Robot Team Exploration with Communication Restrictions

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Abstract

In the event of an earthquake or fire, search and rescue efforts may be delayed until it is safe for a human team to enter the area. A team of robots could enter in advance to provide maps, images and locations of interest to the human team, allowing them to prepare their approach when they can enter. In a disaster area, communication may also be limited. We have developed a set of distributed algorithms that make use of a small number of robots to fully explore an unknown environment even with restrictions on communication, team size, and available sensors. We show, through proofs and experiments, that the algorithm will allow the team of robots to fully explore the environment and maintain the necessary communication to return the information to the search and rescue team waiting outside.

There are multiple methods for a team of robots to explore an unknown environment. Gage (1992) proposed three categories of coverage–blanket, barrier, and sweep. Choset (2001) later presented an extensive overview of coverage path planning algorithms according to those categories. Most coverage algorithms are focused on surveillance, and thus aim to achieve blanket or barrier coverage, but this can require a prohibitively large number of robots. Dirafzoon et al. (2012) provide an overview of sensor network coverage algorithms, many of which rely on individual robots knowing the distance and bearing to other robots around them. Other research has shown that it is possible for a team of robots to achieve full exploration of an unknown environment using only wireless signal intensity to guide the robots (Ludwig and Gini 2006). This algorithm allows the use of small, simple robots, but still attempts to provide blanket coverage, which can require a prohibitively large number of robots. In our work, we have focused instead on algorithms designed to perform sweep coverage of an unknown environment. With this approach, we do not need to know in advance how many robots are needed, as the team will complete a single sweep of the environment to locate points of interest.

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Dispersion and Exploration Algorithms

The main objective of our algorithms is to achieve full exploration of an unknown environment using a team of robots. We do not need blanket or barrier coverage for our search and rescue scenario, so we don't need a large team, and can succeed with even a single robot if needed. We have chosen a distributed approach so that we can best take advantage of the robustness that comes with having multiple robots. We assume that the robots have proximity sensors to avoid collisions, the ability to communicate, and the means to carry and drop beacons (such as ZigBee motes or RFID tags). We also assume a disaster scenario, so the algorithm must function in an unknown and dynamic environment.

The main feature of our algorithms is that the robots use communication not only as a means to send messages, but also as a means to direct their movements. This helps to ensure that the robots stay within range of each other, and the algorithm is not dependent on a specific communication method to function correctly, making it more versatile and usable on multiple types of robots. We have completed the generalized algorithm, which only limits the robots to remain within communication range of each other. In the Rolling Dispersion Algorithm (Jensen and Gini 2013), shown in Algorithm 1, the wireless signal intensity is used by the robots to disperse while maintaining communication with at least one neighbor. Using Algorithm 1, the robots choose different behaviors as they progress through the environment. After reaching maximum dispersion under this

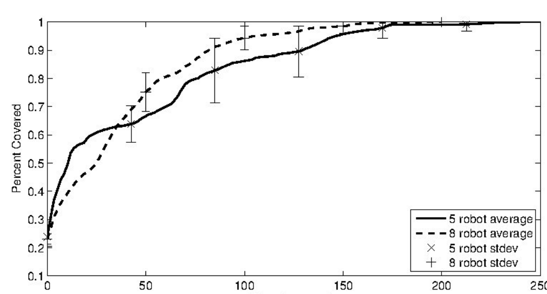

Figure 1: Average time to full exploration using five and eight robots in a cave environment.

Algorithm 1 Rolling Dispersion Algorithm

```
loop
    Update and share connectivity graph
    if I am too close to an obstacle then
        set behavior to Avoid Collisions
    else if I am disconnected then
        set behavior to Seek Connection
    else if I am in a dead end then
        drop a beacon set to Repel
        set behavior to Retract
    else if I am on the frontier then
        set behavior to Guard
        if my only neighbor is my sentry then
            request additional explorers
    else if I have received a request then
        if I am an explorer then
            drop a beacon set to unexplored
            set behavior to Follow Path
        else if I am a sentry w/a beacon parent then
            drop a beacon set to unexplored
            set behavior to Follow Path
        else
            set behavior to Guard
            pass on the request
    else if I have reached the requesting robot then
        set behavior to Disperse
    else if if I am an explorer then
        set behavior to Disperse
    else
        set behavior to Guard
    Apply chosen behavior
```

constraint, the robots move through the environment using a rolling advancement method, leaving behind beacons to mark the path to the entrance or other unexplored locations. This approach is methodical and clears each area before moving forward, similar to the methods used by law enforcement. We have shown that this algorithm completes the exploration in multiple environments in simulation. One set of simulations was run using a cave-like environment that would require ten robots for blanket coverage. Figure 1 shows the average time to fully explore the area using five and eight robots.

In addition to the generalized algorithm, we have begun work on algorithms that function with much greater constraints on communication. In some disaster scenarios, use of wi-fi for communication is not possible due to interference in the environment (building structures, chemicals, etc). In such cases, we still need to guarantee full exploration, but the messages we can send between robots may be highly limited. For example, using chemical signals may restrict us to only three distinct signals, because the robots cannot carry more containers or sensors. We then need to know the minimum number of distinct messages required to achieve full exploration. Our current work posits that we can achieve complete exploration with a sweep exploration algorithm using seven distinct messages, and we expect to have proofs and preliminary experiments with physical robots completed by September 2014. Our experiments include simulation, which uses colors to represent the messages, and physical robot experiments using both simulated chemical signals (in collaboration with Dr. Ken Sugawara from Tohoku Gakuin University, whose experimental setup is shown in Figure 2) and using cameras and LEDs.

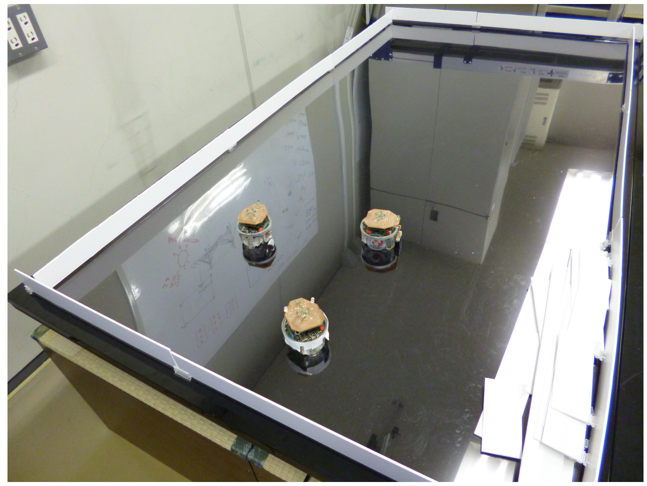

Figure 2: Experimental setup in Dr. Sugawara's lab. Overhead cameras (not shown) track the robots and display simulated chemical signals to the screen below the robots, which the robots detect using color filtered IR sensors.

Our anticipated contribution is a set of distributed algorithms for robot team exploration of unknown environments. We introduce a novel means of completing the sweep coverage, using the communication signal intensity, and show that it is viable with multiple types of communication, including highly restricted forms, such as chemical signals. An additional contribution, which is expected to be completed in early 2015 is the ability of the robots and beacons to work with humans to complete the rescue phase.

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