Proceedings of the 2006 IEEE/RSJ
International Conference on Intelligent Robots and Systems
October 9 - 15, 2006, Beijing, China

Multi-robot Aggregation Strategies with Limited Communication

Yan Meng
Dept. of Electrical and Computer Engineering
Stevens Institute of Technology
Hoboken, New Jersey, USA
yan.meng@stevens.edu

Jeffrey V. Nickerson
School of Technology Management
Stevens Institute of Technology
Hoboken, New Jersey, USA
jnickerson@stevens.edu

Jing Gan
Dept. of Electrical and Computer Engineering
Stevens Institute of Technology
Hoboken, New Jersey, USA
jgan@stevens.edu

Abstract – **The limited power, low radio range, and an ever changing environment make the ability to explicitly communicate between multi-robots decreases in a searching task. When this happens, maintaining the weakened connection will cause robots to cluster during searching, which may be suboptimal with respect to the searching time. In this paper, several integration strategies are proposed to coordinate a team of robots which have limited explicit communication. To speed up the reconnection procedure for the proposed aggregate strategies, implicit communication through vision sensors is proposed in this paper to establish a movement plan to recover the explicit communication. Simulation results are presented and discussed; The real-world experiments with 3 Pioneer robots have been conducted. The proposed strategies can be extended to a large-scale searching environment as well as a combination of humans and robots.**

Index Terms – multi-robot coordination, communication recovery, aggregation strategy.

I. INTRODUCTION

As a community, we would like to be able to deploy teams of robots to explore the environment in order to assist in tasks such as searching. Most multi-robot searching approaches assume that robots will maintain wireless (explicit) communication with each other during the searching. However, since the on-board wireless device of each robot has limited power and low radio range, producing a well connected network with these small wireless devices while maximizing the searching efficiency is a challenging task, especially in an ever changing environment. The wireless networks must continuously deal with the connectivity topology changing. Robots may fail, robots or their surroundings, move around, and the weather might even shift and change which nodes are within radio range of each other.

In the searching task, we eventually want the robots to integrate information on the success of their search. If we relax the requirement of constant connection, the searching task can be conducted in parallel and has potential to cover more areas under certain period. However, without planning, the robots might have to search for each other after they have completed their search and the reconnection can not be guaranteed.

In human survival manuals, there is a simple method recommended for coordinating after a communication loss. Members of a team agree ahead of time on a place to meet, called a rally point [1]. This technique has been studied in relation to robotic communication in emergencies [2, 3]. In the area of robotic search, the use of a rendezvous between two searching robots at a pre-arranged spot has been studied [4].

In this paper, our objective is to manage the coordination between a team of searching robots with a restricted ability to communicate, and improve on rendezvous-at-a-fixed-spot techniques. Furthermore, to speed up the integration procedure when their explicit communication is not available, a hybrid communication mechanism, which combines the implicit communication by vision with the explicit communication by radio, is proposed in this paper. The basic idea is when the radio communication is not available, the vision communication are used to establish a movement plan to get back into radio connection, and is thus in the service of the radio communication need.

II. RELATED WORK

Extensive research has been carried out on the topics of multi-robot coordination, where communication is critical for the success of coordination. In general, the communication mechanism can be classified into two categories: implicit communication and explicit communication.

Implicit communication transmits information through the environment or through the observation of behaviors of other robots. Some researches have been conducted on the implicit communications [5, 6, 7] in multi-robot system. Arkin et. al. in [5, 6] indicated that explicit communication is not always required to achieve an increase in utility. He demonstrates experiments and results for which teams fare equally well without the use of explicit communication. Further, they states that if implicit communication is present, then explicit communication provides little or no improvement.

Roy and Dudek [4] addressed the rendezvous problem of two heterogeneous robots with limited communication range exploring unknown environments. The basic idea of their approach is that the robots have an agreed-on notion of what constitutes a good rendezvous point. At a pre-arranged time, the robots go to the best rendezvous point, and wait for the other robots to arrive. They can then fuse their map and suitably partition any remaining exploration to be done.

1-4244-0259-X/06/$20.00 ©2006 IEEE

Most previous work in multi-robot coordinate relies on explicit communication to keep robots in communication with each other [8, 9]. However, in related empirical work such as urban search and rescue (USAR), explicit communication remains a big issue due to the extremely noise of communication, bandwidth problems, and loss of communication [10].

One way to enhance the communication reliability is to proactively adjust a robot's behaviors to try to avoid communication failure before it occurs [11, 12]. This method relies on maintaining a clear line of sight between the communicating robots. Another way is to design a reactive approach to deal with the network failure when it occurs so that the network can be recovered [13, 14].

Ulam and Arkin [13] implemented reactive communication recovery by integrating a suite of four primitive communication recovery behaviors formulated as motor schemas into the multi-robot simulation environment. Instead of recovering network communication, Dias et al. [14] proposed the TraderBots approach to ensure robustness and promote graceful degradation in team performance when faced with robot malfunctions including communication failures, partial failure of robot resources necessary for task execution and complete robot failure. This approach mainly focused on the overall team performance instead of communication failure recovery.

III. AGGREGATION STRATEGIES

The objective of this study is to design heuristic searching strategies for a team of robots working cooperatively to search for targets in a partially known environment with limited communication ability. Assume a team of robots is heterogeneous, consisting of hosts and searching robots. The host robots have more computation power, with an on-board long-range wireless device, while the searching robots have less computation power with an on-board short-range wireless device. Due to the large scale of robot systems and large scale of the searching area, a team of robots are divided into several sub-teams, where each sub-team consists of one host and several searching robots. Within each sub-team, robots communicate through a short-range mobile ad hoc network. The global communication between the sub-team can be conducted via long-range mobile ad hoc network between the hosts. The host robot integrates the information from other local searching robots, and sends the collected information to other hosts. This hierarchical communication mechanism is power-efficient since only low-power communication is needed within each sub-team to save more power for the searching task.

The host robots make high-level decisions, involving task assignments, global map building, and global target information, whereas the searching robot only holds local perceptual data and some host status information. To cover more searching area in a fixed amount of time, initially the robots, as a sub-team, are dispersed in parallel to different searching areas looking for the randomly scattered targets, even beyond the radio range of the on-board wireless device. The objective is to minimize the searching time, which is defined as the time from the starting point to the time when all of the information about the expected targets are received. To be more robust, the searching system is also expected to handle the emergency situations, where the radio communication is broken due to some environmental reasons or traffic jam.

To make the searching more efficient, we assume the hosts are located within the long-range communication radius. To reduce the communication overhead, decrease the chances to be attacked by the opponents, and diminish the congestion, host-host communication will be conducted only as necessary. Communication should occur if targets are detected or if there is a technical failure. A heartbeat is used to communicate host status.

A. Static Rally Point (SRP) Approach

In the first strategy, for each sub-team, all searching robots which have lost communication move to a rally point when they have finished their own assigned searching area. At the rally point, all the information will be exchanged and collected by the host through an ad-hoc network. Assuming an ad-hoc network, the robots do not have to physically meet the host or each other, but might stop moving at the point at which they connect to the rally point. We call this strategy the *static rally point* (*SRP*).

The location of the rally point for each sub-team depends on the environment and the rally points of other sub-teams. Usually these static rally points should be set up within the long-range communication area between the hosts. The host assigns different searching areas to each searching robot within its sub-team, and each robot uses its path planner to search their assigned area, and moves to the rally point as soon as it finishes its searching area or finds a target, whichever comes first. In this approach, the host robot for each sub-team is located on the rally point for information integration, and does not move after stationing itself. The static hosts can exchange the global searching information with each other.

B. Mobile Rally Point (MRP) Approach

Because there is variability along three dimensions (the searching environment, the robots' actions, and target distribution), setting a predetermined meeting point may not be an optimal strategy. Robots may be able to finish searching faster if the rally point is mobile after they identify the targets.

Therefore, we consider a *mobile rally point* (*MRP*) strategy. In this technique a mobile host for each sub-team fulfills the function of a rally point. All of the other robots periodically reconvene at the host robot at pre-assigned times in order to integrate the searching information. Effectively, the robots perform a series of synchronizations. The searching task will be finished when the host robot has information about all the expected targets after a reconvening session, which may happen before the entire field has been explored.

For example, if the static rally point approach would need 10 minutes to finish the searching, we can use the mobile approach and set the reconvene period as 2.5 minutes. When the period time is up, the host robot stops moving, and the searching robots move back toward the anticipated position of the host to integrate target information. When the synchronization is over, the host moves to the next synch point on the way to the exit and the searching robots resume their own searching. The host robot tells the searching robots to stop during the synchronization period at which the host first realizes all the targets have been found.

To synchronize with other hosts, the navigation path for each mobile host needs to be developed so that the distances between the hosts are within the long range communication area during the reconvening session. In other words, the hosts themselves will need to rendezvous.

This technique will usually integrate information faster than the static rally point technique. In addition, an overall sense of search progress will be achieved at defined times and the hosts only need to communicate with each other during the reconvening session. This will reduce uncertainty. However, robots may need to move back and forth to the rally point more often, which may be wasteful of energy, leading us to consider a third strategy.

C. Mobile Integrator (MI) Approach

The third strategy, which we call the *mobile integrator* (*MI*), is designed to minimize unnecessary movement. Instead of all robots of each sub-team reconvening periodically to exchange the information, only the robot who detects a target or multiple targets will move toward and inform the moving host robot of its sub-team, otherwise it will continue its own searching task. The searching task is over whenever all of the targets are detected. The destinations of the mobile integrators are setup at the some preset points of the searching area, and the host robots move continuously and slowly throughout the search effort, attempting to stay in the middle of the searching crowd within each sub-team. The *stop searching* command will be sent out by the host when the searching task is over if the robots are within the communication range, otherwise, the searching robots will eventually stop at the preset points.

Notice that this strategy involves a tradeoff; there will be less movement than in the previous strategy, but at any particular time there may be less certainty about the progress of a search and the location of the robots as compared to the second strategy, in which the robots synchronize periodically.

Similar to the MRP, to globally synchronize with other hosts, the navigation path for each mobile host needs to be developed so that the distances between the hosts are within the long range of communication during the whole searching time. Compared with MRP method, the communication cost of MI method is higher, and the travel cost is lower. Since movement usually consumes much more power than communication, the overall power consumption of MI should be less than MRP.

D. Mobile Integrator with Time-Out (MITO) Approach

In *MI* approach, in the case when a searching robot detects a target at a very early stage and then informs the host, if the radio communication between the robot and the host is not available when the host sends out the *stop searching* command, the robot may search around for a long time before it finally approaches the host. In order to save the energy of the searching robot, we propose a fourth strategy, which we call *Mobile Integrator with Time-Out (MITO),* to minimize unnecessary movement after the task is over.

The strategy is similar to the *MI* approach, except that the searching robot moves toward the host for more target information after a predefined time-out. This time-out period may be set up according to the size of the environment or the number of the targets. For example, the bigger the environment, the greater the time-out period will be; the more the targets, the shorter the time-out period will be. With this time-out feature, the searching robot may lessen the amount of unnecessary searching.

IV. A HYBRID COMMUNICATION APPROACH

The main motivation of the aggregate strategies is to accelerate the searching task by dispersing the robots as much as possible, so that more areas would be covered in a shorter time. The prerequisite of this approach is that we have to know how to recover the explicit communication between the searching robots and the host so that searching information can be integrated efficiently.

Here, we are proposing a hybrid communication mechanism that an implicit communication through vision is applied to help in locating the host robot so that the recovery can be obtained for the explicit communication. This may seem counter-intuitive, as it inverts the normal relation between vision and radio. The normal assumption is that radio covers a wider range than vision. However, there may be situations in which using vision is preferable to using radio. For example, in adversarial situations, radio transmissions may be detected, and therefore every transmission incurs additional risk. Or radio transmissions may be jammed intentionally, or blocked because of congestion. The use of vision at the very least expands the possible design space of robotic solutions – smaller range radios can be considered, or more intermittent use of radios can be planned for, reducing power requirements and possibly the risk of attack.

During aggregation, it is very straightforward for the searching robot to exchange the target information if its radio channel is available. If the radio channel is attenuated between the searching robot and the host upon aggregation, and the host is still within the visual range of the searching robot, therefore, the visual channel can help to detect and track the host and guide the searching robot to move toward the host until the explicit communication between them is reestablished. In the case where the host is out of both visual and radio ranges of the searching robots, the robot has to rely on the predicted host position based on waypoints exchanged at the last rallying point. It would be desirable if the searching robots could estimate the position of the host upon aggregation time. Then, when the searching robots move toward the estimated point with some errors, the probability of establishing re-connection either by visual or radio channel would be greatly increased. A position estimation method will be discussed in the next section.

V. POSITION ESTIMATION OF THE HOST

Initially all of the robots are assumed to be connected at the entrance. Therefore, the host robot can broadcast its initial planned path to all of the searching robots before the robots to be dispersed to different areas. It is possible for the searching robot to predict the host position at any given time based on this initial planed path information, with the assumption that the host robot always moves at the same given speed.

For the purposes of the experiment we will perform, the wavefront path planner is used as our global path planner, and the Vector Field Histogram Plus local navigation method by Ulrich and Borenstein [15] is used as the obstacle avoidance algorithm. In order to function effectively with an underlying obstacle avoidance algorithm, the planner only transmits waypoints, not the entire path.

Assume that there are n waypoints in the initial planed path for host robot, as shown in Fig. 1, where the SP, WP, and GP represent the starting point, way point, and goal point, respectively. The time intervals between SP to WP, WP to WP, and WP to GP can be obtained by Equation (1) and the angles between the x-axis of the global coordinate and different waypoint phase can be obtained by Equation (2).

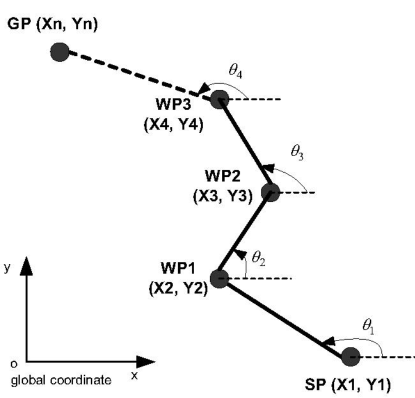

Fig.1. Initial planned path with three waypoints for host robot at the entrance, where WP stands for *waypoint*, SP stands for *starting point*, and GP stands for *goal.*

$$\Delta t_i = \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} / v, \quad i = 1,2,3,...,n \qquad (1)$$

$$\theta_i = arctg \frac{y_{i+1} - y_i}{x_{i+1} - x_i}, \quad i = 1,2,3,...,n \qquad (2)$$

Then the estimated position of the host robot at time t can be obtained by the following equation.

$$\text{when } t \le \Delta t_1$$
$$x(t) = x_1 + vt\cos\theta_1, y(t) = y_1 + vt\sin\theta_1$$

$$\text{when } \Delta t_i \le t \le \Delta t_{i+1}$$
$$x(t) = x_i + vt\cos\theta_i, y(t) = y_i + vt\sin\theta_i, \quad i = 2,3,...,n. \qquad (3)$$

Since it takes time for the searching robot to catch up with the mobile host, it would not be appropriate for the searching robot to set the destination as the host's current estimated location using the above method. Instead, the searching robot has to predict how long it may take to arrive to the host's current position, and predict the host's future location with this time interval, and set up this host's future location as its new path destination. This approach is more cost efficient because the searching robot skips the current location of the host and plans a short-cut path to catch up to the host's future location. To minimize the accumulated estimation error, the host would always inform all the searching robots its current waypoint planner during every aggregation time.

VI. SYSTEM FAULT TOLERANCE

A. When a Host Fails

Under some emergency situations, the host robot may fail due to physical damages or system malfunctions. When a host fails, the corresponding searching robots cannot take over the host role due to their limited computational power and limited radio range. Furthermore, the searching robots only communicate with the local host and they will become isolated from the other sub-teams if their local host fails.

One obvious approach is to remove the failed host and its corresponding searching robots from the team list, and continue the searching with the left-over sub-teams. However, the robot resources would be wasted. Therefore, a dynamical host allocation approach is proposed as follows.

First, each host should be able to dynamically add a new searching robot into its sub-team or remove a lost or failed searching robot from its sub-team. Accordingly, dynamic task allocation is required for each host. Second, the searching robots should store the status and information of their neighboring hosts. If the local host cannot be detected from a close distance for a period of time, the local searching robots can assume that this host has failed. Based on the information of their neighbor hosts, each searching robot will pick the closest neighbor host and move toward to it if the static rally point strategy is applied, or move toward to the next mobile rally point of the closest neighbor host with other aggregation strategies, such as MRP, MI, and MITO, using the proposed host movement estimation approach. The searching robots send *join-in* requests to the neighboring host. After receiving the confirmation message from the host, the searching robots join in the new sub-team to continue the searching task.

B. When a Host is out of Long-Range Communication

It is easy to control the hosts so they are within range of each other when static rally point strategy is applied. However, for other mobile strategies, such as MRP, MI, and MITO, one or more hosts may temporarily move out of the communication range. As long as the hosts are within the communication range for periodic message exchange, there will be no effect on overall system performance. If the host cannot be detected for a period of time, the other host would assume that this host is either lost or failed. To improve the searching efficiency, other hosts continue their searching task. If the host is just temporarily out of communication range, once the lost host finds its way back to the connection, the other hosts will update the new status of the lost host.

To enable the lost host to recover from a disconnection, a centroid-based approach is proposed here. Based on the current location of each host obtained through the host-host communication, the centroid point of all the hosts at the current moment can be estimated. During the searching, we can reasonably assume that the centroid of the hosts will move much slowly compared to the host movement. Therefore, the lost host can move toward the last centroid point before its disconnection until the reconnection is established. To ensure the connection with its local searching robots, the lost robot will inform the local robots of its new motion plan toward the centroid point.

VII. SIMULATION AND EXPERIMENTAL RESULTS

A. Simulation Results

To test the aggregate strategies with a multi-robot system, searching simulations using 9 robots were carried out. These 9 robots are divided into three sub-teams, where each sub-team has one host and two searching robots. The searching area is set up as 150m x 150m with 20 rooms. The three targets are randomly distributed in these 20 rooms. The host-host communication range is 100m, and the short-range between the host and searching robot is 20m. Initially all the robots are placed in the center of the searching area. Then three sub-teams are dispersed into different areas. 100 target configurations are randomly generated, and three aggregation strategies SRP, MRP, and MI are conducted for each configuration.

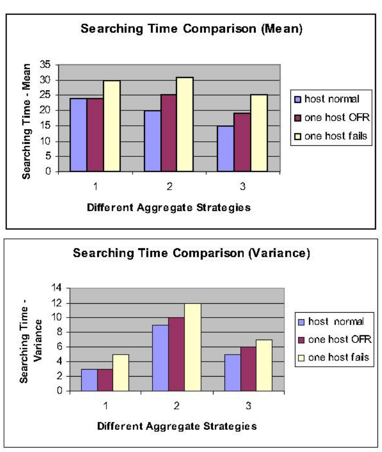

Fig. 2. Searching time comparison (mean value and variance): 1 for SRP, 2 for MRP, and 3 for MI

To verify the proposed aggregation strategies as well as the system robustness, three cases are considered. The first case is for three hosts working normally and within the communication range. In the second case one host is out of range, and in the third case one host fails after 5 minutes. The mean searching time and the corresponding variance for three cases are shown in Fig. 2. The searching time unit is minute.

It can be seen that the MI approach outperforms the other two approaches in the mean searching time. The SRP is fairly consistent compared to other two approaches since the hosts are static, and it is easy for the searching robots to re-connect when their host fails. When one host fails, MRP is worse than SRP because the searching robots will take longer to reconnect to the mobile rally point, and the aggregation time will also take longer due to larger size of sub-team and a larger area to cover. These simulation results suggest that the proposed aggregate strategies work well in a multi-robot system. The system robustness can acceptable for situations in which a host is out of communication range or fails.

B. Experimental Results

The experiments are conducted on three mobile robots in a lab space of 4m x 8m: one Pioneer 3DX equipped with a pan-tilt-zoom camera, laser range finder, and 16 sonars, and two Centribots equipped with a camera and 8 sonars. The communication between the robots are wireless. The radio range is setup as 1m, which can be easily configured by exchanging the current location information between the robots. When the distance between each other is greater than 1m, the robots assume that the communication failure happens, otherwise, they are connected. Different color cylinders are installed on top of each robot for robot recognition using vision. The moving speeds of the robots are setup at 0.1m/second for Pioneer 3DX, and 0.02m/second for Centribots. The vision system can detect the color cylinders anywhere inside the lab. Fig. 3 shows some snapshots of experiment using MI strategy.

Fig. 3. Snapshots of experiment using MI strategy with 3 Pioneer robots

The Adaptive Monte-Carlo Localization algorithm described by Dieter Fox [16] is used for the localization method. Each robot has its own global path planner, which is wavefront path planner, and local obstacle avoidance algorithms, where the Vector Field Histogram Plus local navigation method by Ulrich and Borenstein [15] is used as the underlying obstacle avoidance algorithm.

Since the searching performance with the *MRP* and the *MI* strategies depends on the target distribution, four different target distributions are manually designed. 15 runs for all strategies were carried out on each configuration. Since most cases for randomly searching can not obtain reconnection in hours, to speed up the experiments, 20 minutes is setup as the maximum searching time. Any experiments which exceed 20 minutes are treated as 20 minutes. The experimental results are depicted in Fig. 4. The x-axis shows the 4 different configurations of target distribution, whereas the y-axis depicts the average searching time.

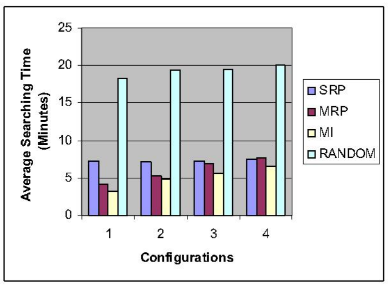

Fig. 4. Experimental results of three integration strategies working on different target distributions.

From Fig. 4, it can be seen that, generally, the searching times with proposed strategies have been significantly reduced compared to randomly searching. The performance of *MI* overcomes the other two strategies for all four target distributions. When the targets can be detected on the early stage of the searching, such as in case 1, the *MI* and *MRP* have much better performance than the *SRP* due to the mobility of their host, while the robots has to wait until the static integration time to inform the detection in *SRP*.

Even as the search configurations become more difficult, the performance of the *SRP* is fairly constant, with a slightly increased time because it may take a little bit longer for robots to detect a target in a corner than in the middle of a room. The searching times of the *MI* increase linearly, which is reasonable due to the fact that the longer the robots take to detect targets, the longer it will take for the host to be informed, and therefore the longer the overall task completion time is. When the target detection becomes more difficult, the *MRP* strategy yields similar performance to the *SRP* strategy, as shown in case 3, and sometimes even worse than *SRP*, as shown in case 4. This is because the robots may be going back and forth to the host without having anything to report. It is worth noting that the mobility attributes of the *MRP* and the *MI* strategies would provide significant performance advantages over *SRP* in a large-scale searching area.

VIII. CONCLUSIONS

In this paper, four hierarchical-based aggregation strategies are presented for coordinating a team of robots with limited communication power in a searching task. Our integration strategies have been implemented and tested in simulation and experimental runs under different target distribution environments using mobile robots. Simulation results suggest that our techniques can significantly reduce the searching time with different degrees of efficiency comparing to the random searching approach and the overall system performance is robust in the case of a lost or malfunctioning host lost. Our simulation and experimental results showed that a mobile integrator approach searched faster than a mobile or static rally point approach.

The approaches discussed here might be extended to a large-area searching task. Theoretically, the robots can traverse vast areas, as the schemes allow them to move in and out of radio communication. In addition, these behaviors can also be applied to mixed teams of robots and humans, as these strategies are ones that humans can easily follow.

REFERENCES

[1] DOD, "US Army Survival Manual: FM 21-76," US Department of Defense 1992.

[2] Nickerson, Jeffrey V., and Olariu, Stephan, (2005). A Measure for Integration and its Application to Sensor Networks, *WITS* 2005.

[3] Nickerson, Jeffrey V., "A Concept of Communication Distance and its Application to Six Situations in Mobile Environments", *IEEE Transactions on Mobile Computing*, Vo. 4, No.5, Sept./Oct. 2005, pp. 409-419.

[4] N. Roy and G. Dudek, "Collaborative robot exploration and rendezvous: algorithm, performance bounds and observations," *J. Autonomous Robot.*, vol. 11, no. 2, pp. 117-136, 2001.

[5] R. C. Arkin. Cooperation without communication: multiagent scheme-based robot navigation. J. Robotic Systems, 9(3):351-364, 1992.

[6] T. Balch and R.C. Arkin, "Communication in reactive multiagent robotic systems", *Autonomous Robots,* 1(1), pp. 27-52, 1994.

[7] D. Kurabayashi, J. Ota, T. Arai and E. Yoshida, "Cooperative sweeping by multiple mobile robots", in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, 1996, pp. 1744-1749.

[8] W. Burgard, M. Moors, C. Stachniss, and F. E. Schneider, "Coordinated Multi-Robot Exploration", *IEEE Trans. on Robotics, Vol. 21, No. 3,* June 2005.

[9] B. S. Pimentel and M. Campos, "Cooperative Communication in Ad Hoc Networked Mobile Robots", *Proceedings of 2003 IEEE/RSJ Intl. Conference on Intelligent Robots and Systems*, pp. 2876-2881, October 2003.

[10] R. Murphy, "Human-Robot Interaction in Rescue Robotics," *IEEE Systems, Man and Cybernetics Part C: Applications and Reviews, special issue on Human-Robot Interaction*, Vol. 34, No. 2, May 2004.

[11] R.C. Arkin and J. Diaz, "Line-of-Sight constrained exploration for reactive multiagent robot teams," in *AMC 7th International Workshop on Advanced Motion Control*, 2002.

[12] S. Anderson, R. Simmons, and D. Goldberg, "Maintaining line of sight communications networks between planetary rovers", *Proceedings of the Conference on Intelligent Robots and Systems (IROS)*, October, 2003.

[13] P. Ulam and R. Arkin, "When good comms go bad: communication recovery form multi-robot teams", *Proc. 2004 IEEE Int. Conf. on Robotics and Automation*, New Orleans, LA, May. 2004.

[14] M. Dias, M. Zinck, R. Zlot, and A. Stentz, "Robust Multirobot Coordinate in Dynamic Environments", in *Proceedings of IEEE International Conference on Robotics and Automation*, 2004, pp.3435 – 3442.

[15] I. Ulrich and J. Borenstein, "VFH+: Reliable Obstacle Avoidance for Fast Mobile Robots", in *Proceedings of the International Conference on Robotics and Automation (ICRA'98)*, Belgium, May 1998.

[16] D. Fox, W. Burgard, F. Dellaert, and S. Thrun, "Monte Carlo Localization: Efficient Position Estimation for Mobile Robots", AAAI 1999.