Experimental Study on the Effects of Communication Range on Cooperative Robotic Search in Complex Environments

Ömer Çayırpunar, Veysel Gazi, Bulent Tavli, Enric Cervera, Ulf Witkowski, and Jacques Penders

***Abstract*—Communication has an important role in multi-robot systems. It can facilitate cooperation, therefore, improve the performance of the system significantly. In this study we investigated the benefits of networked communication by experimentally evaluating the results of two search algorithms which are spiral search and informed random search. The experiments were performed in an experimental area containing obstacles and using e-puck robots where the communication ranges were "simulated" with the help of an overhead camera. Each robot was allowed to (*i*) keep an occupancy grid based local map of the environment containing also information about the cells it has visited and (*ii*) exchange this information with the other robots within its communication range. The effect of the size of communication range on the performance of the system defined as the time of completion of the search task (i.e, locating the target), was investigated.**

***Index Terms*—Multi-robot teams, communication network, cooperative search, transmission range.**

I. Introduction

Search and rescue operations have great importance under disaster situations like earthquakes or terrorist attacks. In such disaster relief missions search and exploration are the initial steps of a larger operation. Traditionally such missions have been performed by human teams; however, there are intensive ongoing research efforts for developing multi-robot search teams to be deployed in such missions. Rescue robotics, or basically the use of autonomous robots in search and rescue operations, is a relatively new field of research. It is a part of the broader field of coordination of a group of mobile robots to achieve a specific objective/goal. In order to achieve cooperative behavior there is a need for effective (direct or indirect) communication methodologies. The use of a network architecture is one possible form of direct communication and will be very essential in many applications that require information exchange between the robotic agents in a team and the team and human operators. In particular, in search and rescue scenarios by combining the communication network with an appropriate search algorithm, an effective search can be achieved by the robots.

It is obvious that it is difficult or even impossible to have global information and implement centralized controllers in systems consisting of large number of agents with limited capabilities. Therefore, recent research has concentrated on decentralized approaches. In such systems, the inter-agent communication and networking algorithms are of paramount importance. In other words, for development of effective practical multi-robot systems besides the need for development and verification of effective coordination and control strategies, there is a need for development and verification of robust and scalable communication and networking algorithms and protocols.

Communication/networking can enhance the performance of multi-robot systems from several aspects [1]. First of all, in the case the group of robots has to fulfill a specific goal, the coordination between different agents becomes very important. Second, with communication the robots can exchange valuable information and significantly improve the performance of the system.

A group of mobile communicating robots constitutes by its nature a wireless ad-hoc network. In such a system there are many issues to be resolved for effective operation. First of all, since the agents will be simple, their communication capabilities (such as range, power, processing capability, etc) will also be limited. Therefore, if there are two agents separated by a distance larger than their direct communication range they will have to relay their messages through other intermediate agents [2]. Therefore, beside the need for development of appropriate message structures and communication protocols, there is a need for development of effective/cooperative routing/networking protocols, as well. A recent survey on the main issues in mobile sensor networks can be found in [3].

Performance of a distributed robotic system using shared communications channels is presented in [4]. It is shown that for surveillance applications it is extremely important to coordinate the robots through wireless communication channels. Yet, the performance of the system is affected by the capacity of the links and the number of robots sharing the links. It is reported in [5] that adding simple communication capabilities to robots improves the predictability of the task completion times. In [6] a multi-robot coverage study is presented. It is shown that by allowing robots to communicate through wireless links, better algorithms for the complete coverage problem can be obtained. In [7] it is shown through simulations

This work was supported in part by the Scientific and Technological Research Council of Turkey (TÜBİTAK) under grant no 104E170 and by the European Commission under the GUARDIANS Project (FP6 contract No. 045269).

O. Cayirpunar and B. Tavli are with the Dept. of Computer Engineering, TOBB University of Economics and Technology, Söğütözü Cad. No: 43, 06560 Ankara, TURKEY. (email: {ocayirpunar, btavli}@etu.edu.tr).

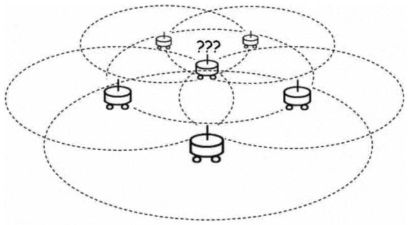
V. Gazi is with the Dept. of Electrical and Electronics Engineering, TOBB University of Economics and Technology, Söğütözü Cad. No: 43, 06560 Ankara, TURKEY. (email: vgazi@etu.edu.tr).

E. Cervera is with the Dept. of Computer Science and Engineering, Jaume-I University, Campus Riu Sec, 12071 Castelló, SPAIN, (email: enric.cervera@icc.uji.es).

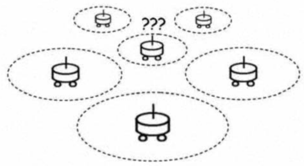
U. Witkowski is with the Heinz Nixdorf Institute, University of Paderborn, Fuerstenallee 1133102 Paderborn, GERMANY, (email: witkowski@hni.upb.de).

J. Penders is with Microsystems and Machine Vision Lab, Sheffield Hallam University, Pond Street, Sheffield S1 1WB, UK (email: j.penders@shu.ac.uk).

ROBOCOMM 2009, 31st Mar – 2nd Apr 2009, Odense, Denmark.
 ISBN 978-963-9799-51-6
DOI 10.4108/ICST.ROBOCOMM2009.5840



(a) Long communication range.



(b) Short communication range.

Fig. 1. The effect of the size of communication.

that use of direct communication (through wireless links) can be beneficial for the effectiveness of the group behavior in performing collaborative tasks.

We can divide communication in multi-robot systems into global communication and local communication. Global communication is the situation in which every agent can communicate with every other agent, whereas local communication describes the situation in which each robot can communicate only with its local neighbors. Global communication is effective for small number of robots in a small area. However, when the number of robots or the size of the search space increases, this becomes difficult to be realized because of the limited communication capacity and increasing amount of communication to handle. Let us suppose that each robot has the ability to adjust its range of communication. If it is too large, the efficiency of information transmission decreases because the communication traffic becomes too congested and the robots cannot handle that traffic (Figure 1(a)). On the other hand, the efficiency is low if output range is too small as well (Figure 1(b)). It is therefore essential to develop methodologies for optimizing communication range in order to provide efficient information transmission between the agents.

In this study we consider cooperative search by a team of mobile robots using a dynamic wireless communication network to convey information among the members of the team. The experiments were performed in an experimental area containing obstacles and using e-puck robots where the communication ranges were "simulated" with the help of an overhead camera. The effects of the communication range in networked communication in a multi-robot cooperative search scenario was investigated by experimentally evaluating the results of two search algorithms which are spiral search and informed random search. In particular, the effect of the size of communication range on the performance of the system defined as the time of completion the search task (i.e, locating the target), was investigated.

II. EXPERIMENTAL SET-UP

Experiments were performed in the set-up available in our laboratory (Figure 2). This set-up consists of a 120x180 cm experimental area, 6 e-puck robots with bluetooth interface, logitech USB camera and Matlab as the main image processing and control development platform. The positions and orientations and ID's of the robots are determined by a labelling system (Figure 3) consisting of small colored dots placed on the top of the robots. The robot position and orientations are determined by three colored dots placed on the edges of an isosceles triangle. Furthermore, robot ID's are determined by a binary coding system consisting of black colored dots placed on the labels. A more detailed description of the set-up can be found in [8].

Fig. 2. Experimental setup consisting of an arena, robots, PC and overhead camera.

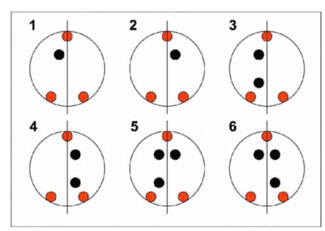


Fig. 3. The robot labelling system for six robots.

The e-puck robot is a small (7.0 cm diameter) mobile robot equipped with some sensors and differential drive locomotion system. These mobile robots are small enough therefore, a high number of robots may be utilized simultaneously in the experiments. They have bluetooth wireless communication modules which we have used as the medium for information exchange. However, that communication hardware is a class II bluetooth device having constant RF output power and therefore could not provide any changeable communication range. Since a communication device capable of adjusting its

Digital Object Identifier: 10.4108/ICST.ROBOCOMM2009.5840
http://dx.doi.org/10.4108/ICST.ROBOCOMM2009.5840

transmission range is not available we had to develop some other methods to simulate this feature.

This paper is mainly focused on to study the effects of communication range on cooperative multi robot search task, thus, in this study we did not consider all the RF impairments and basically focused on and simulated the communication based on the disk communication model. The disk communication model assumes that the communication takes place in a circular area with a constant diameter. Although it is a fact that wireless communication can not be simply represented as an exact distance and it is dependent on the environment, the point here is not to measure those effects.

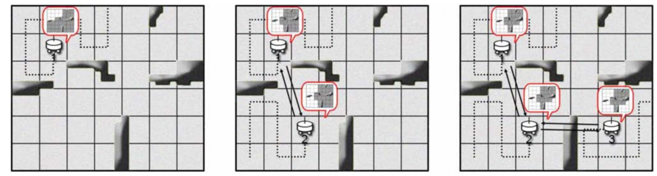
The robots set their motor speeds according to the commands supplied by the computer via the bluetooth interface. In other words, the control algorithm running on the main computer which is based on the search strategy, decides which cell to be visited next. The robot movements are controlled by artificial potential functions. An artificial potential is binded to the target cell to be visited next and a force is applied to the negative direction to the gradient of the potential field. Then, that force is converted to the control outputs as linear and steering angle speeds to be transferred to the robots. All of the nodes of the search space are visited sequentially in that manner. Beside the higher level control by the computer, the robots have an obstacle avoidance behavior running at low-level. In other words, the robot movements are controlled with a weighed sum of the control inputs obtained from the computer and the sensorial information collected from the environment. However, the obstacle avoidance has a higher priority to make sure that the robot does not collide with any obstacles accidentally.

A high quality USB overhead camera is used in the experiments which is directly connected to the computer. A resolution of 640x480 is sufficient for this set-up considering the sizes. The frame rate is not the main criteria in the selection of the camera since the image processing unit can not process more than 5-6 frames per second.

As was mentioned above, the frames of the arena are grabbed and processed to determine the position, orientation and identification of the robots. This information set is supplied to the function running behavior algorithms of agents which output the control inputs (the angular and translational speeds) to the robots. The resulting angular and translational speeds of the agents are transferred to the agents via bluetooth communication modules. The main delay in the system occurs due to the image processing.

III. PROBLEM DEFINITION

Our experiment scenario is basically a search of a predefined object in a complex environment including walls and some obstacles (Figure 4). The search is started individually by the robots from different locations. Robots perform the search by following a random path or a predefined path based on the environment. During the search, when the robots encounter each other (i.e, when they enter each other's communication range) they share their search information database. This concept is demonstrated in Figure 4. In Figure 4(a) robot 1 is performing the search by following the search path which is generated by some search algorithm. The information bubble on top of robot 1 shows the explored areas in the memory of this robot which is simply the occupancy grid map of the previously searched areas. In Figure 4(b) a second robot joins the search from a different location. The arrows show the process of successful information sharing between robots 1 and 2. After the sharing of the search database the newly formed search maps are demonstrated in the information bubbles. Similarly, in Figure 4(c) the cooperation of robots 2 and 3 and the resulting search maps are demonstrated. Finally, in Figure 4(c) the communication takes place in between both robots 1-2 and robots 2-3. Therefore, robots 1 and 3 communicate indirectly through robot 2 and the search maps of all of the robots are combined which will make the continuing search more efficient (i.e, the robots will not search on places which are previously searched by the other robots).



(a) (b) (c)

Fig. 4. Concept of cooperative search by communication.

In Figure 5 the map based on our real experimental environment is represented. This map is a grid map in which zeros represent empty spaces and the ones stand for obstacles in the search space. The search only takes place in the empty places without colliding with any of the obstacles. The search space is divided into a 12 x 18 virtual grids. Six e-puck robots are randomly placed into their initial starting positions within the arena as shown in the figure ($R1$ through $R6$). The robots are placed to the same initial positions at the beginning in all of the experiments in order to get objective results. The label T represents the object which is to be found.

The information which is to be shared between the robots is the occupancy grid maps of the previously searched places. In other words, it is the map of the visited cells. Each robot has it's own local map of those occupancy cells. At each step the robots use that map in order to decide the next cell to visit and to prevent or at least minimize the search of the same area multiple times.

Robots share their map of the visited cells when they are in communication range. That is the maximum distance of data transmission. That communication distance can be changed by filtering the data transmission between the robots. As was mentioned before, an overhead camera is used to calculate the robot positions, orientations and ID's. Based on that information the inter robot distances are calculated and the communication takes place only when the distance between two robots is smaller than the maximum transmission range.

Initially the robots start their search individually. However,

Digital Object Identifier: 10.4108/ICST.ROBOCOMM2009.5840
http://dx.doi.org/10.4108/ICST.ROBOCOMM2009.5840

whenever two robots encounter each other, i.e., two robots enter the communication range of each other, they exchange their local occupancy maps. The communication ranges of the robots and whether they are within that range or not are determined from the images taken by the overhead camera system. In other words, the robot communication ranges are "simulated" through the experimental setup. In this way one can easily experiment with different communication ranges and see the effects of communication.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	0	0	0	*R4*	0	0	0	0	0
0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
0	1	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0
0	0	0	*R2*	0	0	0	0	1	*R1*	0	0	1	1	1	1	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	*T*	0	0	0	1	1	1	0	0	*R6*	0	0
0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0	0	*R3*	0	0	0	0	0	0	0	0
0	0	*R5*	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 5. The search space with obstacles, robots, and target.

In the experiments the communication sizes are varied between 0 to 200 cm with steps of 20 cm. A communication range of 0 means no communication implying that the robots search individually without cooperation. In contrast, a communication range of 200 means global communication in which each agent can communicate with every other agent.

In the following section we will describe the search strategies used in the experiments.

IV. SEARCH STRATEGIES

Two different search strategies are used in the experiments. The first one is a spiral search which is using distance transform to calculate an exploration path and the other is informed random search which is a simply random search having the memory of previously searched places.

A. Spiral Search

We have used an altered version of spiral search as a complete search and coverage algorithm [9] which is mainly focused on the search of the nearest grids first. In that search the robot sweeps all areas of free space in an environment in a systematic and efficient manner. For that reason the map of the search space should be known prior to the experiments.

To achieve the complete coverage behavior the robot follows a path which moves away from a starting point keeping track of the cells it has visited. In other words, the robot only moves into a grid cell which is closer to the current cell if it has visited all the neighboring cells which lie further away from the current cell. In order to do this, the search algorithm first calculates the distance transform of all the cells with respect to the starting point then generates a path for complete coverage. In Figure 6 the results of the distance transform applied to robot $R1$ is shown. Additionally, in Figure 7 the complete coverage and exploration path generated for robot $R1$ is presented.

9	8	7	6	6	6	6	5	4	4	4	4	4	4	5	6	7	8
9	8	7	6	5	5	5	5		3	3	3	3	4	5	6	7	8
9	8	7	6	5	4	4	4		2	2	2	3	4	5	6	7	8
9					4	3	3		1	1	2	3	4	5	6	7	8
9	8	7	6	5	4	3	2		*R1*	1	2					7	8
9	8	7	6	5	4	3	2	1	1	1	2	3	4	5	6	7	8
9	8	7	6	5	4	3	2	2	2	2	2	3	4	5	6	7	8
9	8	7	6	5	4	3	3	3	3				4	5	6	7	8
9	8	7		5	4	4	4	4			6	5	5	5	6	7	8
9	8	8		5	5	5	5	5	5	6	6	6	6	6	6	7	8
9	9	9		6	6	6	6	6	6	6	7	7	7	7	7	7	8
10	10	10	8	7	7	7	7	7	7	7	7	8	8	8	8	8	8

Fig. 6. Distance transform applied to robot $R1$.

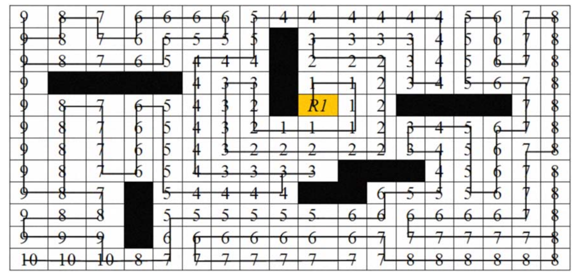


Fig. 7. Complete coverage and exploration path generated for robot $R1$.

Closer observation of the above described path of complete coverage shows that the path of complete coverage produces too many turns. This is because the coverage path follows the "spiral" of the distance transform wave front that radiated from the start point. As a result the search can take longer than expected. In certain configurations of obstacles in an environment this can produce unsatisfactory performance. Therefore, complete coverage paths of the type shown in Figure 7 are somehow difficult to execute on a mobile robot. To overcome such undesirable results in our experiments the path is checked with a secondary algorithm, which looks for dead ends and handles them by changing the path to the nearest unsearched areas.

B. Informed Random Search

The second search algorithm is a type of random search (i.e., the robots move in the search space randomly). However, the robots keep the track of the previously searched spaces. By using this information the robots randomly select their next destination cell from the unvisited cells in the near vicinity. Every grid on the search map is connected to 8 other cells. Therefore, the algorithm randomly chooses the next target from those neighboring 8 cells. In Figure 8 the exploration path generated by this algorithm is demonstrated. In addition, while exploring around, the information about the visited cells at the past are kept on an occupancy grid map. For the later steps the algorithm considers the visited cells while randomly choosing the next target. Therefore, the search becomes an informed random search. To overcome unwelcomed results such as in the cases where all of the nearby cells are visited the algorithm looks for the previous cells recursively to find unsearched areas then selects those empty places for new target destinations.

Digital Object Identifier: 10.4108/ICST.ROBOCOMM2009.5840
http://dx.doi.org/10.4108/ICST.ROBOCOMM2009.5840

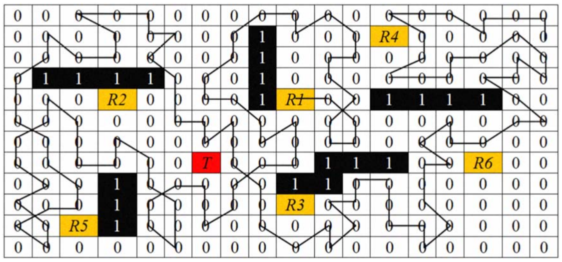


Fig. 8. The exploration path for robot 1 generated by informed random search.

V. EXPERIMENTAL RESULTS

In all of the experiments the mission is to find a hidden object in the search space. With this objective the performance is measured as the mission's completion time (i.e., the time it takes the robots to locate the position of the target).

Robots can only communicate when they are in communication range of each other. They share/exchange their local occupancy grids during each encounter. Then using the information obtained from the encountered robots they update their own occupancy grid maps (using a single binary "OR" operation). Since in this manner, through intermediate robots, a robot can obtain also information about the cells searched by a robot it has never directly encountered. Therefore, the communication strategy has some characteristics of multi-hop communication. Because of the nature of multi-hop networking, the information can be shared between the agents although they are not in range of each other. The information can be carried over and over for longer distances. Therefore, it is not necessary to have a wide communication range always. In other words, it is not needed to have a global communication between the agents for the best performance.

The experimental results in Figures 9 and 10 show the average results over 5 runs for each communication distance to be tested. The communication ranges are distributed between zero communication and global communication. In our experiment setup the maximum distance between two different robots can be approximately 210 cm. Therefore, a communication distance larger than 210 cm can be described as global communication. Additionally, the search performance of different number of robots are collected. Accordingly the search experiments are repeated for 6, 3 and 1 robots and the results are presented in the figures. It is seen that the performance is increasing proportional to the number of the robots as they are cooperating while searching.

Initially, a small increase in the communication range is enhancing the search performance significantly. However, after some point the increase in the communication range does not result in significant change. Moreover, it is observed that the communication range does not need to cover the whole search space. In random informed search with 6 robots the distance beyond which no significant change in the performance occurs is about 90 cm (Figure 10(a)) and in spiral search this distance is only 30 cm (Figure 9(a)).

In this study the main point is not to compare the two type of search strategies. In contrast, the main point is to investigate the benefits of networked communication on the search performance. Still, for the experiments conducted it was observed that informed random search shows better performance than the spiral search which can be seen in the experimental results. However, one should also note that it is not guaranteed that the informed random search can always locate the target because of the algorithms stochastic nature and because the search algorithm is terminated due to a predetermined timeout. Nevertheless, the possibility to find the target is very high (96 percent for the experiments in this article). Only in 2 of the 50 experiments the target could not be found. In contrast, the spiral search guarantees a complete coverage because of the distance transform applied.

In spiral search the total number of cells which have been visited before finding the target is 25 percent more than the informed random search (Figures 9(b) and 10(b)). Also the number of multi-visited cells is much higher. Cells are usually being visited multiple times when a robot is visiting a cell and is unaware that it has been visited before.

In random search the robots usually disperse the area very quickly and because of their random movements they find the target object in a faster manner than the spiral search even if no communication exits between them. Additionally, in random search because of the robots random movements the information exchange becomes very effective even in short communication ranges. The robots not only move very actively over the space but also encounter each other very often. Therefore, they share their information more frequently. This, on the other hand, leads to the fact that they keep more up to date maps of the visited cells which leads to increase in the search performance.

VI. CONCLUDING REMARKS

In this study a cooperative search by mobile robots is presented. The cooperation is by the networked communication of the agents. The results of the study are collected by real experiments with e-puck mini mobile robots. We measured the performance of two search strategies which are namely a modified version of spiral search and informed random search, for different communication ranges and for different number of robots. We observed in our experiments that informed random search has better performance with equal ranges of communication as compared to the spiral search. In addition, we observed that, the performance of the systems improves with the increase of communication range. Also, when the number of cooperating robots are increased the search performance is increasing proportionally. As it is seen from the results the performance of the system consisting of 6 robots is better than that of 3 robots and similarly 3 robots search performance is better than 1 robot search. The results also show that it is not necessary to have a global communication for better performance. In other words, it is not needed that the communication range to cover all the search area. The effective communication between the agents is highly dependent on the

Digital Object Identifier: 10.4108/ICST.ROBOCOMM2009.5840
http://dx.doi.org/10.4108/ICST.ROBOCOMM2009.5840

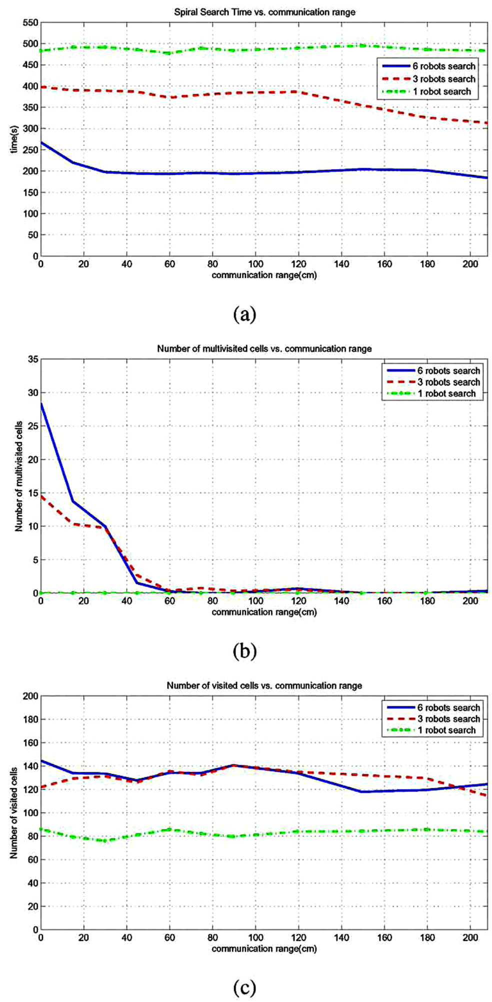


Fig. 9. Experimental results of spiral search.

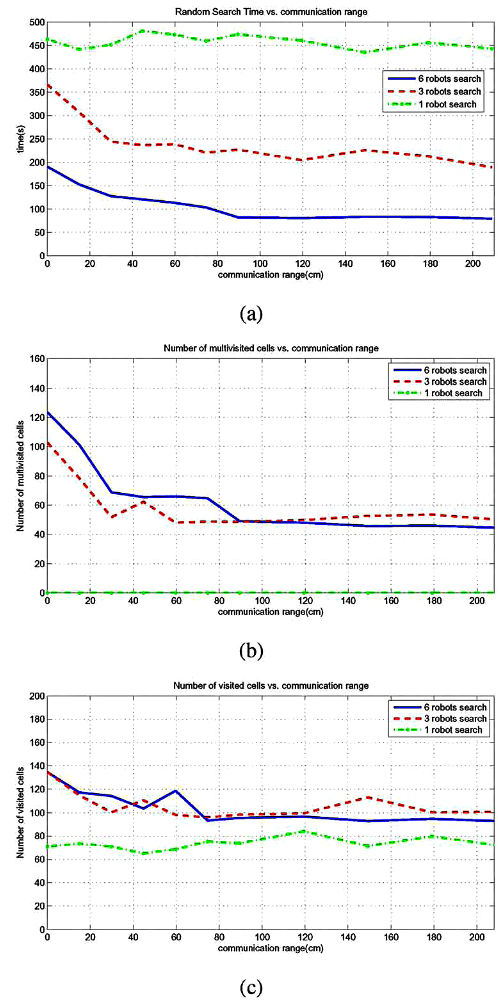


Fig. 10. Experimental results of random informed search.

environmental parameters such as the size of the search space and the number of the robots. Similarly the characteristics of the search algorithm is an important factor affecting the performance of the search.

Future research can concentrate on developing an algorithm for selecting the optimum communication range dynamically in order to minimize the power usage without significantly affecting the performance of the system. In addition, the effects of unequal communication ranges between the robots can be investigated. At the time of the experiments a communication hardware which can adjust its transmission range was not available. Therefore, we had to simulate this feature. If such hardware is available, more realistic experiments can be conducted as well.

REFERENCES

[1] T. Balch and R. Arkin, "Communication in reactive multi-agent robotic systems," *Autonomous Robots*, vol. 1, no. 1, pp. 1–25, 1994.

[2] O. Cayirpunar, V. Gazi, and B. Tavli, "Dynamic robot networks for search and rescue operations," in *Proceedings of the EURON/IARP International Workshop on Robotics for Risky Interventions and Surveillance of the Environment*, Benicassim, Spain, January 2008.

[3] I. Akyildiz, W. Su, Y. Sankarasubramniam, and E. Cayirci, "A survey on sensor networks," in *IEEE Commununications Magazine*, vol. 40, no. 8, August 2002, pp. 102–114.

[4] P. Rybski, S. Stoeter, M. Gini, D. Hougen, and N. Papanikolopoulos, "Performance of a distributed robotics system using shared communications channels," in *IEEE transactions on Robotics and Automation*, vol. 18, August 2002, pp. 713–727.

[5] P. Rybski, A. Larson, H. Veeraraghavan, M. LaPoint, and M. Gini, "Communication strategies in multi-robot search and retrieval: Experiences with mindart," in *Proc. Int'l Symp. on Distributed Autonomous Robotic Systems*, June 2004.

[6] I. Dekleitis, V. Lee-Shue, A. New, and H. Choset, "Limited communication, multi-robot team based coverage," in *Proceedings of the IEEE international Conference on Robotics and Automation*, vol. 4, April 2004, pp. 3462–3468.

[7] V. Trianni, T. Labella, and M. Dorigo, "Evolution of direct communication for a swarm-bot performing hole avoidance," in *Lecture Notes in Computer Science (LNCS)*, vol. 3172, 2004, pp. 130–141.

[8] A. Samiloglu, O. Cayirpunar, V. Gazi, and A. Koku, "An experimental set-up for multi-robot applications," in *International Conference on Simulation, Modeling and Programming for Autonomous Robots (SIMPAR 2008)*, 2008.

[9] A. Zelinsky, R. Jarvis, J. Byrne, and S. Yuta, "Planning paths of complete coverage of an unstructured environment by a mobile robot," in *Proceedings of the International Conference on Advanced Robotics*, 1993, pp. 533–538.

Digital Object Identifier: 10.4108/ICST.ROBOCOMM2009.5840
http://dx.doi.org/10.4108/ICST.ROBOCOMM2009.5840