is calculated. In the end, the wireless connection is terminated.

The second demo is to demonstrate how the Nanotron system [NAN07] can be used for determining the positions of robots. Three robots are used as anchor points where it is assumed that their positions are already known. For instance, their positions can be obtained either by the aid of laser-range measurements done in the first demo or through odometry. The three robots, together with a local server, are used for determining the position of a forth robot, which is driving around. The measurements take place as follows: robot one, two and three calculate the distances between each of them and robot four via measurements with the Nanotron Positioning System. Afterwards they send their results as well as their own coordinates to the local server, which calculates the position of robot four. Tracking the coordinates of robot four, the local server compares the position data to the predefined path driven by the robot, and presents them graphically on its monitor. Hence, the differences between the actual and calculated positions are visualized on screen. According to the performed tests and measurements, results estimated an accuracy range of about 1 meter if the distances between the robot and the anchors are less than about 10 meters especially if LoS (line of sight) conditions are present. In worse cases, the accuracy range increased to about 2 meters.

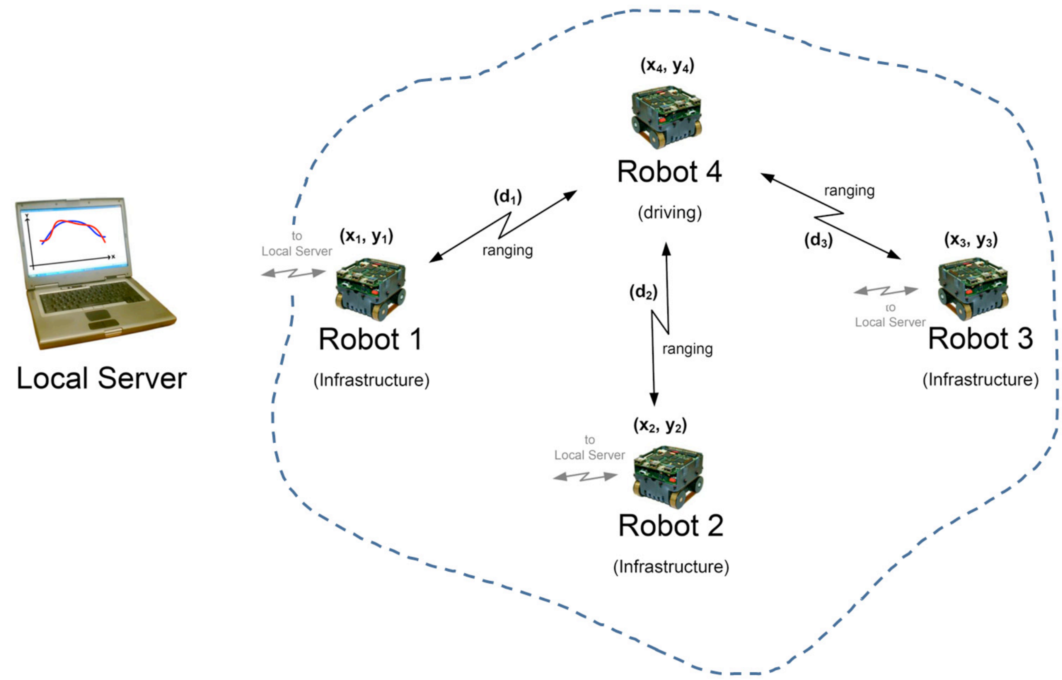

Figure 7: Configuration of the second demo: A network of three mobile robots (called Infrastructure) support a forth robot (driving) with position data by performing time of flight measurements. Robot's trajectory is displayed and analyzed on the local server (for demo purpose only).

4 Conclusion

Main aim of the GUARDIANS project is the development of a team of robots being able to support human fire fighters on several levels to increase overall safety and to extend the operational area of the fire fighters. One of the key issues is a robust communication system providing both communication between all team members and position data. We are focusing on an ad-hoc network communication system based on the mobile robots as communication nodes. In our approach we use a cell based grid with master nodes in each cell to form 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 positioning other mobile robots or humans and at the same time form the infrastructure to support communication all over the search area. In two experiments we have shown that a combination of distance and radio signal quality measurements as well as dedicated swarming behaviors of the robots results in a suitable distribution of the robots. Communications standards considered for the ad-hoc network are Wireless LAN, Bluetooth and ZigBee. All are integrated on a miniature robot for experiments in real size environments. To distribute the robots a combination of communication-based swarming, swarming without explicit communication and dedicated control algorithms are used. By using map data of the operation area collected during the operation as one result of the dynamic triangulation the efficiency of the human-robot-team can be enhanced in terms of area coverage and increased safety.

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