University of California San Diego

CSE276A: Introduction to Robotics

HW5: Roomba System

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Link to the Video: https://youtu.be/51b-IGixWY0

1 World Representation & Architecture

1.1 World Representation

We set up a square area measuring 1.6 meters by 1.6 meters and use a two-dimensional grid as a simplified representation of the world, which will be explained in more detail in Section 2. Three AprilTags are placed on each side of the square. We set $(0.3, 0.3, 0)$ as the initial pose of the robot, and a 1 meter by 1 meter square as the area we need to cover, of which the left bottom point is the initial position of the robot. Our map is shown as in Figure 1.

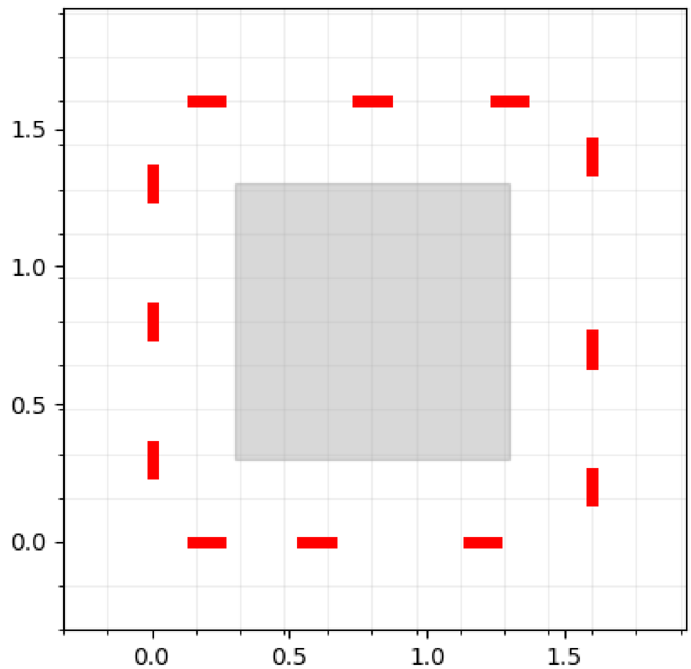

Figure 1: The sketch of our map in the top-down view layout, where the red lines represent AprilTags. The gray area indicates the area our roomba need to cover.

1.2 System Modules Diagram

We design an offline path planning algorithm to generate Hamiltonian path for the desired area coverage, and use the EKF-SLAM system in HW3 to estimate the position of the landmarks as well as localize the robot. The algorithm will be introduced in Section 2. Our diagram is shown in the following Figure 2.

1.3 Behaviors Needed to Provide Coverage/Avoidance

Initially, the robot embarks on an Exploration phase, during which it investigates the area to construct an Enclosed Map. This phase persists until the entire mappable region is enclosed. Upon completion of the map, the robot transitions to the Path Planning stage, formulating a path that ensures comprehensive traversal within the enclosed map. Subsequently, the Navigation phase commences, with the robot adhering to the planned path to achieve Full Coverage.

The process concludes if Full Coverage is attained. Nonetheless, should there be alterations in the map during navigation—indicative of dynamic elements within the environment—the robot undertakes a Map Update. This necessitates a return to Path Planning for route modifications. This iterative cycle of Path Planning, Navigation, and Map Updating persists until the robot uniformly covers the entire area, effectively addressing

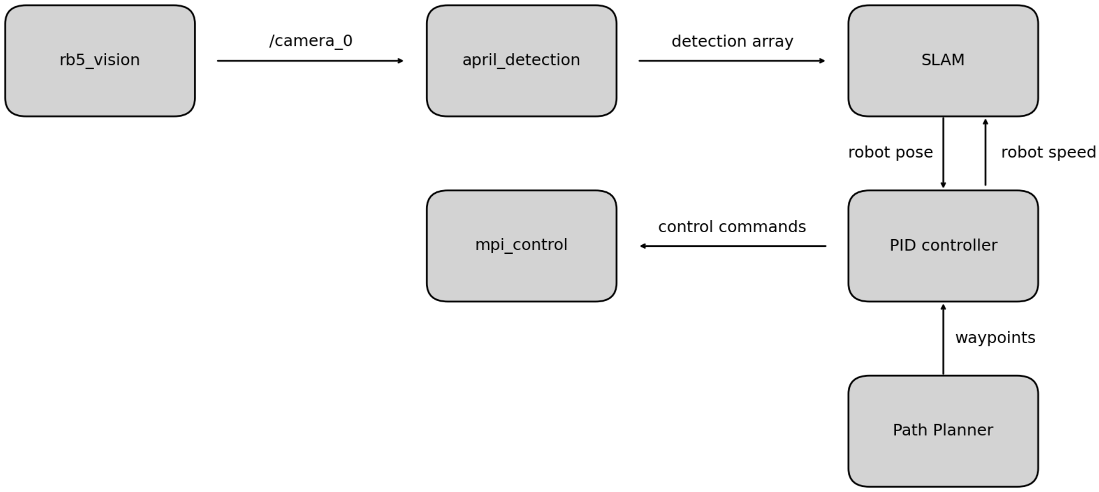

Figure 2: The diagram of our system.

environmental variations. This system, as shown in Figure 3, not only ensures thorough area coverage but also facilitates the obstacle avoidance of the robot, dynamically adapting to maintain both objectives.

2 Path Planning Algorithm

In coverage path planning on a grid map, the target area is initially transformed into an $m \times n$ grid. This step includes representing physical obstacles as impassable cells within the grid. Ensuring the connectivity of the coverage area is crucial, as it eliminates the presence of isolated sections.

Subsequently, a spanning tree is constructed to facilitate a cycle-free path connecting all reachable cells. Each cell of the $m \times n$ grid is then subdivided into 2×2 subcells, effectively creating a finer $2m \times 2n$ grid. This subdivision enables more precise path planning, particularly in proximity to obstacles.

The next phase involves a preorder traversal of the spanning tree, beginning at the root and sequentially progressing through each child node. At each node, a loop is formulated, linking the node to its children and ultimately circling back to the node. This approach guarantees a single, non-repetitive visit to each node. The over all process of our path planning algorithm is shown in the following Figure 4.

3 Proof of Coverage

Within the grid map, each node connects to a maximum of four neighbors: up, down, left, and right. In the constructed spanning tree, excluding the connected parent, each node has up to three children, forming a ternary tree structure. It is critical in algorithm execution to ensure every child node is visited and returns to its parent, achieved through a specific visitation sequence and path.

Focusing on the penultimate layer of the tree, we established a methodology to enter from one entry point and exit from another, adaptable to all scenarios, as shown in Figure 5. This approach, consistent at each node, is recursively applicable to every subtree, ensuring that each node is visited exactly once without exclusion.

By integrating these steps, we formulate a Hamiltonian path that traverses all nodes without repetition, covering all accessible grids and accounting for cell connectivity. Thus, the algorithm efficiently generates a comprehensive coverage path, ensuring complete area coverage even in environments with obstacles.

Through this logical and structural analysis, we establish that regardless of the size and shape of the grid map, provided the coverage area remains connected, our algorithm can invariably identify an effective Hamiltonian path for comprehensive coverage path planning, aligning with the core objectives of path planning.

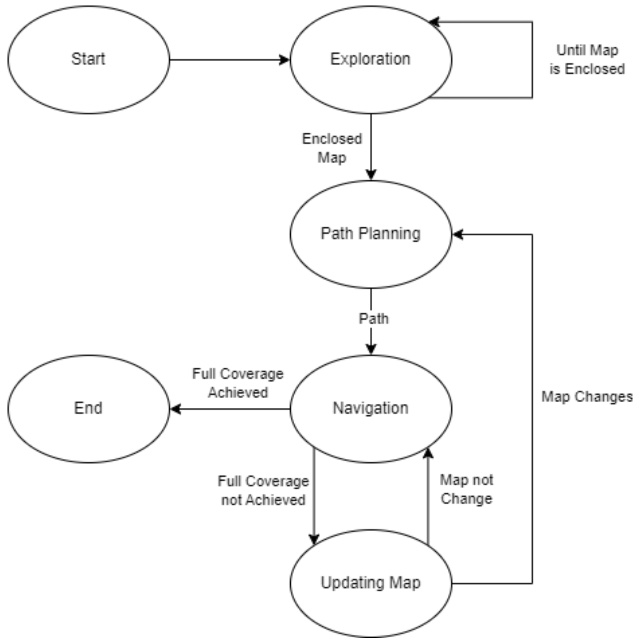

Figure 3: Behaviors needed to provide coverage/avoidance.

4 Visualization and Results

4.1 Path Visualization

The paths generated by the algorithms are visualized on the grid map, as shown in Figure 6. The path is represented by the green line. Our generated path covers the whole desired square area without exclusion, and each grid is visited exactly once. The robot return to the starting point eventually.

4.2 Trajectory Visualization

We recorded every waypoint the robot passed through during its actual operation, as well as the estimated landmark position by our SLAM system, as shown in the Figure 7. The trajectory of the robot is depicted by blue dots, while the areas covered by the robot are indicated by green circles (we set the radius of the robot to be 10cm). Red circles represent the estimated landmark locations as determined by the SLAM system. Additionally, blue ellipses are utilized to illustrate the covariance associated with these estimations. It can be observed that the actual performance of the robot largely aligns with the planned path in Figure 6.

The robot effectively covered the designated square area (illustrated as a gray square), achieving intensive coverage throughout. However, marginal deficiencies in coverage were observed along the edges. These discrepancies are likely attributable to errors in mapping and localization. The mean error of landmark location estimation is 0.11, and the total distance of the robot trajectory is 10.23.

5 Conclusion

The capability of our path planning algorithm in covering designated area has been showcased in this report. Future work may focus on the online and dynamic path planning.

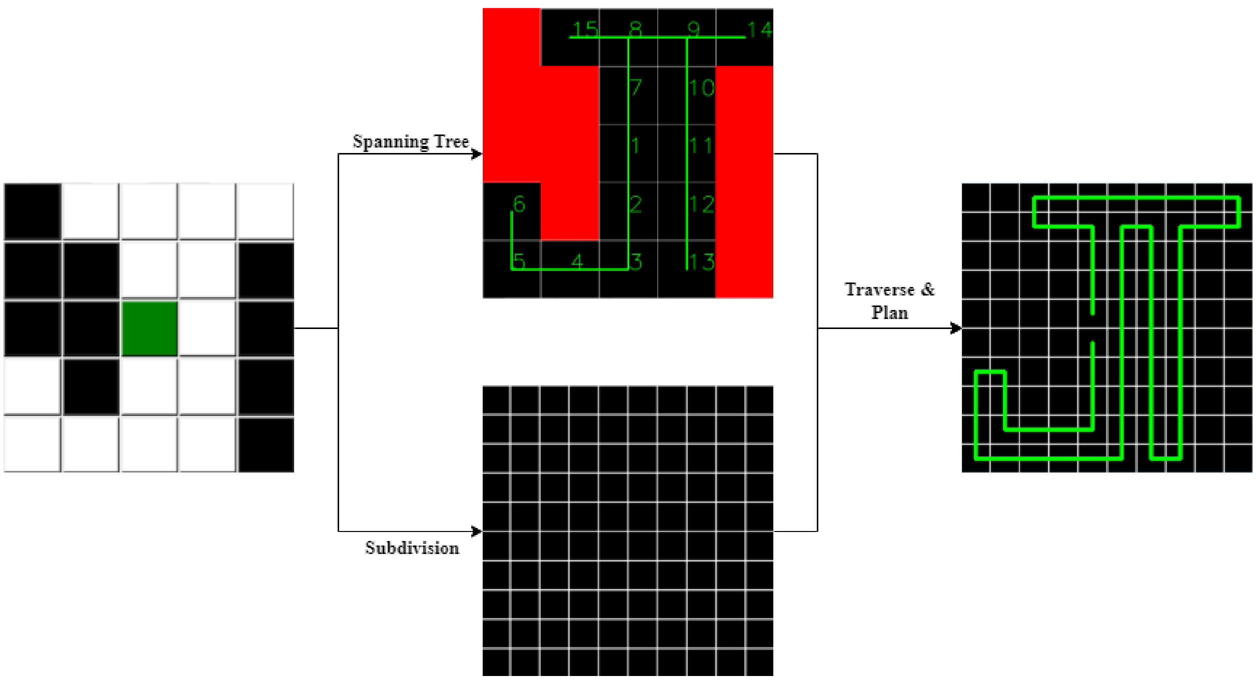

Figure 4: The overall process of our algorithm. Black grids in the left grids map represents obstacles, while the green grids represents the starting point of the robot.

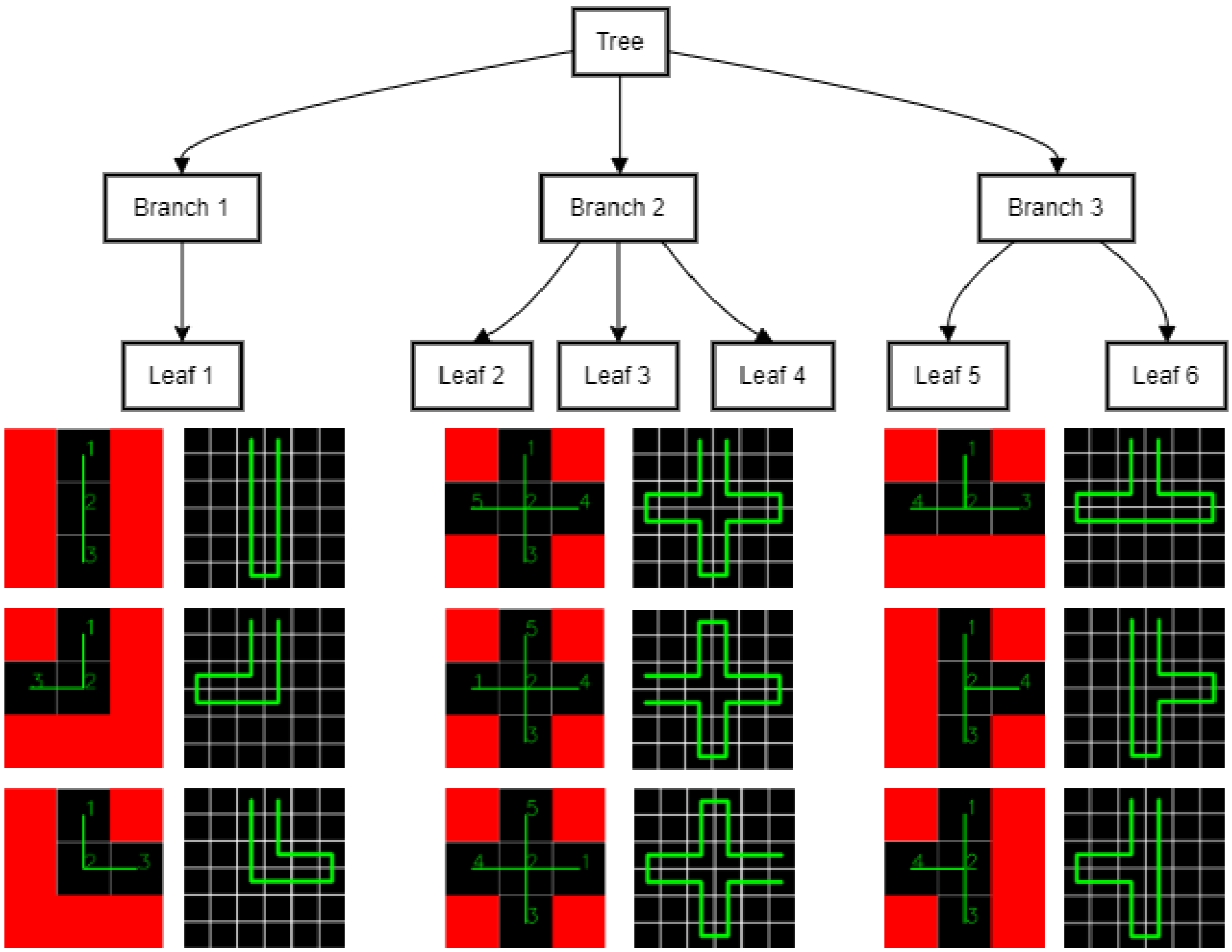

Figure 5: Spanning Tree Structure

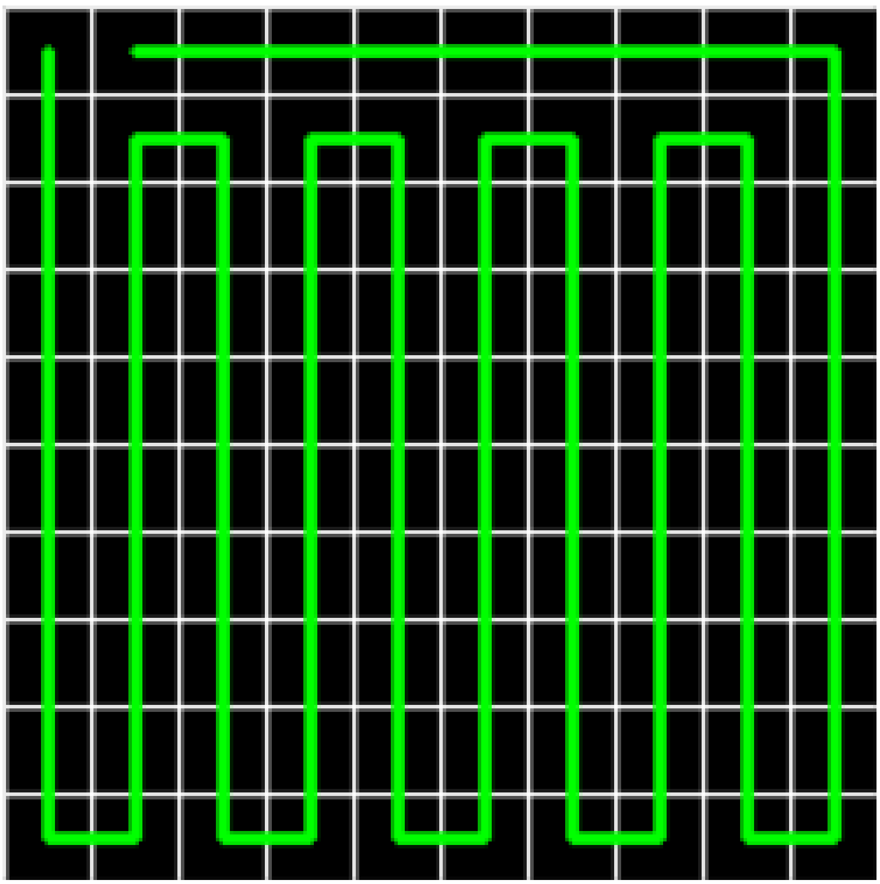

Figure 6: The paths generated by the algorithms, represented by the green line.

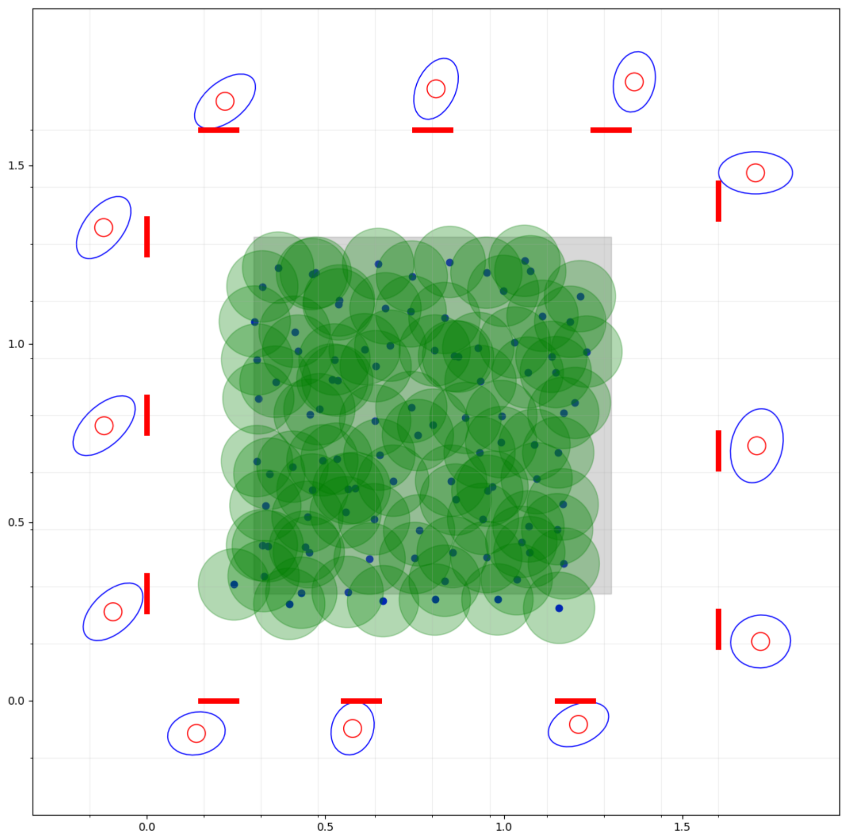

Figure 7: The actually coverage of the robot during operation, in which blue dots represent the waypoint robot passed through, and green circles represent the coverage area of the robot.Red circles represent the estimated landmark locations as determined by the SLAM system, while blue ellipses are utilized to illustrate the covariance.