Sector-Search with Rendezvous: Overcoming Communication Limitations in Multirobot Systems

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Dr. Briana Lowe Wellman is an assistant professor in the department of Computer Science and Information Technology at the University of the District of Columbia. She joined UDC in May 2012 after receiving her Ph.D. in Computer Science from The University of Alabama in December 2011.

Dr. Wellman's area of specialization is robotics. Her research focus is on cooperative multirobot systems and sensor networks in search, coverage, and surveillance applications. It also includes using robotics in education. Her research is highlighted in numerous international conference and journal proceedings.

As an educator, researcher, and mentor, Dr. Wellman's overall goal is to continue her research while teaching and training the next generations of computer scientists. One of her favorite inspirational quote is by Marian Wright Edelman: "Education is for improving the lives of others and for leaving your community and world better than you found it."

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Tommy Suriel Gonzalez is a computer science undergraduate junior at the University of The District of Columbia(UDC). He was born in August 16th 1991 in Manhattan NY and after two months of being born he was taken back with his family to The Dominican Republic. He was raised and lived there until the age of seventeen. At the age of seventeen he moved to the United States of America to live in Washington DC where he completed High school at the Age of eighteen and then started Attending UDC at nineteen. He recently has been doing research at UDC with Dr Briana Wellman in robotics regarding Sector-Search with Rendezvous in Multi-robot Systems. In March 2013 He attended the ERN conference in Washington DC where he gave an Oral presentation of this research ,the 70th Joint Annual Meeting of the BKX and NIS in Reston VA where he presented a poster of this research and won 3rd place for his presentation and the 5th Annual ARTSI Student Research Conference and Spelman College Computer Science Olympiad XI where he also gave a poster presentation(won 2nd place for his presentation) and participated in the Olympiad with the UDC robotics team.

Evanna Maria Reynoso

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Abstract

Cooperative multirobot systems are advantageous in coverage applications such as surveillance, search and rescue, and hazardous waste cleanup. They can work in parallel and complete tasks faster than a single robot. If one robot fails, the other robots can continue with the task. In addition, if there is a dangerous mission, robots can be deployed instead of human teams to prevent human injuries and casualties.

When multiple robots cooperate to complete a task, communication between robots can speed up completion. Communication can prevent robots from interfering with one another and reduce duplication in coverage. Typically, point-to-point communications can be used to coordinate robots. However, in many coverage tasks the efficiency of communications can be unpredictable due to unknown environmental characteristics and network conditions. Because persistent intra-team digital communications are not guaranteed, cooperation paradigms that do not rely upon message passing throughout exploration are needed.

In previous work, the novel approach, Sector Search with Rendezvous, was proposed to overcome communication limitations. Robots explore an unknown environment in sectors, or designated areas, and periodically meet to communicate map information of what they have explored. Using simulations, it was compared to other communication paradigms. Preliminary results suggest that Sector Search with Rendezvous can serve as an alternative to continuous point-to-point communications. However, there can be discrepancies between results of simulation and physical experiments. In this paper, results from simulations and real robots experiments are discussed. Results suggest that Sector Search with Rendezvous is efficient in coordinating a team of robots.

Introduction

Communication in cooperative multirobot systems is essential. It can prevent duplicate coverage and reduce robot interference allowing for an increase in team performance. If the communication network is unrestricted, then robots can disperse in the environment, explore different areas, and continuously update each other of new information found. However, in scenarios that take place in unknown and unpredictable environments, such as bomb detection or search and rescue, the communications network is not always reliable or guaranteed.

The efficacy of communications between robots is influenced by environmental configurations[1]. Obstacles such as walls can interfere with communication transmissions. In addition, if robots are exchanging large amounts of data, then there is a risk of receiving incomplete information[2]. Several researchers have implemented systems that do not require message passing to coordinate robots. Some systems make use of potential fields[3] where robots attract and repel each other. Other approaches use ant or swarm robots[4,5] where virtual pheromones or trail markings are placed in the environment to influence robot behavior. However, both approaches rely on local interactions where after a certain distance they can no longer coordinate.

Other researchers that consider message passing with communication network constraints include: an approach in which robots are required to maintain line-of-sight with other robots[6], an approach in which message size is reduced by allowing robots to communicate polygonal representations of the map[7], and an approach where rendezvous approaches allow robots to meet up to exchange information about the environment[8]. However, there is limited research in multirobot rendezvous using physical experiments.

In previous research, Sector Search with Rendezvous is presented as an approach to overcoming communication limitation. Instead of continuously passing messages throughout the entire exploration, robots explore in designated areas and rendezvous to communicate what was found. In simulation, team performance for when robots used the proposed approach was comparable to when robot communicated the entire time. However, simulation results can be inconsistent with real world results.

In this paper, Sector Search with Rendezvous is investigated further on physical robots. It is compared to multirobot systems using a direct communication (message passing throughout exploration) approach in simulations and physical robot experiments. We hypothesize that Sector Search with Rendezvous can serve as an alternative to continuous point-to-point communications.

Related Work

Several researchers have investigated approaches that coordinate robot teams without communications. One approach makes use of potential fields. Howard et al. present a distributed virtual field force that attracts robots to targets and repels them from obstacles and other robots causing robots to spread out[10,11]. However, this approach depends on local interactions, which after a certain distance robots no longer coordinate.

Researchers also gather inspiration from social insects such as ants and swarms. Ferranti et al. present an approach were agents communicated indirectly by leaving information on tags deployed in the environment[12]. They coordinate by reading and updating information on the tags. Similarly, Koenig demonstrate coordinating robots to cover a terrain similar to ants[13]. Robots communicate via markings left by other robots and do not coordinate based on memory or maps. While these approaches do not rely on direct communications, they require local interaction to distribute robots.

Some research focuses on the maintaining line-of-sight so that robots remain in communication range with each other. Rekleitis et al. address the implementation of coordinating robots when information sharing was restricted to line-of-sight communication in an unknown environment[14]. In similar work, Arkin et al. investigated how a team of robots can self-organize during exploration by maintaining line-of-sight communications[15]. Experiments involved robots searching for hazardous materials with varying degrees of prior knowledge. The line-of-sight approaches work well when there is a requirement for robot cohesiveness, but in general will not be as efficient in a large environment when a small number of robots have to spread out more to cover the environment.

Meier et al. present a technique for assigning targets to robots and deciding what information to transmit when using communication with limited bandwidth[16]. Each robot explores an unknown environment and creates a polygonal approximation of a map. To reduce message sizes, polygonal representations of the map are communicated. Using their approach, they were able to effectively coordinate a team of robots under bandwidth limitations. Nevertheless, communicating polygonal representations of a map can result in an overhead of communication efforts.

Approach

Importance of Physical Experiments

Simulations in multirobot research are used more often than real experiments [17]. Simulations are beneficial because the resources and time it takes to acquire and maintain real robots can be expensive. In addition, simulations are a way to validate algorithms and predict robot behavior in the real world. However, typically in simulations, network and environmental conditions are optimized. Therefore, there can be discrepancies between simulations and physical robot experiments [17]. The next step in this research is to validate the results from the simulation on physical robots. Real world results provide insight of important factors such as the environment, number of robots, and communication that can result in better or worse results in simulations.

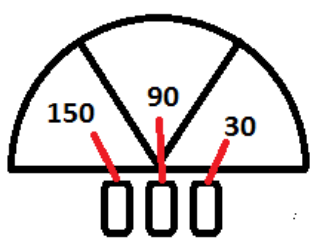

Figure 1: Robots disperse and search pre-agreed sectors. Since the environment is unknown, sectors are determined by using a semicircle to represent the environment. The arc of a semicircle is always 180°. If there are N robots, then sectors can be divided and robot will disperse 180°/N apart.

Sector Search with Rendezvous Algorithm

In Sector Search with Rendezvous, robots explore pre-agreed areas or sectors and periodically rendezvous to share information about what was found. Each robot performs frontier-based exploration in their sectors. Frontier-based exploration[18] involves robots recursively exploring an unknown environment while building a map represented by an occupancy grid[19]. Robots use a distance sensor to detect areas that are open, occupied, unknown, or a frontier. Frontier areas are the borders between open and unknown space. Robots explore frontier areas to expand their knowledge of the environment. As an asynchronous approach, robots select frontier areas based on individual utility allowing fault tolerance against individuals being disabled or out of range. When robots communicate, they only share information about open area.

Sector Designation

Although the environment is unknown, robots are designated sectors to explore. In the beginning of execution, the robots start in adjacent locations. The environment can be represented by a semicircle in which can be divided by the number of robots. The arc of a semicircle always measures as 180°. Therefore, if there is N number of robots, the angles for sectors can be determined by 180°/N. For example, if there are three robots, robots will disperse 60° apart from each other (Figure 1).

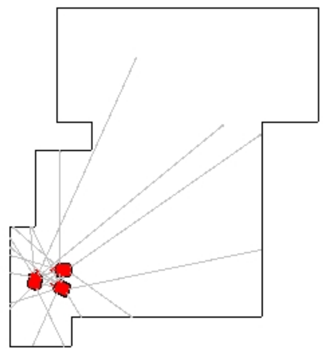

Figure 2: Robots rendezvous to exchange information after exploring in sectors. The initial rendezvous location is at the start point.

Rendezvous Locations

Since the environment is unknown, one challenge is determining the rendezvous locations. The initial rendezvous point is the start location of the robots (Figure 2). As robots explore their sector, they build individual maps. This map information is communicated when they rendezvous. After the rendezvous is finished, each robot chooses the most center point in their map as subsequent rendezvous locations. Although robots communicate map information at each rendezvous, there is a possibility that they have incomplete maps. In addition, robots may not make it to the rendezvous. As a result, robots choose different rendezvous points. However, even with partial map information or if they do not make it to a rendezvous, robots are capable of efficiently exploring because they distribute in sectors.

Simulations and Experimental Setup and Results

Simulations and physical experiments were conducted to compare Sector Search with Rendezvous to a robot team that communicates during the entire time of exploration (direct communications). Results include percentage of coverage and time to cover the environment. The experiments were performed in a lab environment with obstacles (Figure 3). We hypothesize that Sector Search with Rendezvous is a good alternative to continuous message passing (direct communications) in the real world and simulations.

Figure 3: The physical experiments were conducted in a lab with obstacles. The equivalent simulated lab is illustrated in Figure 2.

Figure 4: Three Amigobots were used to conduct simulations and real world experiments.

Setup

The robots used were Adept Amigobots featured with eight sonar sensors (Figure 4). The controller was written using MobileRobots' Advanced Robot Interface for Applications (ARIA) [20], a C++ library SDK for MobileRobots platforms, on a Quad Core 3.2 GHz machine running Linux with 6GB of RAM. MobileSim, software for simulating MobileRobots platforms was used for simulations. The real robots communicated using a standard wireless IEEE802.11b network. The same code and machine were used for both simulations and real world experiments.

As mentioned in the approach, robots performed exploration using a frontier-based algorithm in which robots use their sonar sensors to detect the environment. The approaches tested included direct communications (continuous communications between robots) and Sector Search with Rendezvous. Three trials were conducted for each approach.

Results

Two metrics were chosen to evaluate the performance of each approach. The *area covered* is a percentage for the amount of area that the entire robot team covered from start of execution. *Completion time* indicates the average times in minutes for when 50% and 90% of the area is covered by the robot team.

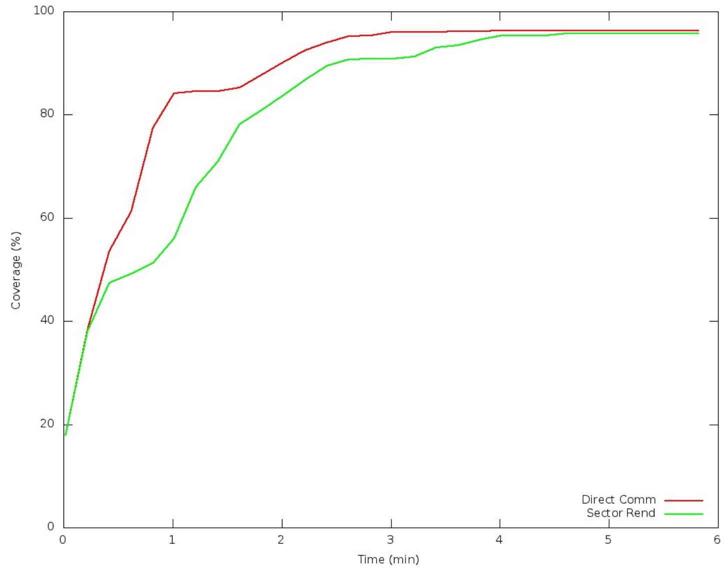

Figure 4. Comparison of coverage and time for Direct Comm and Sector Rend approach in simulations.

Direct Comm	**Average (min)**	**Standard Deviation (min)**
50%	0.22	0.02
90%	0.85	0.03
Sector Rend		
50%	0.36	0.07
90%	2.26	1.04

Table. 1. Time that Robot team covered at 50% and 90% of the environment in simulations.

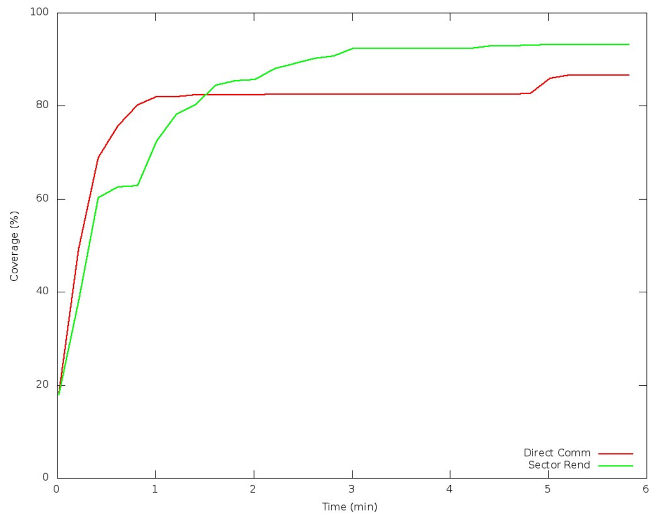

Figure 5. Comparison of coverage and time for Direct Comm and Sector Rend approach in physical experiments.

Direct Comm	**Average (min)**	**Standard Deviation (min)**
50%	0.34	0.26
90%	1.80	0.91
Sector Rend		
50%	0.60	0.26
90%	2.40	0.85

Table. 2. Time that Robot team covered at 50% and 90% of the environment in physical experiments.

In the beginning of execution, the simulated robot team performing direct communications covered the environment quicker than the team using Sector Search with Rendezvous. However, Sector Search with Rendezvous demonstrated improvement over direct communications towards the end. The slower performance rate of Sector Search with Rendezvous is due to the time taken for robots to meet and communicate (Figure 4). The lower standard deviation suggests that results for the runs in simulations are similar in each trial (Table 1).

As expected, results in physical robot experiments were different than results in simulation. Direct communications outerperformed Sector Search with Rendezvous up until after the first rendezvous (Figure 5). The larger standard deviation demonstrates how spread out and unpredictable real robot experimental results can be from trial to trial (Table 2).

Discussion

The slower performance rate of Sector Search with Rendezvous is due to the time taken for robots to meet and communicate. As demonstrated in Figure 4 and 5, at around the first and third minute, robots are rendezvousing. At those times, robots were communicating rather exploring so there is a decrease in coverage. However, after the first meeting and robots had updated their maps with information transmitted from other robots, team performance starts to improve.

Team performance for the physical robot experiments was slower when compared to the results from simulation for both approaches. For example, on average it took almost a minute longer for the real robots to cover at least 90% of the environment when using direct communications. The difference was lesser at 14 seconds for team performance of simulated and the real robots using Sector Search with Rendezvous. Note that with direct communications, robots are passing messages every time a new area is discovered. The message delay from when the message is transmitted to when is received is greater for the real robots. In addition, unlike with simulations, the real robots communicated wirelessly.

Even though Sector Search with Rendezvous ended with better results towards the end of execution, it can serve as an alternative in risky scenarios with limited communication. Robots are capable of exploring the environment even if communication is unreliable because robots search in sectors and use individual utility to determine action selection. The advantage of this approach is that robots are not exchanging messages the whole time they are exploring. Therefore, in cases were there are environmental configurations such as obstacles preventing communications, robots make an effort to meet and share information.

Future Work and Conclusion

With Sector Search with Rendezvous, robots explore in sectors and rendezvous to communicate what was found. The approach was compared with a direct communication approach which robots continuously communicate. Simulations and real experiments were conducted. We hypothesized that Sector Search with Rendezvous can serve as an alternative to when robots communicate throughout exploration. Results suggest that Sector Search with Rendezvous is efficient in coordinating robots in a coverage task and can be an alternative to direct communications in real work experiments.

Results also demonstrate differences in team performance for simulations and real robot experiments. While simulations are good for quicker testing and a cheaper solution than purchasing equipment, conducting experiments with real robots allows for more accurate results. In physical experiments, there are many factors, such as robot interference, an unknown environment, and delayed communications, which can influence results. However, running real experiments are required to accurately test the efficiency of an approach. Future work includes examining these factors further.

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