Distributed, Complete, Multi-robot Coverage of Initially Unknown Environments using Repartitioning

(Extended Abstract)

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ABSTRACT

We consider the problem of coverage path planning by multiple robots in an environment where the location and geometry of obstacles are initially unknown to the robots. We propose a novel algorithm where the robots initially partition the environment using Voronoi partitioning. Each robot then uses an auction-based algorithm to reallocate inaccessible portions of its initial Voronoi cell to robots in neighboring Voronoi cells so that each robot is responsible for covering a set of contiguous connected regions. We have verified the performance of our algorithm on e-puck robots within the Webots simulator in different environments with different obstacle geometries and shown that it performs complete, non-overlapping coverage.

Categories and Subject Descriptors

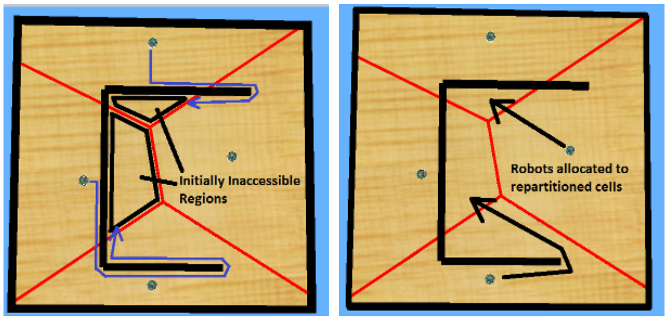
I.2 [**Artificial Intelligence**]: Robotics

Keywords

Multi-robot systems; coverage; Voronoi partition

1. INTRODUCTION

Coverage path planning is a central aspect of multi-robot systems where the objective is to completely cover the surface area of an environment using multiple robots [2]. Our research in this paper is based on the key insight that when the initial partition of the environment is done equitably between robots, exactly one robot occupies a cell. Then, even if the cell that a robot is covering gets disconnected due to obstacles, as shown in Figure 1(a), because the free space is connected, the inaccessible portion of the cell must be adjacent to at least one of the neighboring cells and accessible to the robot in that cell. Consequently, the robot performing coverage in the adjacent neighboring cell could be requested to augment its coverage with the inaccessible portion of the disconnected cell, as shown in Figure 1(b). Based on this insight, we first partition the environment into complete non-overlapping cells using Voronoi partitioning [1] and then propose a novel algorithm called *Repart-Coverage*, that uses a low-overhead coordination protocol between robots to systematically repartition only those portions of their cells that are inaccessible to them from within their respective cells, due to obstacles. We have verified the performance of our proposed algorithm on simulated e-puck robots within the Webots simulator.



(a) (b)

Figure 1: (a) The Voronoi cells of two robots are partially inaccessible due to obstacles. The blue solid arrows show the path taken by a robot to reach the inaccessible portions of its cell using a bug-like path planning algorithm. (b) Robots coordinate with each other to repartition the initial Voronoi cells so that each robot has a contiguous region to cover.

2. DISTRIBUTED SPATIAL PARTITIONING

We assume a set of robots are deployed at arbitrary positions within an initially unknown environment. The environment is partitioned into disjoint regions or cells using Voronoi partitioning, based on the initial position of each robot. Each robot is then assigned to cover the free space within the Voronoi cell it is currently located in. To realize this, each robot first covers the boundary of its Voronoi cell using an algorithm called Egress[3], while recording unreachable portions of its Voronoi cell, if any, caused by the presence of obstacles. These inaccessible regions are called *patches*. A robot systematically analyses each of its patches while communicating information about the patch's location with neighboring robots to determine which neighboring robot has access to and is most suitable for covering the patch.

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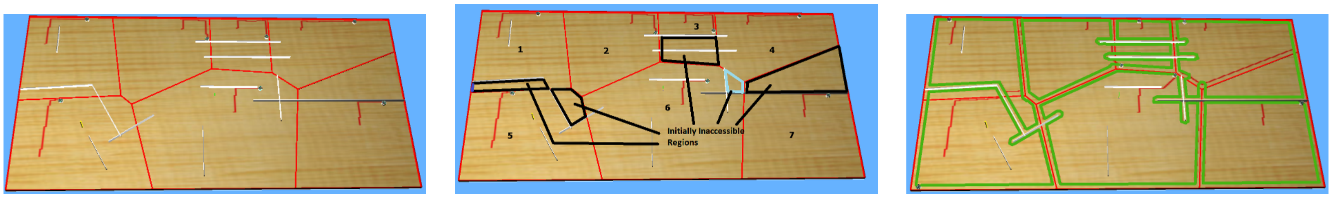

(a) (b) (c)

Figure 2: Snapshots from Webots showing repartition coverage by 7 robots in a 3×6 m^2 environment with different obstacle features, (a) initial Voronoi partition, (b) robots performing boundary coverage on Voronoi cell, black/light blue boundaries show inaccesible regions. (c) repartitioned cells and robots completing coverage of entire environment.

The patches are allocated to neighboring robots using an auction protocol as shown in Algorithm 1. After a robot determines the inaccessible patches in its initial Voronoi cell, it sends a bid request message with information about the patches to robots in its neighboring Voronoi cells. Every neighbor robot calculates a bid for the patches, and sends it to the auctioning robot. In the current implementation of the algorithm, these bids are calculated as the perimeter of the bidding robot's current region. The robot that submits the lowest bid is selected as the winner of the auction and assigned the inaccessible portion of the Voronoi cell. The auctioning robot informs the winner, which then appends the region to the list of regions it needs to cover, and starts to perform boundary coverage of its newly assigned region. The auction algorithm possesses the essential properties (completion, non-overlapping coverage), but it reduces communication and coordination overhead by combining adjacent patches belonging to different robots, when the patches are accessible from each other.

Algorithm 1: Algorithm used by a robot to perform repartition coverage.

```
Repart-Coverage($V_i$)
Input: $V_i$: Voronoi cell of robot $i$
Output: $V_i'$: Repartitioned coverage region for robot
perform boundary coverage in $V_i$ and determine $V_i^{i0}$
$\mathbf{S}_{ij}^b \leftarrow$ set of blocked patches comprising $V_i \backslash V_i^i$
for each $S_{ij}^b \in \mathbf{S}_{ij}^b$ do
    $\mathbf{j} \leftarrow$ set of Voronoi neighbor robots of $i$ that have Voronoi cell boundaries with $S_{ij}^b$
    send coordinates of polygon representing $S_{ij}^b$ to all robot in $\mathbf{j}$
    wait for bids
    $\mathbf{bid} \leftarrow$ set of bids received
    $j_{win} \leftarrow \arg\min_j \mathbf{bid}$
    $V_i \leftarrow V_i \backslash S_{ij}^b$ //remove $S_{ij}^b$ from $V_i$
    send message to robot $j_{win}$ to add $S_{ij}^b$ to $V_{j_{win}}$
handleBidMessages() //for robot $j$
if received bid request for $S_{ij}^b$ from robot $i$ then
    $bid_j = \begin{cases} \text{currently covered perimeter of } V_j, & \text{if} S_{ij}^b \text{ reachable} \\ \infty, & \text{otherwise} \end{cases}$
    send $bid_j$ to robot $i$
if received winner message for $S_{ij}^b$ from robot $i$ then
    $V_j \leftarrow V_j \cup S_{ij}^b$ //add $S_{ij}^b$ to $V_j$
    Repart-Coverage($V_j$)
```

3. EXPERIMENTAL RESULTS

We have implemented our proposed Repart-Coverage algorithm using simulated e-puck robots within the Webots simulator. E-puck robots use Bluetooth protocol for inter-robot communication, and have a GPS and compass for localizing w.r.t the environment. Figure 2(a)-(c) show an instance of the operation of the Repart-Coverage algorithm for a 3×6 m^2 environment with 7 robots. The scenario includes some unique obstacle features like narrow channels between obstacles and obstacles that span across multiple Voronoi cells, which require the inaccessible regions to be re-allocated to robots multiple times. For example, the region towards the center of the environment marked with a light blue boundary is initially within robot 6's Voronoi cell. Using the Repart-Coverage algorithm, robot 6 first allocates it to robot 7 as robot 7 has a smaller region to cover (smaller perimeter after its initial boundary coverage). However, robot 7 determines that it is unable to access the region because of an obstacle and runs the algorithm again to reallocate the region to robot 4. Robot 4 is then able to access this region successfully and adds it to its coverage cell. This shows that our algorithm successfully terminates and is able to find complete, non-overlapping regions for complex obstacle geometries. We have further verified the operation of our algorithm in different-sized environments with different numbers of robots and ensured that it guarantees complete, non-overlapping coverage in every scenario tested.

4. CONCLUSIONS AND FUTURE WORK

We proposed a novel technique for distributed spatial partitioning of an initially unknown region by multiple robots for a multi-robot coverage application. We are investigating techniques for balancing the coverage load between different robots and for succinctly representing the topological information that is communicated between robots.

5. REFERENCES

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