HIERARCHICAL MULTI-ROBOT COORDINATION
Aggregation Strategies Using Hybrid Communication

Yan Meng, Jeffrey V. Nickerson, Jing Gan
Stevens Institute of Technology, Castle Point on Hudson, Hoboken, NJ 07030, USA

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Abstract: Multi-robot coordination is important for searching tasks. Usually discussions of this coordination presuppose a reliable explicit communication infrastructure. However, limited power, low radio range, and an ever changing environment all hinder communication. Maintaining weakened connections will cause robots to cluster during searching, which may be suboptimal with respect to the searching time. In this paper, hierarchical-based aggregation strategies are proposed to coordinate a team of robots with limited communication. To speed up the reconnection procedure for the proposed aggregate strategies, a hybrid communication approach is proposed in this paper to establish a movement plan to recover the explicit communication through vision sensors. Simulation results are presented and discussed. Experiments with 3 Pioneer robots have been conducted, and the experimental results show that our proposed strategies using a hybrid communication mechanism are feasible and efficient in a searching task. The proposed strategies can be extended to a large-scale searching environment as well as to a combination of humans and robots.

1 INTRODUCTION

As a community, we would like to be able to deploy a team 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 radio (explicit) communication with each other during the searching. However, since the on-board wireless device of each robot has limited power and a low radio range, producing a well connected network with these small wireless devices while maximizing the searching efficiency is a challenging task, especially in a changing environment. Mobile ad hoc networks must continuously deal with the connectivity topology changing. Robots may fail, robots or other elements of the environment move around, and weather can change which nodes are within radio range of each other.

In an adversary environment, such as combat environment, continuous radio communication is easily to be attacked or hacked by the adversary. Or in a hazardous environment, radio communication may be very difficult, if not impossible, to perform well due to the spectrum or signal constraints. Under these situations, visual communication mode would be a more appropriate and convenient way for multi robots.

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 the potential to cover more areas in a given timeframe. Without planning, however, the robots might have to search for each other after they have completed their search and their 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 (DOD, 1992). This technique has been studied in relation to robotic communication in emergencies (Nickerson, 2005). In the area of robotic search, the use of a rendezvous between two searching robots at a pre-arranged spot has been studied (Roy, 2001), drawing from work in the theory of search games (Alpern & Gal, 2003).

As we know, the longest searching time of a mobile robot is totally depends on the on-board battery. To extend the searching time of the overall multi robot system, a power-efficient hierarchical architecture is proposed in this paper. Based on this architecture, several heuristic aggregation strategies are proposed to manage the coordination between a team of searching robots which had difficulty to communicate. To speed up the integration procedure

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when robots have lost radio communication, a hybrid communication approach combining implicit communication via vision with explicit communication via radio is proposed. When radio communication is broken, vision is applied to establish a movement plan to get back into radio connection.

2 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 research has been conducted on the implicit communications (Arkin, 1992; Balch, 1994; Kuniyoshi, 1994) in multi-robot system. Arkin (1992) indicated that explicit communication is not always required to achieve an increase in utility. In a follow-up study (Balch, 1994), he concludes that "(Explicit) communication is not essential in tasks which include implicit communication" but that "(Explicit) communication improves performance significantly in tasks with little environmental communication."

(Roy and Dudek, 2001) 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.

Most previous work in multi-robot coordinate relies on explicit communication to keep robots in communication with each other (e.g. (Hu, 1998; Pimentel, 2003)). However, in related empirical work, it is known that the CRASAR teams at the World Trade Center had a difficult time communicating with their robot since at the World Trade Center, 25% of communication between wireless robot and control unit was extremely noisy and therefore useless. Bandwidth problems, loss of communication resulted in the loss of one robot (Murphy, 2004).

One way to enhance the communication reliability is to proactively adjust a robot's behaviors to try to avoid communication failure before it occurs (Arkin, 2002; Sweeney, 2002; Anderson, 2003). 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 (Ulam, 2004; Dias, 2004).

Some research has focused on architectures for multi-robot cooperation. Grabowski et al. (Grabowshi, 2000) consider teams of miniature robots that overcome the limitations imposed by their small scale by exchanging mapping and sensor information gathered by the other robots. In this architecture, a team leader integrates the information gathered by the other robots. Furthermore, the leader directs the other robots to move around obstacles or sends them to unknown areas. Stroupe et al. (Stroupe, 2004) recently presented the MVERT-approach. Their system uses a greedy approach that elects robot-target pairs based on proximity. The goal of the action selection is to maximize cooperative progress toward mission goals.

3 AGGREGATION STRATEGIES

We assume a team of heterogeneous mobile robots working cooperatively to explore an environment with a preliminary map, seeking for randomly scattered targets, where the number of the targets is given in advance. 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 has one host and several searching robots locally connected with 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, which is shown in Fig.1. The host robot integrates the information from its local searching robots, and sends this collected information to other hosts. This hierarchical communication mechanism is power-efficient since only low-power communication is needed for each sub-team.

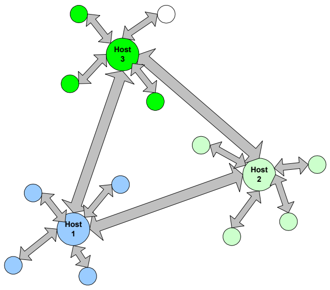


Figure 1: A hierarchical structure of multi-robot system in a searching task.

The host robots make high-level decisions, such as task assignments, global map building, global target information, whereas the searching robot only holds local perceptual data and the hosts' status. The robots will be dispersed to different searching areas looking for the randomly scattered targets. The objective is to minimize the searching time, which is defined as the time from the starting point to the time when the host robot receives all of the information of the expected targets.

3.1 Static Rally Point (SRP) Approach

Without any plan, disconnected robots might search at random for targets, and then search at random to find each other and compare results. Such a technique is obviously inefficient, and so we look for a simple organizing principle.

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 searching area. At the rally point, all the information will be exchanged and collected by the host robot. 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 rally points should be set up within the long-range communication area between the hosts. The host assigns different searching areas to each robot, and each robot uses its path planner to cover 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.

3.2 Mobile Rally Point (MRP) Approach

The *SRP* strategy is simple to implement, but it lacks flexibility for different target distribution environments, especially for large scale searching areas. Therefore, we consider a *mobile rally point* (*MRP*) strategy. In this technique a mobile host robot for each subteam 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 the information of all the expected targets after a reconvening session, which may happen before the entire field has been explored.

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 of communication during the reconvening session.

The overall sense of search progress of MRP will be achieved at defined times and the hosts only need to communicate with each other during the reconvening session. 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.

3.3 Mobile Integrator (MI) Approach

The third strategy, which we call the *mobile integrator* (*MI*), is designed to minimize unnecessary movement. Only the robot who detects a target or multiple targets will move toward and inform the moving host robot, otherwise it will continue its own searching task. The destination 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.

Compared with MRP method, communication cost of MI method is higher, and the travel cost is lower. Since movements usually consume much power than communication, the overall power consumption of MI should be less than MRP.

3.4 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 explicit communication between the robot and the host is not available when the host sends out the “game over” command, the robot may search around for a long time before it finally approaches the exit point. 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. With this time-out feature, the searching robot may lessen the amount of unnecessary searching.

4 HOST POSITION ESTIMATION

It would be good if the searching robots could estimate the position of the host of each sub-team upon aggregation time. It is possible for the searching robot to predict the host position at any given time based on the initial planed path information broadcasted by the hosts before searching, with the assumption that the host robot always moves at the same given speed.

To function effectively with an underlying obstacle avoidance algorithm, the wavefront path planner only transmits waypoints, not the entire path. The wavefront planner finds the longest straight-line distances that don't cross obstacles between cells that are on the path. The endpoints of these straight lines become sequential goal locations for the underlying device driving the robot.

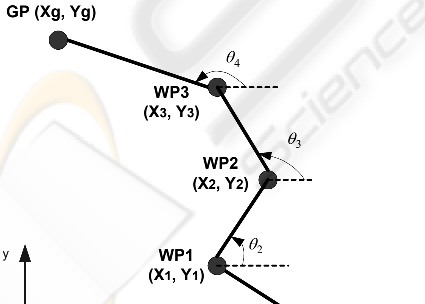


Figure 2: Initial planned path with three waypoints for host robot at the entrance, where WP stands for *waypoint*, SP stands for *starting point*, and GP stands for *goal.*

Assume that there are three waypoints in the initial planed path for host robot, as shown in Fig. 2. The time intervals between starting point to waypoint, waypoint to waypoint, and waypoint to goal point 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).

$$\begin{aligned}
\Delta t_1 &= \sqrt{(x_1 - x_s)^2 + (y_1 - y_s)^2} / v \\
\Delta t_2 &= \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} / v \\
\Delta t_3 &= \sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2} / v \\
\Delta t_4 &= \sqrt{(x_4 - x_3)^2 + (y_4 - y_3)^2} / v \qquad (1)
\end{aligned}$$

$$\theta_1 = arctg\frac{y_1 - y_s}{x_1 - x_s}, \theta_2 = arctg\frac{y_2 - y_1}{x_2 - x_1},$$

$$\theta_3 = arctg\frac{y_3 - y_2}{x_3 - x_2}, \theta_4 = arctg\frac{y_g - y_3}{x_g - x_3}. \quad (2)$$

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

$$\begin{aligned}
&\text{when } t \le \Delta t_1 \\
&x(t) = x_s + vt\cos\theta_1, y(t) = y_s + vt\sin\theta_1 \\
&\text{when}\Delta t_1 \le t \le \Delta t_2 \\
&x(t) = x_1 + vt\cos\theta_2, y(t) = y_1 + vt\sin\theta_2 \\
&\text{when}\Delta t_2 \le t \le \Delta t_3 \\
&x(t) = x_2 + vt\cos\theta_3, y(t) = y_2 + vt\sin\theta_3 \\
&\text{when}\Delta t_3 \le t \le \Delta t_4 \\
&x(t) = x_3 + vt\cos\theta_4, y(t) = y_3 + vt\sin\theta_4 \qquad (3)
\end{aligned}$$

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 host’s current estimated location as the destination. Instead, the searching robot has to predict the travel time to the current host position from its current position, and predict the host’s future location with this travel time interval, and set up this host’s future location as its new path destination.

The prediction of the time interval from the searching robot to current location of the host, and the estimation of future location of host can be computed in a way similar to what is shown in Fig. 3. If the environment dynamically changes, then the above approach may not be able to obtain the expected results. To minimize the accumulated estimation error, the host would always inform all the searching robots its current waypoint plan during every aggregation time.

5 A HYBRID COMMUNICATION APPROACH

The above approach may not be able to obtain the expected results since the initial path may be modified due to the dynamic environmental changes, such as some unexpected obstacles or mobile robots on its way. A hybrid communication is proposed in this section, where communication via vision is applied to help in detecting and locating the host in order to accelerate the reconnection of the radio communication.

If the radio channel of a searching robot is broken due to the weak radio signals or traffic jams, and the host is still within the visual range of the searching robot, the visual channel can detect and track the host and guide the searching robot toward the host until radio communication is reestablished. Sometimes, even if the radio communication cannot be reestablished at a very short distance, the visual channel at least can prevent the searching robot moving further from its teammates, so that once the communication is available again, the robot can exchange information immediately.

However, the vision system does not always help in some environment, such as a highly object density environment. Sometimes, for a very large scale multi-robot system, the robot vision system might often be blocked by other mobile robots if they are not distributed far way. Under these situations, the hybrid approach would not be faster (but would also not be slower) than a pure radio communication approach.

6 SIMULATION AND EXPERIMENTAL RESULTS

6.1 Simulation Results of Hybrid Communications

To evaluate the hybrid communication approach, a simple proof-of-concept simulator was written using C/C++ under Windows environment, where only two robots are simulated: one is a lost robot and the other is a networked robot. A city grid simulation environment is setup, where the area is 16m by 16m square with nine 4m by 4m square block evenly distributed and 1m width streets in between. The lost robot and the networked robot are distributed randomly on the grid at their starting points. Then both move at a speed of 1m/step to a preset rendezvous point while searching for each other on their way.

The simulation results with different radio ranges are depicted in Fig. 3(b), using 100 runs for each radio range. It can be seen that the recovery times tends to decrease with increasing radio ranges. There are diminishing returns once the radio coverage has increased beyond a size where participants are likely to connect to each other quickly.

It is noted that the scalability of the proposed hybrid communication is limited because the chance the robot field of view is being blocked by other mobile robots increase dramatically with a very large scale multi robot system.

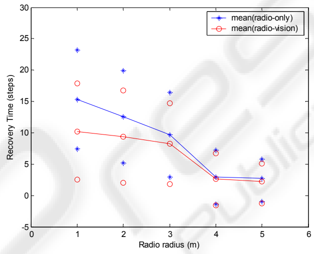


Figure 3: Means (joined by lines) and standard deviation values (unjoined points) of recovery times with different radio radius when the vision radius is 15m.

6.2 Simulation Results of Aggregate Strategies

To apply the proposed aggregate strategies to a large scale multi-robot system, searching simulations using 10 robots are carried out. These 10 robots are divided into two sub-teams, each sub-team has one host and four searching robots. The searching area is set up as an office building with 20 office rooms and three targets are randomly distributed within these office rooms. 100 target configurations are randomly generated, and for each configuration, four approaches, SRP, MRP, MI, and MITO, are conducted. The power consumption for each robot is calculated as

$$P(t) = k_1 * d(t) + k_2 * c(t) \tag{4}$$

where *d(t)* denotes the travel distance, *c(t)* denotes communication power consumption. k_1 and k_2 are coefficients. The simulation results are shown in Fig 4.

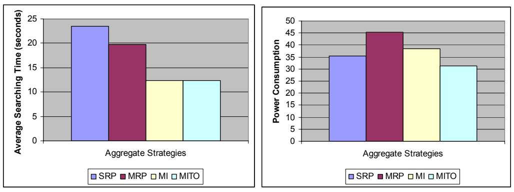


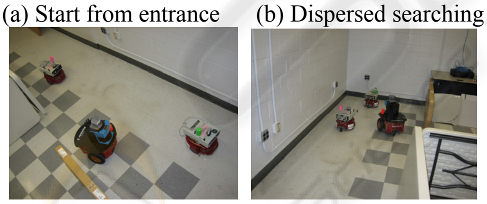
Figure 4: (a) average searching time comparison; (b) average power consumption comparison.

The MITO approach outperforms other three approaches in both average searching time and power consumption. These simulation results demonstrate that the proposed aggregate strategies are efficient and scalable to a large scale multi-robot system.

6.3 Experimental Results of Aggregate Strategies

The experiments are conducted in a small lab area (6m x 8m). Three mobile robots are used: one Pioneer 3DX equipped with a pan-tilt-zoom camera, laser range finder, and 16 sonars, and two Centirbots where each is equipped with a camera and 8 sonars. The communication between the robots is 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 vision system can detect the color cylinders anywhere inside the lab. The moving speed is setup at 0.1m/sec for Pioneer 3DX and 0.05m/second for Centribots. Fig. 5 shows some snapshots of experiment using MI strategy.

(a) Start from entrance (b) Dispersed searching



(c) Finish searching (d) Aggregation

Figure 5: Snapshot of experiment using MI strategy.

The pioneer 3dx is first running around to build the environment map and send this map to other robots. Each robot can localize itself (Fox 1999) at any time based on this map. And each robot also has the navigation algorithm (Ulrich, 1998) installed to move from one point to the destination point.

We assume that all of the robots are initially connected through an ad hoc network and located at the entrance, which is on left-bottom corner, and eventually they reconvene at the left-top corner. The period of reconvening of *MRP* is set at 2 minutes. A random search approach is also conducted in the experiment for performance comparison. Since the *MITO* approach would have the same searching time with *MI* approach, only *MI* approach is conducted on the experiment.

As the searching performance of the *MRP* and the *MI* strategies depends on the target distribution, four different target distributions are manually designed in Fig. 6, where blue stars are targets and color circles are robots.

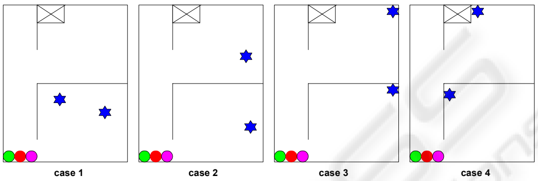


Figure 6: Different target distributions.

15 runs for each strategy were carried out on each configuration. To speed up the experiments, 20 minutes is set as the maximum searching time. Any experiments which exceed 20 minutes are treated as 20 minutes long. The experimental results are depicted in Fig. 7. The x-axis shows the 4 different configurations of target distribution, whereas the y-axis depicts the average searching time.

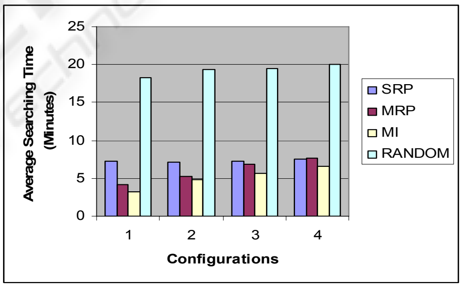


Figure 7: Experimental results of three integration strategies working on different target distributions.

From Fig. 7, it can be seen that, generally, the searching times with proposed strategies have been significantly reduced compared to those without any strategy. 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 have to wait until the rendezvous at a fixed point to learn of the detection in *SRP*.

It is worth noting that although *MRP* may have worse performance than *SRP* under some conditions in the searching environment as in Fig. 6, the mobility attributes of the *MRP* and the *MI* strategies would provide significant performance advantages over *SRP* if the searching environment increases to a large scale space. In a large scale space, the latency caused by the *SRP* might create too much anxiety back at the base. However, if a robot is abducted or malfunctions, it is easier to detect with *SRP* and *MRP*, while it would be difficult for the *MI* strategy since there is no mandatory checkpoint, and the *MITO* approach accommodates this drawback.

7 CONCLUSIONS

In this paper, four aggregation strategies are presented for coordinating a team of robots with limited communication power in a searching task. To improve the efficiency of the searching procedure, we distribute the robots in the environment as far as possible to cover the whole area, aware we are breaking the communication link, and let them reconvene at some point to exchange information.

Our integration strategies have been implemented and tested in experimental runs under different target distribution environments using three real-world mobile robots. Experimental results presented in this paper suggest that our techniques can significantly reduce the searching time with different degrees of efficiency comparing to the randomly searching approach. Our experiments suggest that MI has the best search time performance compared to MRP and SRP.

The future research topic will extend the searching task in an unknown environment, where machine learning techniques will be applied to learn the environment and adaptively response to the environment changes.

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