

GUARDIANS multi-robot team as a self-organising system

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Abstract —The GUARDIANS robot swarm is self-organising and can be seen as a hybrid of a (heterogeneous) swarm, a mobile ad-hoc network and an (evolving) topological map of the environment. We assume that robots cooperate in order to deploy themselves, search the area and construct a (online) map of the environment. We present a novel approach of distributing robots on site that takes advantage of a cooperating robot team (with respect to a single robot) allowing us to accurately determine robot positioning and guide deployment in a pre-determined manner. This in turn leads to a topological representation of the environment that can be further developed to a metric map and used as the basis of building ad-hoc mobile wireless communication and sensor networks. The presented algorithms take into consideration also sensor limitation.

The algorithms are to be applied on a group of Khepera III robots, specially upgraded to fulfill the needs of our approach.

Multi-robot team : Self-organising system, topological representation, relative positioning, cooperative map building, ad-hoc communication network

I. INTRODUCTION

In the GUARDIANS project¹ scenario the robots are autonomous and assist fire-fighters in search and rescue operations in an industrial warehouse in the event or danger of fire [13]. The tasks of the robots can be roughly split into two, partially overlapping, categories. In the first category the robots directly assist the fire-fighters, namely by guiding or accompanying a fire fighter and indicating possible obstacles and locations of danger. The second category comprises the tasks for a robot team acting without a human squad-leader, such as on site deployment, positioning as beacons and maintaining communication. The robots also need to be able to

gather relevant environmental information. In this paper we focus on the tasks for GUARDIANS robots in the second category, and propose a new approach for on site deployment of robots for setting up a communication network and building a map of the environment.

Maintaining communication faces two major problems. The first is that the metal cages present in a warehouse render radio reception problematic. The second problem is that of position detection or localisation. For indoor environments GPS is not generally available and simultaneous localisation and mapping (SLAM) has to be based on other sensors. However, because of smoke conventional light based sensors may not produce useful data, in particular vision sensors such as cameras. The radio signal for the wireless communication will not be disturbed by smoke and serves as a coarse fall back. For communication various wireless technologies are available including Wireless LAN, Bluetooth and ZigBee.

In our approach we assume that the use of the LRF is still possible. Such assumption has sense even in the presence of smoke as smoke starts developing close to the ceiling and the robots involved such as Erratics or Khepera III are low or very low in height. The main use of the LRF is two-fold: for robot detection and for distance estimation, which eventually yields accurate localisation and positioning of robots; detection is backed up by wireless communication. However, the idea behind the approach is generic, and the LRF can be substituted by other sensors or sensor system, such as the system based on infrared developed in [14]. Besides the LRF and WiFi, odometry is also taken into consideration. The supplementary, more conventional use of the LRF is for obstacle avoidance and building metric maps. However, the main result of our approach is a topological representation of the environment; the robots play active roles in constructing such a representation,

¹GUARDIANS, Group of Unmanned Assistant Robots Deployed in Aggregative Navigation supported by Scent Detection, EU FP6 ICT 045269

being ‘dynamic nodes’ in the representation as well as acting as landmarks. One of novel features is that the topological map is the first to be built, that can later be upgraded to a more detailed metric representation. In robotic literature topological approaches are, in general, not viewed as independent, as topological maps are built on the top of grid-based map or feature-based maps by partitioning them into coherent regions [9].

Our algorithms have been implemented in C++. We use Player/Stage middleware [17] for validation and testing in simulation environments. Player, which is a distributed device repository server for robots, sensors and actuators, can control either a real or ‘simulated’ robot thus allowing direct application of developed algorithms to real-life scenarios. The robots used for experimentation are Khepera III, produced by the partner K-Team. The robot has been specially upgraded for installing the LRF, Hokuyo; both models URG-04LX and URG-04LX-UG0 can be used [5]. The set-up for a real-life implementation is in the final stage of developing.

We also developed a TCP/IP suite for wireless communication, which is independent of Player.

II. RELATED WORK

The problem of global self-localisation when no *a priori* information about the environment is known, is considered as one of the most difficult in robotics. This problem is related to the famous SLAM problem of a robot simultaneously localising and building a map of the environment. Most existing work on the subject focuses on a single robot only, and the approaches are mainly probabilistic in their nature due to uncertainty.

In the last decade, several works appeared that tackle the problem of cooperative multi-robot localisation [4], [15], [7].

These works fall mostly into the three categories. The first category is related to the multi-SLAM problem when robots build the map separately and then the obtained maps are fused in a global one. The second category is related to robot on site distribution. The third category that partially overlaps with the first two is when the advantage of the use of several robots is applied in full strength: the robots are used as temporary landmarks for mutual recognition and hence, for more accurate representation of the environment.

Our approach belongs to the third category. Our robots represent a self-organising system, and can act as permanent or temporary beacons, whilst other robots are mobile. We also achieve on site distribution consisting of nodes connected by virtual edges, thus describing

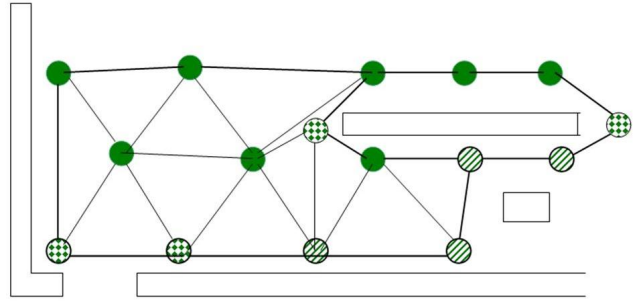


Fig. 1. A full triangulation with obstacles. The dotted robots are beacons, striped robots represent possible beacons. The thicker solid lines indicate the boundary of the environment, covered by the built network.

the environment by means of a graph. The nodes in these graphs are either virtual or real (robots) and their positions are calculated by applying our well-defined schema of robots moves and detection. Depending on the number of robots some robots can become static beacons that can be used for building a robust ad-hoc communication network. Our approach is ‘in tune’ with the methods proposed in [12] and [15].

In our approach four or five robots are sufficient for accurate topological representation of the environment. Three robots are actually required in order for reliable detection of each robot position, but four robots provide a more robust system, as one robot becomes a stationary beacon and may be used as a point of reference.

We also propose a robot detection approach, based on the robot shape and size, as well as taking into consideration that robots are ‘dynamic’ objects. This detection system can be further improved by labelling each robot with a special retro-reflective tag that can be detected by a laser range finder by analysing the intensity of the reflected laser beam. A similar approach was used in the works of Howard et al. on multirobot simultaneous localisation and mapping (see, for example, [7]).

III. SCHEMA OF TOPOLOGICAL MAP BUILDING IN THE GUARDIANS PROJECT

A. A brief historic perspective

The theoretical consideration behind our approach to topological map building is described in detail in [1].

After the distribution of the robots in the environment the network layout can indicate the boundaries of the environment as well as obstacles present, as schematically represented in Fig. 1.

Our approach is a combination of guided positioning and distribution strategies. The main sensors used are

the Laser Range Finder (model Hokuyo) and WiFi. Each robot, therefore, has two fields of view, one related to the LRF and the second - to WiFi. The sensing ranges of the aforementioned sensors differ considerably. The LRF Hokuyo sensing range is within 4 or 5.6 meters depending on the model, whereas the transmission range of a reliable radio signal (IEEE 802.11) is 30m or more.

Initially we thought of using only the strength of the radio signal, to distribute the robots on the site.

Several algorithms have been implemented with Player/Stage. The algorithms are concerned with deployments of robots/nodes as fast as possible while achieving maximised coverage and keeping the network/graph formed by robots connected. An algorithm based on the Clique intensity method [3] has been implemented and compared with the Trivial algorithm [2]. In the first algorithm wireless signal intensity is used as a rough approximation of distance to assist a large number of small robots to disperse (without knowing the relative location of neighbouring robots). This method is applicable in the ‘worst case scenario’, when most of sensors fail, and only radio signals and tactile sensors are ‘functioning’. The performance of the algorithm regarding time and area coverage was similar to the trivial algorithm for the same number of robots. The Trivial algorithm is used for area coverage benchmark but does not guarantee connection between robots.

In Figures 2 and 3 one result of the algorithm based on the clique intensity method, applied to 12 robots, is presented.

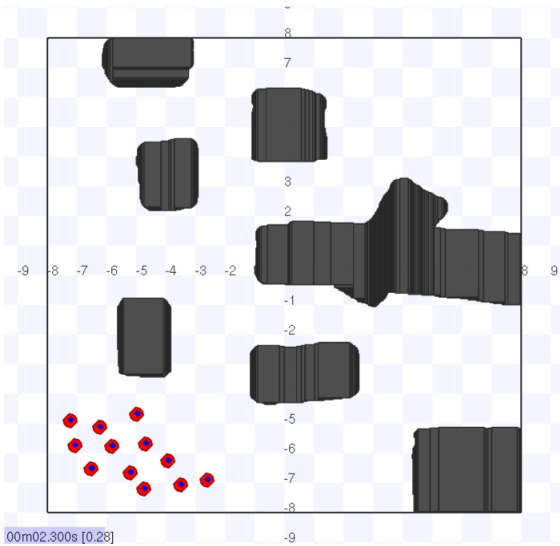


Fig. 2. Robot deployment on a site: Initial configuration.

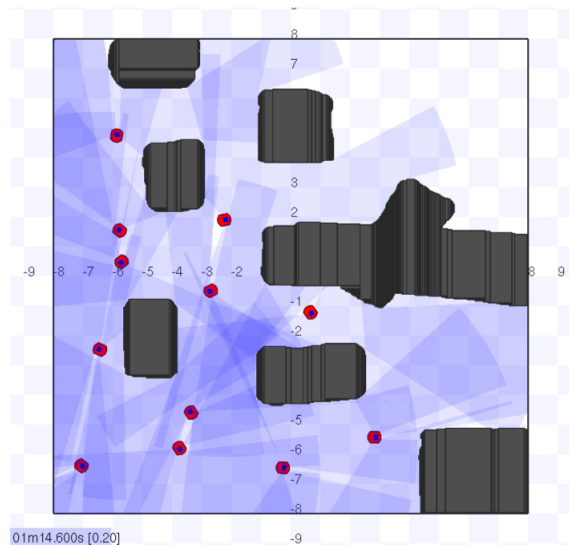


Fig. 3. Robot deployment on a site: Final deployment configuration.

Nevertheless, despite encouraging simulation results, the distribution based solely on radio signal intensity has several flaws. The first one is that the strength of a radio signal is not a precise measure, and therefore the estimated positions might be not reliable. Another flaw is that the graph/network formed by robots is not uniform. One reason for this is that for collision avoidance the potential artificial field method was used.

Positioning based solely on radio signal is therefore employed only as a fall back. The LRF is used as the main sensor ‘responsible’ for position detection now, and all our robots are equipped with the Hokuyo model of LRF.

B. Main concepts behind the schema

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 Fig. 4

The grid can be seen as infinitely being spanned in all direction, and the GUARDIANS robot, while exploring the site, will make a part of the grid ‘real’.

Each robot forms an attainable visibility domain (AVD), determined *a priori*. As it will become clear later, the radius of this domain is equal to at most half (or smaller, such as one third) of the sensing range of the measurement sensor to be used. In our case this sensor is the LRF, but it can be substituted by another, suitable sensor. This domain is depicted in Fig. 5.

As one can see, the domain is in the form of a hexagon, where the black node indicates the robot, and

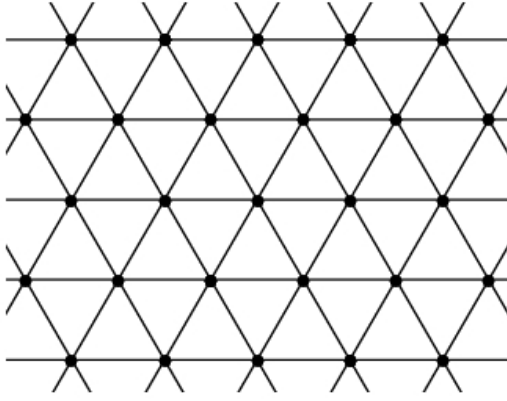


Fig. 4. Virtual triangular grid.

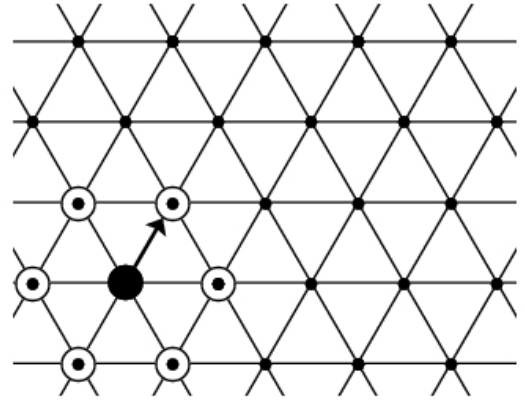


Fig. 6. Domain of a robot on the site.

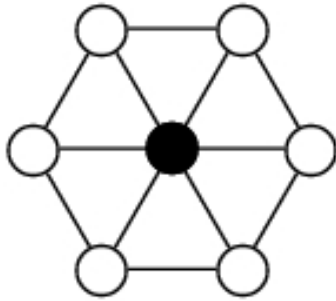


Fig. 5. Visibility domain of a robot

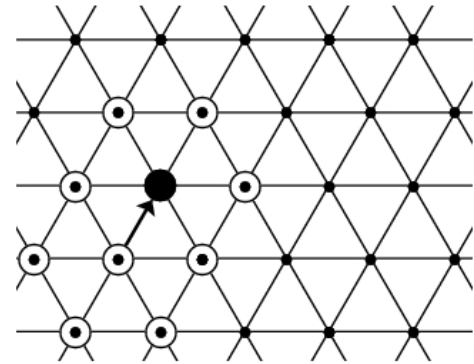


Fig. 7. Explored part of the site.

white dots are nodes in the grid that the robot can ‘sense’. The ‘sensed’ nodes are also the grid nodes to which the robot can also move. It is not necessary that the robot visits all ‘sensed’ nodes, but the ‘sensed’ nodes mean that this part of the environment is explored. Initially, the AVD is virtual, but after robot’s deployment on the site it becomes ‘real’ (see Fig. 6).

The actual range of the Hokuyo LRF is 240 degrees, but as the robot can turn, we consider the AVD as 360 degrees. Moreover the node behind the ‘rear’ of the robot is often the node already visited. 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 Fig. 7).

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 the corresponding node together with all its incident edges is

removed from the AVD and from the ITSM (Fig. 8).

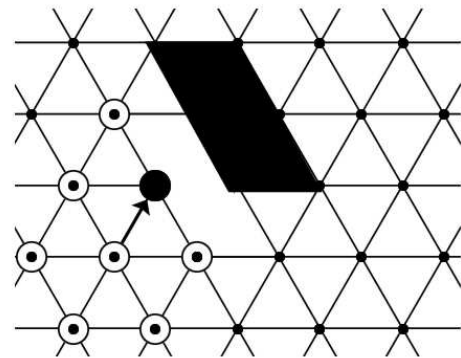


Fig. 8. Explored part of the site with an obstacle present.

C. Guided distribution and positioning

In the previous subsection we described the moving strategy for a robot. In this subsection we upgrade this strategy to a group of robots that additionally allows

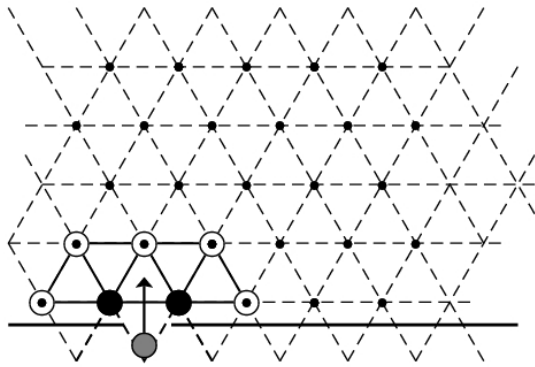


Fig. 9. Robots guided distribution. Initial step.

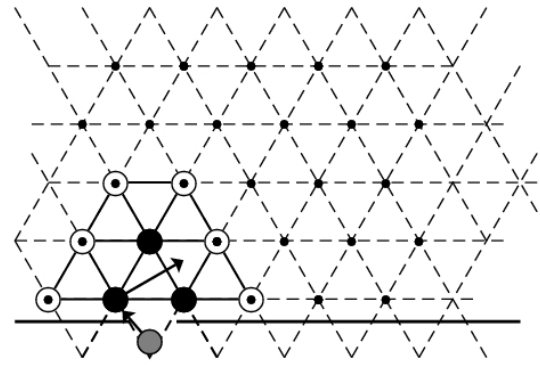


Fig. 11. Robots guided distribution. Next step.

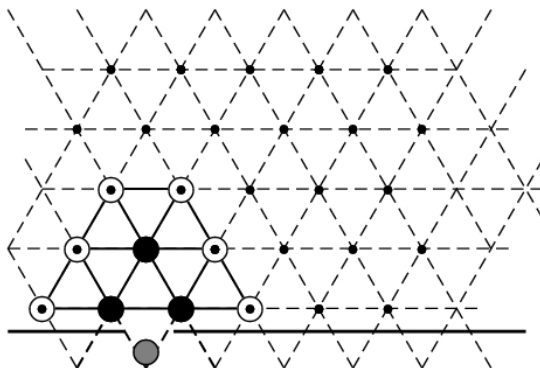


Fig. 10. Robots guided distribution. Forming a triangular cell.

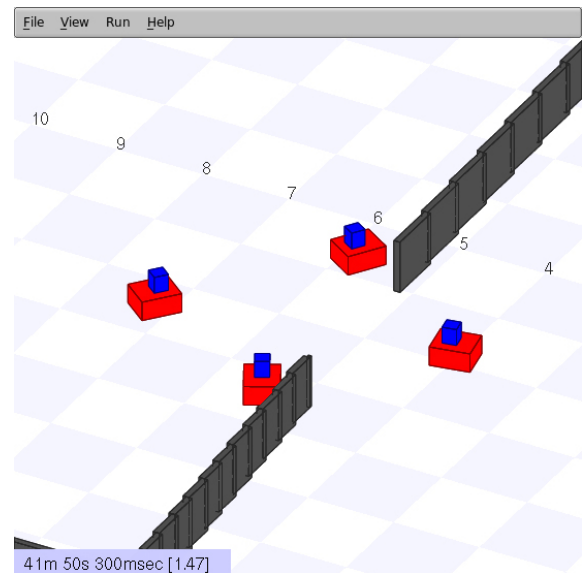


Fig. 12. Robots guided distribution. Initial step. STAGE snapshot.

for accurate robot positioning and localisation. The main step is depicted in Fig. 9.

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 in what follows as *sentinels*.

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 (Fig. 10).

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 Fig. 11

The aforementioned steps are illustrated by two snapshots of its implementation in PLayer/Stage, presented in Fig. 12 and Fig. 13.

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,

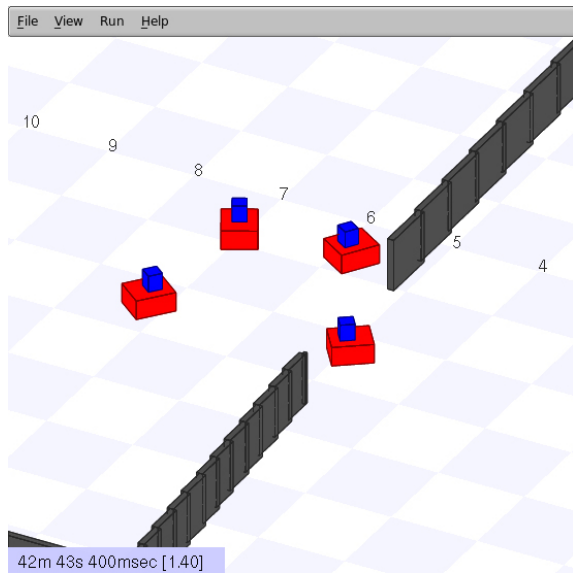


Fig. 13. Robots guided distribution. Next step. STAGE snapshot

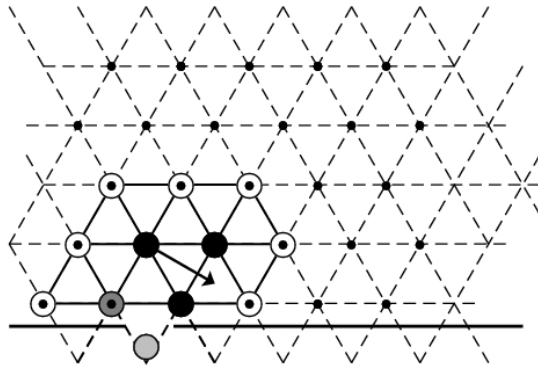


Fig. 14. Robots guided distribution. Moving around.

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 Fig. 14).

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 Fig. 15.

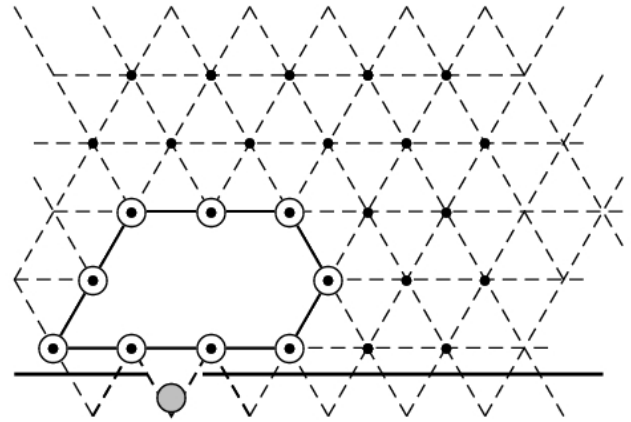


Fig. 15. An example of the topological map, built by the robots.

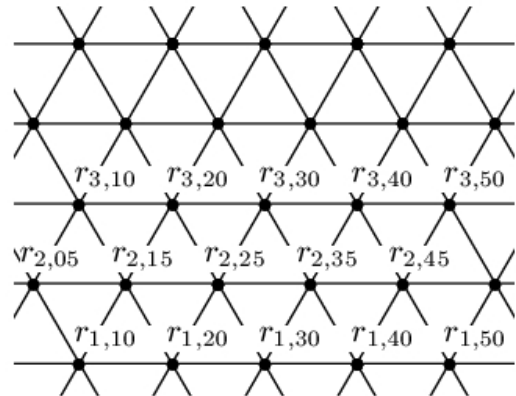


Fig. 16. Grid coordinate system.

D. Triangular system

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 (see Fig. 16).

E. Corners and obstacles

Fig. 17 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 (by any other robot finding itself in that position). On encountering a corner, the robot

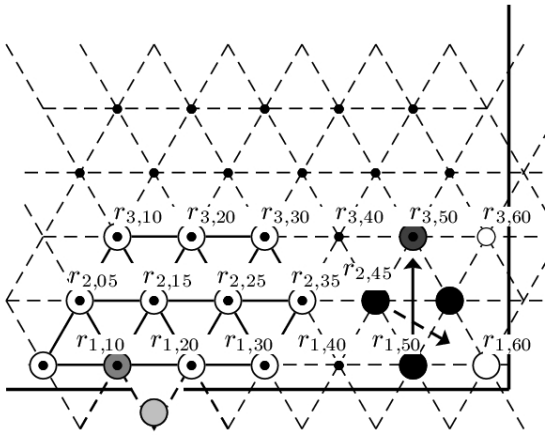


Fig. 17. Corner strategy.

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.

IV. IMPLEMENTATION

In order to test and validate our approach miniature Khepera III robots are used. The robot size allows us to test the algorithms in environments of varying complexity, but the robots are still compact enough to be used in the laboratory. On the other hand, the robots are sufficiently powerful to apply to them sophisticated algorithms. Detailed descriptions of the robots and the sensors are given below.

A. Robots and sensors

The Khepera III robot [11] is based on 10 years of expertise in miniature robotics. Features available on the platform can match the performances of much bigger robots: velocity max of 5m/s for a robot diameter of 130mm. Khepera III has a weight of 690g with a payload of 2kg. Upgradable embedded computing power using the Korebot II system [10] can be added (800 MIPS 624MHz PXA270 processor, 128MB Ram, 32 MB Flash). The robot base includes an array of 9 Infrared Sensors for obstacle detection (0.5-25 cm)

as well as 5 Ultrasonic Sensors for long range object detection (0.2-4.0 m). It also provides an optional front pair of ground Infrared Sensors for line following and table edge detection. The robot motor blocks are Swiss made quality mechanical parts, using very high quality DC motors for efficiency and accuracy. The replaceable battery pack system provides a unique solution for almost continuous experiments (1.5h), as an empty battery can be replaced in a couple of seconds. Through the KoreBot, the robot is also able to host standard Compact Flash extension cards, supporting WiFi, Bluetooth, extra storage space, and many others. A Player/Stage driver for this robot was developed in a previous work during the Guardians project [16].

B. LRF

Each robot is equipped with Hokuyo LRF to get information about the environment as well as for robot localisation and positioning.

Hokuyo company has laser range finder (LRF) sensors with two small models available for small mobile robotics (URG-04LX /URG-04LX-UG0). For an electrical consumption less than 0.5 Amperes at 5 Volts, a serial/usb connection for data transfer and even power supply by USB with the second model above, it provides a measurement range of 0.6-4.1 [m] on a circular aperture of 240° with a measure point every 0.36° and a 0.1s refresh rate with a range error of 1% resp. 3% (see Fig. 18. Hokuyo provides a software programming guide and a library for this sensor [6]. Player/Stage provides a driver for the LRF sensor named ‘urglaser’ [18].

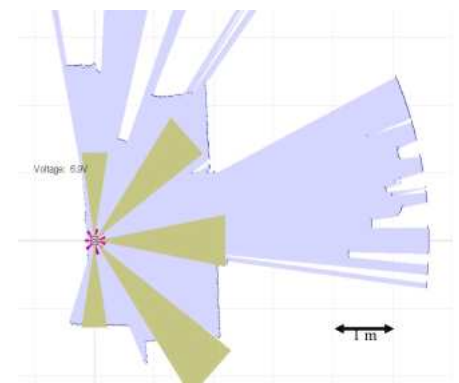


Fig. 18. Khepera III and Hokuyo’s LRF in Player/Stage.

An electronic board was developed for integrating this LRF sensor on the Khepera III robot. Besides the communication data to the robot, it contains also a battery system for the sensor power supply with an autonomy of about 2.5 hour.



Fig. 19. Khepera III and Hokuyo's LRF.

The robot can be controlled remotely by a Player/Stage client and its sensors monitored on it. A Khepera III robot equipped with a Hokuyo LRF (situated on the top) is pictured in Fig. 19). The ultrasonic sensors (range 0.2-4m) can be seen in the second from the bottom 'ring'. The IR sensors, covering the nearest range around the robot are also displayed (next to the bottom).

C. TCP/IP suite for communication

In order to achieve efficient on site distribution the robots communicate by an ad-hoc wireless network. This network is built by the robots and represents a part of the self-organising GUARDIANS robotic system. Each robot is equipped with a WiFi flash card (IEEE 802.11b/g, Ambicom WL500G-CF). A purpose built threaded TCP/IP class was developed to handle communication independent of Player/Stage. This class acts as a general message and data transmission server/client, but also serves to relay routine robot queries which are often required by higher level functions. These routine functions include requests and commands for robot positioning and orientating, odometry settings, laser ranges, and so on. Automating such requests 'behind the scenes' results in cleaner and clearer implementations of the more advanced higher-level functions such as sentinel/anonymous robot identification and co-operative sentinel/robot/laser manoeuvring.

V. EXPERIMENTAL SET-UP

A. Robot detection and recognition

Robot recognition using the laser sensor is one of the major challenges in this project. Each robot has to identify other robots and distinguish them among

obstacles that could be found around the robot. Once the robots identify other robots, one can figure out its own position based on the positions of the other robots using the triangulation method described earlier.

As mentioned earlier in this paper, the use of light based sensors, such as cameras, is not reliable due to low visibility. So, in this section, laser based robot detection is developed and tested as will be explained shortly.

Because of the small size of the LRF sensor, it will be difficult to detect such a small shape. So, an extra shape of a larger size is designed and fixed onto the robots as shown in Fig. 20.

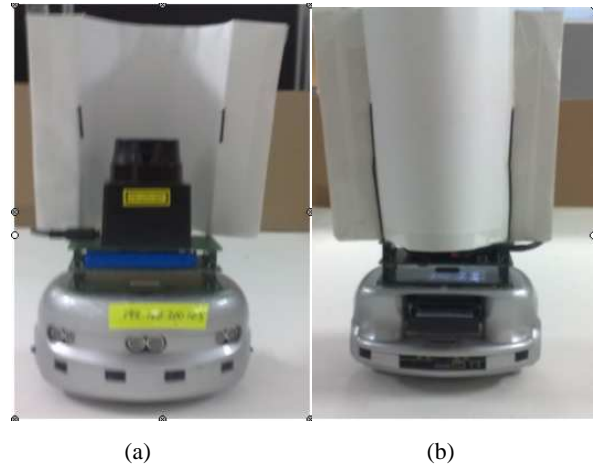


Fig. 20. Khepera III robots with extra shape for laser detection (a) Front view. (b) Rear view.

Our robot detection approach is carried out using the so-called 'two scans' method. Firstly, the scanning robot scans the surrounding environment using its LRF sensor. Then, this robot broadcasts a message using the TCP/IP socket asking all other robots to move forward by a short distance, 10 cm in our example. Afterwards, the scanning robot scans the environments for the second time. Because only the robots have moved between the two scans, the absolute difference between these scans will emphasise the location of these robots leading to detection of the robots and illumination of all obstacles.

The proposed algorithm has been tested to recognise the robots as shown in Fig. 21.

In Fig. 21 the actual experimental setup is presented; the robot near the edge of the area is the scanning robot which scans the arena to detect the other robot. Figure 22 shows a 2D laser scan of the environment (local map) of the scanning robot.

Figures 23 and 24 show the laser measurements (distances taken) of the first and second scan respectively.

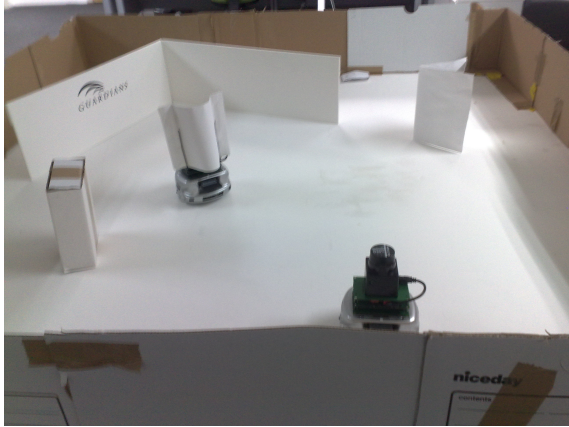


Fig. 21. Experimental set up.

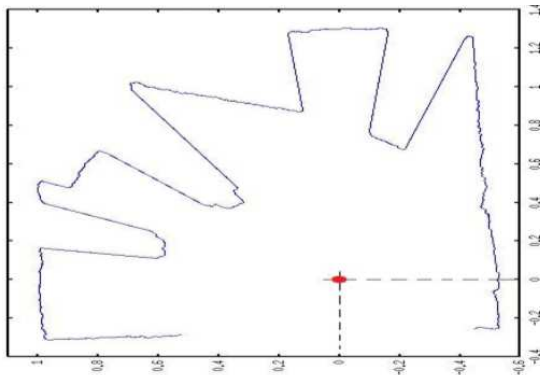


Fig. 22. 2D laser scan.

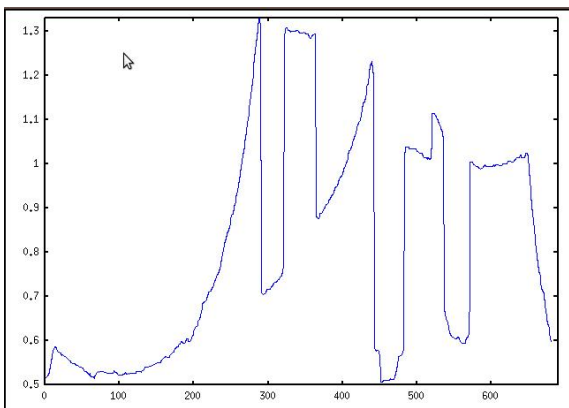


Fig. 23. First scan measurements graph.

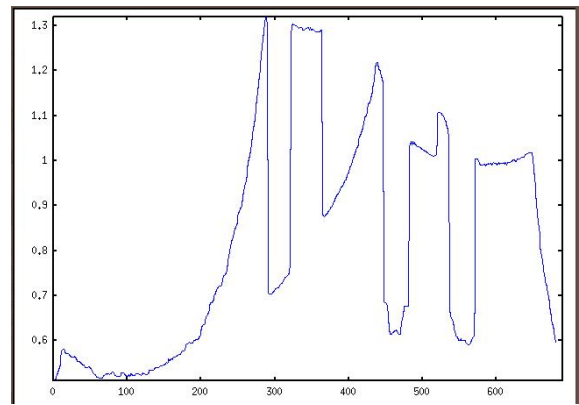


Fig. 24. Second scan measurements graph.

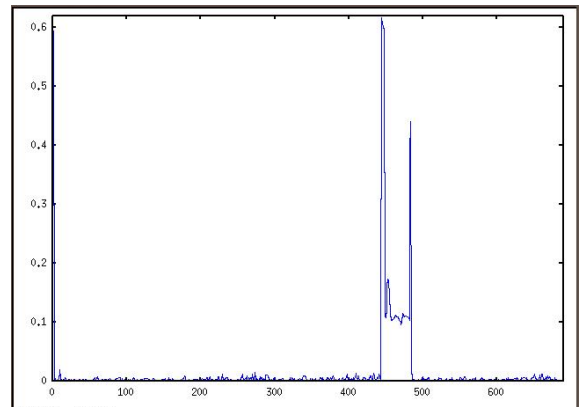


Fig. 25. Difference graph of the scan measurements.

Figure 25 shows the absolute difference between the two profiles shown in previous figures. Clearly, this difference eliminates all of obstacles as they still remain static between the two scans. Only the difference in the positions of the robot has non zero values. Finding the robot position is carried out by selecting the central index of the non-zero values. In our particular example, the central index is found at 465 which means that the robot is located 51 cm away from the scanning robot and at the angle of 40 degrees which matches the physical angle and distance between robots.

Recall that our strategy for robot movement requires that only one robot moves at a time, which simplifies the recognition process even further. However, our approach is more general, and allows recognition of several robots in the vicinity of the scanning robot. Actually, the method can be used also without communication, but communication provides robustness if there are moving obstacles as well. In the latter case not only one robot scans the environment, but the other robots as well.

Based on the obtained differences in the scans and communicated approximate positions each robot can detect other robots in its AVD.

VI. CONCLUSION

We have proposed an approach that consists of cooperative positioning system (CPS) that accurately determines robot positions through cooperative control of individual robots in the group, construction of the topological map of the site and an ad-hoc wireless communication network.

A practical set-up for a real-life scenario is also described.

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