Market-Based Coordination of Recharging Robots

Victor Marmol

Advisor:
M. Bernardine Dias, Ph.D., Assistant Research Professor, Robotics Institute

Mentor:
Balajee Kannan, Ph.D., Research Engineer, Robotics Institute

I. Introduction

The effectiveness of mobile robots has always been affected by the amount of time they can spend in the field. Most mobile robots today are equipped with rechargeable batteries which allow a robot to recharge in the field without extended interruption of its work. Mobile recharging units are crucial for a team of robots to effectively perform their assigned tasks over long periods of time. Mobile recharging stations allow robots the option of performing the work-recharge cycle without returning to the base station. This extends the amount of time the robots can spend in the field and consequently increases the productivity of the group as a whole. When groups of worker robots are sharing recharger robots it is critical that these robots coordinate amongst themselves to optimize the team's work-recharge cycles. The first hypothesis of this thesis is that coordinating the efforts of the rechargers and workers will increase the amount of work completed by the team of robots.

Market-based approaches have risen in popularity over the last few years for tackling the problem of multi-robot coordination. Three features that propel the popularity of market-based approaches are their simplicity, their distributed nature, and their fault tolerance. In short, market-based coordination utilizes a simulated economy where robots buy and sell tasks according to their estimated costs for completion. In this way, the robots effectively coordinate amongst themselves to allocate the necessary tasks according to the best information they have at the time. The second hypothesis explored in this thesis is that market-based coordination techniques can be used effectively to allocate recharging tasks to maximize the productivity and efficiency of the team. The metric I will use to evaluate the effectiveness of my proposed solution is the total quantity and duration of work performed by the team of robots, both rechargers and workers, engaged in autonomous exploration and mapping of unknown environments.

II. Related Work

The topic of autonomous recharging has been gaining traction in the literature recently. A large number of the related work to date has focused on the mechanics of recharging whether through a static docking station ([1], [2], [12]) or through mobile recharge stations ([3], [6], [10], [11]). Mobile recharge stations have increasingly become popular as they offer a lot of flexibility and promise for on-the-go charging for a deployed team of robots. These mobile charging stations also pose a series of challenges as their location and limited recharging capabilities have to be considered when coordinating the team. Some work to date has focused on the location of the mobile or static recharge station and how that affects the performance of a group of workers [9]. A station that was far from the work area was found to decrease productivity as it took a long time to reach it. However, a station that was too close to the work area was found to interfere with the non-charging workers. There has also been research on when the working robots should recharge. Some of the approaches which have been examined include recharging when a particular battery threshold is reached ([2], [8], [12], [13]), the robot has worked for a particular amount of time [5], and when the robot has just enough battery to reach the charge station ([4], [7]). The threshold approach proves to be simple but does not always correctly account for the time required to reach the charge station.

The approach that relies on the amount of time worked keeps the robots in a consistent and predictable work-recharge cycle but allows for little adaptability. The last approach, recharge when the robot has just enough battery to reach the recharger, leaves the robot little room for error and can cause problems when the recharge station is already in use by a different worker. All of these approached are greedy in nature and thus can lead to inefficient work-recharge cycles across the team since many robots can meet these criteria simultaneously and there is no coordination amongst them.

Most of the existing works on autonomous recharging deals with a single worker robot. The existing work that deals with multiple workers attempting to recharge simultaneously addresses the coordination issue through conflict resolution rather than coordination between the robots [12]. As mentioned before, this greedy approach can lead to less desirable situations where a group of workers *queue up* around a charge station waiting for their turn. Under certain conditions this *queuing* can lead to two adverse outcomes: First, where workers exhaust their batteries while they are waiting to recharge, second where the charge station is completely blocked, effectively rendering it useless.

III. PROPOSED RESEARCH

This thesis explores the design, implementation, and evaluation of a system which uses market-based coordination to organize the tasks executed by a group of rechargers and worker robots. Our hypothesis is that this proposed coordination will increase the efficiency and productivity of the team.

A. *Existing Infrastructure*

For implementing and testing the proposed approach, I have been working with the existing system of the rCommerce group at the Robotics Institute. The rCommerce group has 6 Pioneer P3DX robots (Figure 1) with mapping capabilities and 2 with mapping and recharging capabilities. I also have access to a complete market-based system through TraderBots [14]. This existing system allows the robots to receive, auction, and execute a variety of simple and complex tasks. My research integrates with the existing system to coordinate the group of robots.

Figure 1 - 3 Pioneer P3DX robots equiped with laser scanners, gyroscopes, and wheel encoders.

B. *Research Plan*

The research plan in this thesis is comprised of two core research components:

1. *Create a recharge-aware system* where worker robots are aware of their charge state and schedule and trade their tasks accordingly. This system is also capable of sending the worker robots to recharge at a robot's designated static recharging station, referred to as *home base*. This system will include no mobile recharging agents.

2. *Integrate mobile recharging agents into the system* and allow these agents to meet workers for recharging when appropriate as an alternative to forcing the workers to go to home base. This will decrease the amount of travel the workers must execute to recharge their batteries and thus increase the amount of work they generate. This component can be extended to utilize multiple recharging agents.

C. Experimental Domain

The chosen domain for implementing and testing this approach is autonomous exploration and mapping in an unknown environment. The team output is measured as the area explored and duration of exploration and mapping. Our tests comprise of a group of 2-3 Pioneer P3DX worker robots and 1-2 Pioneer P3DX recharging agents exploring and mapping an indoor environment.

IV. Approach

This thesis research is divided into two main components:

A. Creating a Recharge-Aware System

A recharge-aware system is comprised of a series of components:

1. *Battery state monitoring.*

The first step for any robot to be recharge-aware is for the robot to know its own charge state. Towards that end, I have enabled a battery logging mechanisms on our Pioneer robots. Battery voltage is recorded at about 2*Hz* with a precision of tenths of a Volt.

2. *Battery charge and work estimation.*

Towards the goal of estimating what tasks can be completed given the robot's current charge, we must create a mechanism for translating from the robot's battery state to its estimated runtime. Similar to how a car reports a distance to empty measurement, our robots can report their remaining runtime. While cars report their distance to empty in miles, our robots will report this in meters. We ran several experiments and logged battery data for the robots to determine that our robot's battery is fully charged at 13.3 Volts and is depleted at 12.5 Volts. The robot covered a total of 1,300*m* during that battery cycle. This represents 8 different readings we can differentiate and a total runtime distance of 1,300*m*. This makes it very difficult to estimate runtime given the current battery state with sufficient granularity.

To solve this resolution problem we implemented a more fine-grained runtime estimation mechanism. We found that during battery run-down tests the battery state plots of our robots exhibited a significant linear region. Thus, we determined that we could estimate runtime in between the 8 different states we could read directly from the battery. A robot's runtime can be classified into two types of activities: sit idle and move from one location to another. We therefore developed models for both of these activities to estimate the remaining runtime given a small time delta. Therefore:

$$runtime = lastRuntime - idleModel(idleTime) - movingModel(moveDistance)$$

Where $idleTime$ is the number of seconds spent idle in the last time step and $moveDistance$ is the number of meters traversed in the last time step. Since our runtime is expressed in meters both models return a number of meters. The moving model is directly related to the distance traveled in the last time step while the idle model translates the number of seconds to possible meters traversed had the robot moved rather than idled. This strategy allows us to estimate a robot's runtime with sufficient accuracy beyond what is possible with 8 discernable levels.

3. *Task costing.*

In order for the robots to account for remaining runtime while performing their tasks they must account for this during their scheduling and trading of tasks. Market-based systems define cost functions to perform these calculations. These functions estimate the cost of performing a series of tasks in a particular order (or schedule). In particular, we use pairwise costing to determine the cost of a schedule. Pairwise costing involves the application of cost functions to consecutive pairs of tasks in a schedule. A pairwise cost function of tasks A and B computes the cost to task B given the completion of task A. Our cost functions plan such that we have enough power to return to home-base to recharge after A is completed. If the robot has enough power to travel from A to B and then home, its cost for getting from A to B is the distance from A to B. If the robot does not have enough power its cost is then the cost of going from A to home base and then to B. We ensure that we can at least recharge after A by checking the cost function before running the next pair of tasks.

4. *Scheduling recharging tasks.*

Given the cost of any particular schedule we must find the optimal placement of tasks and recharging tasks. In order to do this we run two optimizers on a robot's schedule. The first optimizer seeks to optimize the ordering of tasks. This is done by removing all tasks from a schedule and then inserting each task optimally. To insert a task optimally we exhaustively try every possible insertion point. This produces an optimal schedule of tasks. We must then decide the optimal place to insert recharging tasks. This is not immediately obvious since inserting a recharging task early into a schedule might cause the need for another recharging task later in the schedule. We exhaustively test the insertion of a recharging task at every possible position in the schedule and then insert any other recharging task if necessary.

B. Incorporating Mobile Recharging Agents

The incorporation of mobile recharging agents necessitates the following components:

1. *Robot rendezvous and docking.*

One of the most important parts of mobile recharging agents is how they rendezvous and dock with the worker robot they are to recharge. Our system relies on the costing and trading mechanism to establish a rendezvous point. When a recharging agent wins a recharging task, the task comes with a specific rendezvous point. Both robots honor their rendezvous point and meet there. Our mobile recharging agents are equipped with docking arms and must dock with the worker agent. The recharging agent receives the position and heading of the worker robot. It then lines up facing the robot and about a meter distance from the robot. At this point the robots are too close to use the laser scanner with precision so a pair of onboard short-range IR sensors take over. The recharger slowly approaches the worker fixing any errors with the short-range IR and docks with the recharger.

2. *Task costing and scheduling.*

Recharging agents have their own cost functions that assure their tasks are in optimal order and all scheduled rendezvous are honored in a first come first served basis. When a worker needs to recharge it has the option to go recharge at home-base or to auction a recharging task to recharging agents. The worker will calculate its cost given the need to go to home-base (as this is considered the worst case) and then try to improve its cost by auctioning a recharging task. The goal of the recharging agent is to intercept the worker somewhere on its schedule for recharging. Recharging agents receive auction calls for recharging tasks which contain the robot that wishes to be recharged and its schedule up to the point where the worker will recharge at its home base. Its cost functions calculate the optimal place along the worker's tour to rendezvous given the recharging agent's schedule. It then bids for that task given its distance cost. Unlike worker schedules, a recharger's schedule is not optimized in order to keep the first come first served nature of their requests. Rechargers must honor the contracts they have with workers.

V. Experiments

We will conduct a series of experiments in order to test and verify the components of our system.

A. Battery Charge & State Estimation

To test the effectiveness our method of estimating runtime, we have run a series of tests to collect data on battery discharge rates. We tuned our state estimation models and ran further tests to evaluate our models.

B. Docking

We tested the effectiveness of our recharging hardware by running a series of tests where one robot attempts to dock with a stationary robot. We tested with both the recharger and the worker robots having the stationary and the moving roles. We also varied the angle at which the moving robot attempts to dock. These tests provided us with evaluation of the recharging hardware and the possible docking angles.

C. Recharging

To test our recharge-aware system, the robots will perform a team task with recharge-awareness enabled and disabled. In the enabled case the robots will determine when recharging is necessary and recharge accordingly. Meanwhile, in the disabled case it is up to the human operators to determine when the robots should recharge and instruct them to do so. We will evaluate the performance of both of these approaches in order to test the effectiveness of our recharge-aware system. As an extension to the previous test we will incorporate mobile rechargers into the system and run the same set of tasks. We will then compare the three setups: no recharging, recharge-aware, and recharge-aware with mobile recharging.

References

[1] Seungjun Oh, A. Z. & K. Taylor (2000). Autonomous battery recharging for indoor mobile robots, in the proceedings of Australian Conference on Robotics and Automation (ACRA2000).

[2] Silverman, M.C ; Nies, D ; Jung, B & Sukhatme, G.S (2002). Staying alive: A docking station for autonomous robot recharging, in IEEE Intl. Conf. on Robotics and Automation, 2002

[3] Kottas, A., Drenner, A., and Papanikolopoulos, N. 2009. Intelligent power management: promoting power-consciousness in teams of mobile robots. In *Proceedings of the 2009 IEEE international Conference on Robotics and Automation* (Kobe, Japan, May 12 - 17, 2009). IEEE Press, Piscataway, NJ, 2459-2464.

[4] J. Wawerla and R. T. Vaughan. Optimal robot recharging strategies for time discounted labour. In Proc. of the 11th Int. Conf. on the Simulation and Synthesis of Living Systems, 2008.

[5] D. J. Austin, L. Fletcher, and A. Zelinsky, .Mobile robotics in the long term,. in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Oct. 2001.

Litus, Y., Vaughan, R. T., and Zebrowski, P. (2007). The frugal feeding problem: Energy-efficient, multi-robot, multi-place rendezvous. In Proceedings of the IEEE International Conference on Robotics and Automation.

Wawerla, J. and Vaughan, R. T. (2007). Near-optimal mobile robot recharging with the rate-maximizing forager. In Proceedings of the European Conference on Artificial Life.

[6] M. Silverman, B. Jung, D. Nies, G. Sukhatme. "Staying Alive Longer: Autonomous Robot Recharging Put to the Test." Center for Robotics and Embedded Systems (CRES) Technical Report CRES-03-015. University of Southern California, 2003.

[7] Alex Couture-Beil and Richard T. Vaughan. Adaptive mobile charging stations for multi-robot systems. In Proceedings of the IEEE International Conference on Intelligent Robots and Systems (IROS'09).

[8] St. Loius, MO, October 2009.Zebrowski, P ; Vaughan, R (2005). Recharging Robot Teams: A Tanker Approach, International Conference on Advanced Robotics (ICAR'05), Seattle, Washington, July 18th-20th, 2005.

[9] Yaroslav Litus, Pawel Zebrowski, and Richard T. Vaughan. A distributed heuristic for energy-efficient multi-robot multi-place rendezvous. IEEE Transactions on Robotics, 25(1):130-135, 2009.

[10] Munoz A., Sempe F., and Drogoul A. (2002). Sharing a Charging Station in Collective Robotics.

Sempé F., Muñoz A., Drogoul A. “Autonomous Robots Sharing a Charging Station with no Communication: a Case Study.” Proceedings of the 6th International Symposium on Distributed Autonomous Robotic Systems (DARS'02). June 2002.

[11] M. B. Dias, “Traderbots: A new paradigm for robust and efficient multirobot coordination in dynamic environments,” Ph.D. dissertation, Robotics Institute, Carnegie Mellon University, January 2004.