Motion Planning for Marsupial Robotic Systems

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A key advantage of heterogeneous multi-robot teams is their ability to exploit individual team member strengths to dramatically improve overall system resilience to dynamic environments and changing objectives. Here, we consider a specific sub-class of heterogeneous robot teams, the *marsupial* team. As defined in [9, 5], the marsupial relationship is defined by a larger robot transporting a smaller robot, where each robot typically has different mobility characteristics. For instance, quadrotors, while having superior mobility, are energetically expensive. By using an unmanned ground vehicle (UGV) to carry a quadcopter or other unmanned aerial vehicle (UAV), the marsupial robot system is able to exploit the UAV's mobility while reducing overall cost-of-transport. Thus, an effective marsupial robotic team can dramatically improve overall system resilience in challenging environments when team member mobility and efficiency are inversely related.

Here, we work toward an approach for marsupial robot motion planning that is able to reason about both mobility and spatial constraints to achieve near-optimal motion of the overall team through topological multi-graphs. We believe that our approach will enable fast, light-weight receding-horizon planning and re-planning of multiple marsupial robot sub-teams under unknown and changing conditions.

Algorithmic Approach

We decompose the marsupial robot planning problem into a hierarchal planning problem. We first solve the multi-robot coordination problem by reasoning about the environment's geometric constraints. We then use this "high-level" plan to facilitate "low-level" trajectory optimization, which ensures kinematically and dynamically feasible trajectories for the individual robot team members.

A. High-Level Marsupial Team Planning

1) Watershed Segmentation: Watershed segmentation is a well known algorithm widely used in image processing [1]. Following [2], our algorithm applies watershed segmentation to a voxelized distance map, segmenting the world into large free space regions (i.e., the catchment basins) and boundaries between these regions, or *watersheds*. It is these watersheds that we use as features to assign potential locations for marsupial deployment.

2) Construction of Topological Multi-Graph: To facilitate high level trajectory planning, a topological multi-graph for the team is created from the union of edges from each robot's individual topological graph. The graphs contain two types of nodes: nodes signifying large free-space regions in the world and threshold nodes signifying the entrances and exits from these regions. To construct topological graphs for the individual robots, free-space nodes are connected to threshold nodes within the the same catchment basin. Adjacent threshold nodes are connected to one another across the watershed if the size of the watershed is larger than the robot's largest dimension. The robot-specific topological graphs can be combined into a multi-graph by using directed edges that encode deployment actions. Planning across this multi-graph for the multi-robot system is then straight-forward through the use of the A* search algorithm and produces a high-level motion and coordination plan. To account for an optimization objective (e.g., minimize energy), we can run the search algorithm with a scalar cost applied to each edge in the multi-graph.

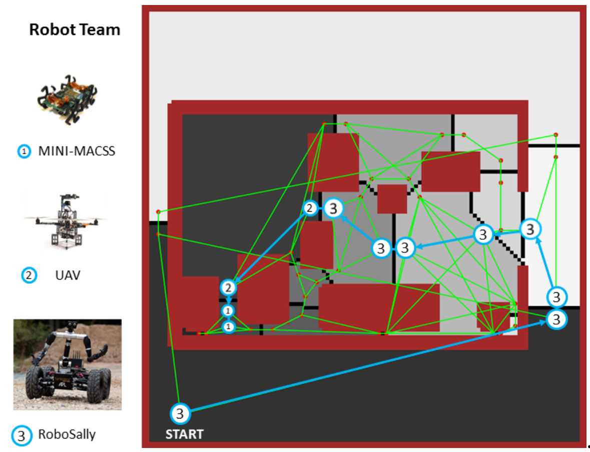

Fig. 1. Depiction of two-dimensional planning for the nested marsupial system described in [8, 6], consisting of a carrier UGV (3), a quadcopter UAV (2), and a miniature UGV (1). Red represents occupied space, grayscale represents the catchment basin, green represents the multi-graph, and black the watersheds.

B. Low-Level Motion Planning

Once the optimal path on the topological graph has been found, a low-level planner is used to translate this path and coordination plan into a set of optimal trajectories that satisfy kinodynamic constraints. First, a simple RRT as defined in [7] is used to create a coarse, collision-free path between each topological node. This RRT path is then used as a seed for optimal trajectory generation. For each robot, a direct collocation [4] problem is formulated and solved using [3] to compute a collision free, dynamically feasible trajectory.

Discussion

Preliminary results demonstrate that our proposed approach is feasible in two (see Figure 1) and three dimensions. In the near-term, we plan to explore the application of our approach to unknown environments through real-time re-planning across a receding horizon.

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