DISTRIBUTED COVERAGE OF UNKNOWN/UNSTRUCTURED ENVIRONMENTS BY MOBILE SENSOR NETWORKS

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Abstract In this paper we present an algorithmic solution for the distributed, complete coverage, path planning problem. Real world applications such as lawn mowing, chemical spill clean-up, and humanitarian de-mining can be automated by the employment of a team of autonomous mobile robots. Our approach builds on a single robot coverage algorithm. A greedy auction algorithm (a market based mechanism) is used for task reallocation among the robots. The robots are initially distributed through space and each robot is allocated a virtually bounded area to cover. Communication between the robots is available without any restrictions.

Keywords: Multi-Robot coverage, Automated De-mining, Market-based approach, Morse decomposition

*Work done while at Carnegie Mellon University.

1. Introduction

The task of covering an unknown environment, common in many applications, is of high interest in a number of industries. Among them are manufacturers of automated vacuum/carpet cleaning machines and lawn mowers, emergency response teams such as chemical or radioactive spill detection and clean-up, and humanitarian de-mining. In addition, interesting theoretical problems have emerged especially in the areas of path planning, task (re)allocation and multi-robot cooperation.

The goal of complete coverage is to plan a path that would guide a robot to pass an end-effector (in our case equivalent to the footprint of the robot) over every accessible area of the targeted environment. In the single robot case, previous work has produced algorithms that guarantee complete coverage of an unknown arbitrary environment. Introducing multiple robots provides advantages in terms of efficiency and robustness but increases the algorithmic complexity.

Central in the multi-robot approach is the issue of communication. When communication is restricted to close proximity (Latimer-IV et al., 2002) or line of sight (Rekleitis et al., 2004) the robots have to remain together in order to avoid covering the same area multiple times. When unrestricted communication is available then the robots can disperse through the environment and proceed to cover different areas in parallel, constantly updating each other on their progress. The challenge in this case is to allocate regions to each robot such that no robot stays idle (thus all finish covering around the same time) and also to reduce the amount of time spent commuting among the different regions instead of covering. Providing an optimal solution for minimizing travel time is an NP-hard problem as it can be mapped into a multiple traveling salesman problem. An auction mechanism is used in order to re-allocate regions to be covered between robots in such a way that the path traveled between regions is reduced. The auction mechanism is a greedy heuristic based on the general market based approach.

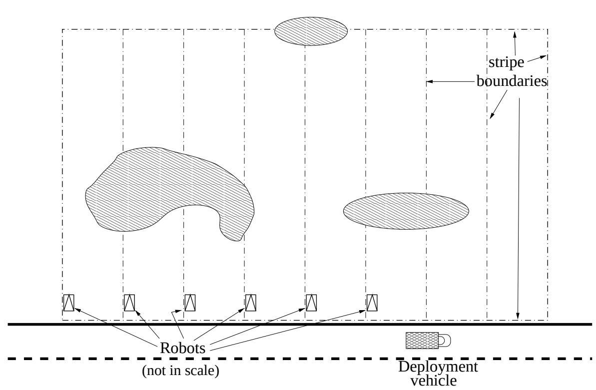


Figure 1 A large unknown area is divided up in vertical stripes. Each covering robot is assigned a stripe to cover. A deployment vehicle is utilized that distributes the robots at the beginning of the stripes. The robots do not know the layout at the interior of each stripe.

We assume that the robots know their position and orientation with respect to a global reference frame (e.g. via access to a GPS system). The robot sensors are able to detect both static obstacles and mobile robots, and differentiate between the two. The sensors have limited range and a good angular resolution.

The working paradigm in our approach is the application of humanitarian de-mining. A team of robots is deployed along one side of a field to be cleared, at regular intervals (as in Fig. 1). The interior of the field is unknown, partially covered with obstacles, and divided into a number of virtual stripes equal to the number of robots. Each robot is allocated initially the responsibility of the stripe it is placed at, and the coverage starts.

In the next section we present relevant background on the Coverage task and on the market based approach. Section 3 provides an overview of our algorithm and the next Section presents our experimental results in multiple simulated environments. Finally, Section 5 provides conclusions and future work.

2. Related Work

This work employs a single robot coverage algorithm for each individual robot and an auction mechanism to negotiate among robots which areas each robot would cover. Due to space limitations we will briefly outline the major approaches in multi-robot coverage (for a more detailed survey please refer to (Rekleitis et al., 2004)) and then we will discuss related work on market based mechanisms in mobile robotics. Finally, we present a brief overview of relevant terminology used in coverage and exact cellular decomposition. This work takes root in the Boustrophedon decomposition (Choset and Pignon, 1997), which is an exact cellular decomposition where each cell can be covered with simple back-and-forth motions.

Deterministic approaches have been used to cover specialized environments (Butler et al., 2001) sometimes resulting in repeat coverage (Latimer-IV et al., 2002; Kurabayashi et al., 1996; Min and Yin, 1998). Non-deterministic approaches include the use of neural networks (Luo and Yang, 2002), chemical traces (Wagner et al., 1999), and swarm intelligence (Ichikawa and Hara, 1999; Bruemmer et al., 2002; Batalin and Sukhatme, 2002). The non-deterministic approaches can not guarantee complete coverage.

2.1 Market-based Approach in Robotics

Cooperation and task allocation among mobile robots is crucial in multi-robot applications. To facilitate task re-allocation a new methodology based on market economy has gained popularity. For a comprehensive survey please refer to (Dias and Stentz, 2001). Currently market based approaches have been used to solve the multi-robot task allocation problem (Goldberg et al., 2003) in the domains of: exploration (Berhault et al., 2003; Dias and Stentz, 2003), failure/malfunction detection and recovery (Dias et al., 2004), and box pushing (Gerkey and Mataric, 2002).

2.2 Boustrophedon/Morse Decomposition

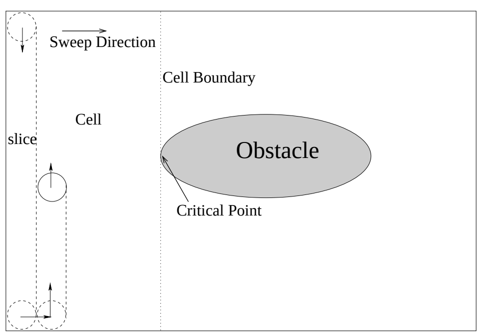
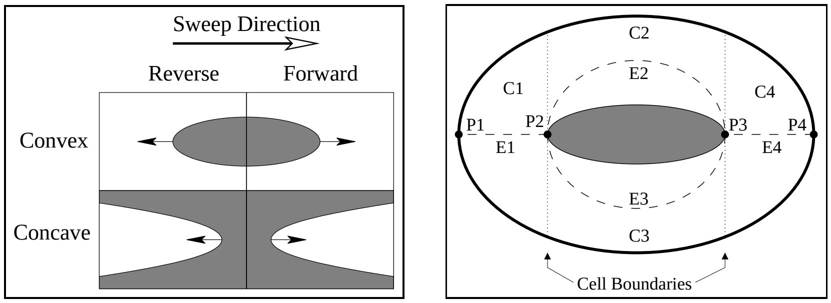


Figure 2 Illustrates the terms borrowed from single robot coverage with a single robot and one obstacle in the target environment. The robot is performing coverage with simple up-and-down motions.

To better describe the multi-robot coverage algorithm, we borrow the following terms from single robot coverage: *slice*, *cell*, *sweep direction*, and *critical point* (see Fig. 2). A *slice* is a subsection of a *cell* covered by a single, in our case vertical, motion. A *cell* is a region defined by the Boustrophedon decomposition where connectivity is constant. In our current work a cell is further constrained by the boundaries of the stripe (the space allocated to a robot). *Sweep direction* refers to the direction the slice is swept. Lastly, a *critical point* represents a point on an obstacle which causes a change in the cell connectivity. The critical points have been described in length in (Acar and Choset, 2000) (see Fig. 3a for an overview). We also borrow the concept of a Reeb graph, a graph representation of the target environment where the nodes are the critical points and the edges are the cells (Fig. 3b).

3. Algorithm Overview

Our approach consists of two behaviours, exploration and coverage. The robots initially try to trace the outline of the areas assigned to



(a) (b)

Figure 3. (a) Depicts the four types of critical points, based on concavity and the surface normal vector parallel to the sweep direction. Note that the shaded areas are obstacles and the arrows represent the normal vectors. (b) Here a simple Reeb graph is overlaid on top of a simple elliptical world with one obstacle. P1-P4 are critical points which represent graph nodes. E1-E4 represent edges which directly map to cells C1-C4.

them in order to be more knowledgeable about the general layout of the free space. The connectivity of the free space is recorded in a graph that consists of the Reeb graph augmented with extra nodes (termed Steiner points) placed at the boundaries of the assigned stripes for each robot. The edges of the graph represent areas of accessible unexplored space and each edge belongs to a robot. During the exploration phase the robots exchange information and if the stripe a robot has assigned is not fully explored, then, that robot calls an auction for the task of exploring the remaining area of the stripe.

3.1 Cooperative Exploration

The robot uses the cycle algorithm developed in single robot Morse Decomposition for exploration of the stripe boundary. The cycle path is a simple closed path, i.e., by executing the cycle algorithm the robot always comes back to the point where it has started. This same cycle algorithm is used for both exploration and coverage. Before describing the cycle algorithm, we need to define 2 terms: lapping and wall following. Lapping is the motion along the slices while wall following is the motion along obstacle boundaries. A simple cycle algorithm execution will consist of forward lapping, forward wall following, reverse lapping and reverse wall following (as shown in Fig. 4a). This is sufficient for exploring the stripe boundary.

To explain the cooperative exploration algorithm, we will look at an example. Fig. 4b shows an unknown space with a single obstacle, being

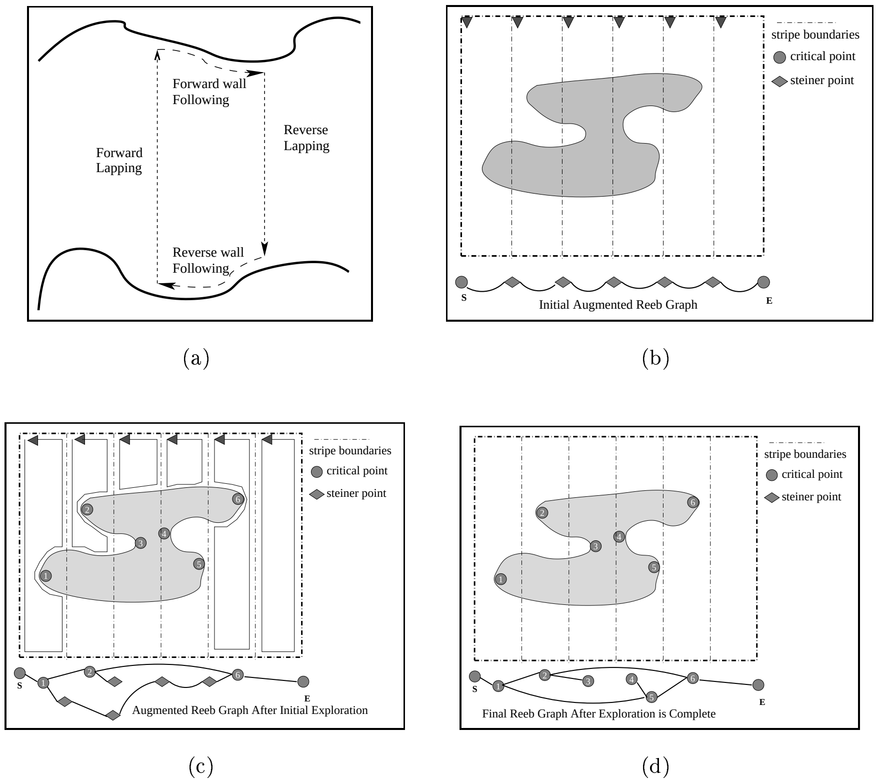


Figure 4. (a) A simple cycle path consisting of forward lapping, forward wall following, reverse lapping and reverse wall following. (b) Simple environment with initial Augmented Reeb Graph. (c) Initial exploration of stripes. (d) The final Reeb Graph after exploration is complete.

divided into 6 stripes. The Reeb graph of each robot is initialized with 2 critical points (**S**tart and **E**nd) and 5 Steiner points (representing the stripe boundaries).

The robots access their respective stripes and perform initial exploration using the cycle algorithm (forward lapping, forward wall following, reverse lapping and reverse wall following). During exploration, the robots modify their knowledge of the environment by updating the Reeb graph as they discover critical points and new information about the Steiner points. After completing a cycle, each robot shares its updated partial Reeb graph with the rest of the robots. At the end of the initial exploration, the updated global Reeb graph is as shown in Fig. 4c.

In the process of exploration, the robots will realize that there are spaces in their stripe that they are not able to reach easily. Those robots that are in such a situation will formulate the unreachable portions of the stripe as auction tasks and call auctions to re-allocate these parts of their stripe. In this manner, cooperative exploration is achieved. Fig. 4d shows the completed Reeb Graph after exploration is complete. Robots that do not have any exploration tasks can start performing partial coverage of known stripes in order not to waste time. Coverage of a cell is considered an atomic task, thus a robot that has started covering a cell would finish covering it before starting another task. The global Reeb graph is updated to represent the increased knowledge of the environment.

3.2 Cooperative Coverage

After all the stripe boundaries are completely explored (fully connected Reeb graph without Steiner points), the cells are owned by the robot that discovered them. The environment is fully represented by the Reeb graph, hence it is decomposed into a set of connected cells (the union of all the cells represents the free space), and all free space is allocated to the robots. Next the robots proceed to cover the cells under their charge. Coverage of a single cell is the same as single robot Morse Decomposition; if there are no obstacles within the cell, the coverage is a series of simple cycle paths. If there are obstacles within the cell, the robot performs incremental modification of the Reeb graph within that cell and shares the information with the other robots. If there is a robot that is without a task it calls an auction to offer its service to other robots. If all robots have completed their cell coverage and there are no uncovered cells in the Reeb graph, then the robots return to their starting positions and declare the environment covered.

3.3 Auctioning Tasks

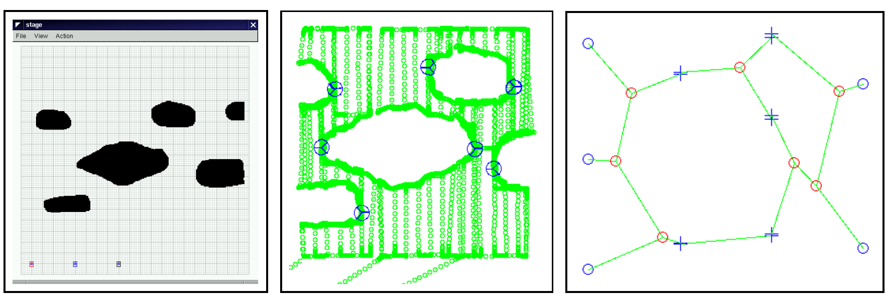
A simple auction mechanism is used to investigate the feasibility of auction to enable cooperation among robots. At any auction a single task is auctioned out. In general, the auction mechanism operates as follows: (a) A robot discovers a new task and calls an auction with an initial estimated cost. (b) Other robots that are free to perform the task at a lower estimated cost, bid for the task. (c) When the auction time ends, the auctioneer selects the robot with the lowest bid and assigns the task. The winning robot adds the task into its task list and confirms that it accepts the task by sending an accept-task message back to the auctioneer. The auctioneer deletes the auction task and the task auction process concludes. As stated in the previous sections, auction is used in two separate ways: for cooperative exploration, and for cooperative coverage.

During exploration, a robot can encounter a situation where the stripe it is exploring is divided into two (or more) disconnected parts (see for example the middle stripe in Fig. 5a) because of an obstacle. The robot starts with forward lapping, encounters the obstacle and performs wall following. The wall following behaviour brings it to the stripe boundary associated with reverse lapping. As a result, the robot infers that there exists a disconnected stripe. At this point, it will formulate a new stripe to be explored and calls an auction for this new exploration task. Please note that the robots generally do not have sufficient information to know accurately the cost of performing the exploration task. It can only estimate the cost based on whatever information is available. Cost is the only parameter that decides the winning robot in an auction and it is thus the factor that determines the quality of cooperation. The estimation of the cost can be potentially a complex function of many variables (such as time spent, fuel expended, priorities of the task, capabilities of the robot). For this investigation, the task cost for the bidder is estimated based on 2 components: (a) Access cost: Based on the bidder's current estimated end point (the point where its currently executing atomic task will end), this is the shortest Manhattan distance to access the new stripe; (b) Exploration cost: Assuming that the robot can access the desired point in the stripe, this is the minimum distance that it needs to travel in order to explore the stripe completely (as parts of the stripe could already have been explored, the starting point of the exploration could result in different costs for different robots).

When an initial estimate of the cells is available (exploration is complete) the robot that has discovered a cell is initially responsible for covering it. The robot without any tasks will offer its service by also calling an auction. Any robot that has extra cells (less the cell that it is currently covering) will offer one of the cells, based on the auctioneer's position. Each robot without extra cells will estimate the current cell workload and offer to share its cell coverage task if it is greater than a threshold. The auctioneer prefers to takeover a cell rather than to share coverage of a cell. It will use the estimated distance to access the cell as a selection criteria if there are more than one cell on offer.

4. Experimental Results

The distributed coverage algorithm was implemented in simulation using Player and Stage (Gerkey et al., 2001) with 3 robots. We adopted a highly distributed system architecture because it can quickly respond to problems involving one (or a few) robots, and is more robust to point failures and the changing dynamics of the system. Our architecture is based on the layered approach that has been used for many single-agent autonomous systems (Schreckenghost et al., 1998; Wagner et al., 2001). We are employing two layers for each robot instead of the traditional three layers: Planning and Behaviour. The *upper* layer consists of *Planner* and *Model* and the lower layer is *Behaviour*. Model is where the Reeb graph resides. Planner is where Morse Decomposition, auction mechanism, task scheduling and task monitoring take place. The Behaviour process serves the same function as in traditional layered architecture, controlling the robots to perform atomic tasks such as Goto, Follow Wall and Lapping.



(a) (b) (c)

Figure 5. (a) The environment and the three robots at the starting position in Stage. (b) The traces of the robots (marked as circles which are smaller than the footprint) and the critical points encountered. (c) The augmented Reeb graph with the critical points (circles) and the Steiner points (crosses).

A sample environment for testing the algorithm is shown in Fig. 5a. Each robot is allocated a stripe and the Planner of each robot receives the stripe information. The Planner determines the point where it wants to access the stripe and sends the way-point to the Behaviour process for execution. After accessing the stripe, the Behaviour process sends a message to the Planner informing the Planner that access of the stripe is completed. Based on the stripe information and the robot pose, the Planner plans for Forward Lapping and sends this task to the Behaviour. The Behaviour executes the forward lapping task. For this task, the 3 robots experience different terminating conditions because of the environment: The left and the right robots complete the exploration of their stripes without any problems. The middle robot realizes that it can not complete the exploration of its stripe and calls an auction. The robot on the right wins the auction and proceeds to explore the remaining part of the middle stripe. In the mean time the left and middle robots start partial coverage. Finally when exploration is complete the robots exchange cells via auction and completely cover the environment. Fig. 5c shows the Reeb graph after exploration is completed. Fig. 5b shows the trace of the three robots plotted as circles (the trace is smaller than the robot footprint for illustration purposes).

During our experiments the robots continuously explored and covered the environment. After a few auctions it was impossible to predict which task was scheduled next by each robot. It is worth noting though that the distance traveled by each robot was approximately the same thus showing that the workload was distributed evenly.

5. Summary

In this paper we presented an algorithmic approach to the distributed, complete coverage, path planning problem. Under the assumption of global communication among the robots, each robot is allocated an area of the unknown environment to cover. An auction mechanism is employed in order to facilitate cooperative behaviour among the robots and thus improve their performance. In our approach no robot remains idle while there are areas to be covered.

For future work, we would like to compare the performance between the distributed approach described here with the formation-based approach with limited communication presented in (Rekleitis et al., 2004). Augmenting the cost function to take into account individual robot capabilities (especially in heterogeneous teams) is an important extension. Accurate localization is a major challenge in mobile robotics; we would like to take advantage of the meeting of the robots in order to improve the localization quality via cooperative localization (Roumeliotis and Rekleitis, 2004). Finally, developing more accurate cost estimates for the different tasks is one of the immediate objectives.

Acknowledgments

The authors wish to thank Edward Rankin for his help with the algorithm implementation and experimentation; Vincent Lee-Shue and Sam Sonne for providing valuable input during the early stages of this project; Bernadine Dias, Danni Goldberg, Rob Zlot and Marc Zink for their help with the Market based approach. Finally, Luiza Solomon provided valuable insights on the software design and an implementation of a graph class. Furthermore, we would like to acknowledge the generous support of the DSO National Laboratories, Singapore, the Office of Naval Research, and the National Science Foundation.

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