Title: Dynamically Formed Heterogeneous Multi-robot Teams

Motivation: Humans are inherently good at cooperation in teams, and our ability to work together enables us to overcome challenges that a single individual would otherwise be unable to complete. The same can be said for autonomous robotic systems: for many applications a team of robots working together can complete a task more efficiently than an individual robot working alone. Another advantage of multi-robot systems is that the agents can be mechanically simpler than a single, general purpose agent required to complete the same set of tasks. Introducing heterogeneous robot types into the team allows specialized agents to focus on the tasks they are good at, and in many cases, increases the efficiency of the team.

Specialization improves teams, but introduces a new challenge: if a team is confronted with a task that no members of the team have the expertise to complete, the team will fail. The current solution to this challenge is to create large teams with a high diversity of agents, but this solution is inefficient and leaves highly specialized agents in the team under-utilized. Humans solve this problem intuitively: if the team does not have a capable member then one is recruited from an outside source, and when that task is complete and that person's skill set is no longer required, they are released from the team. Consider a situation where a child is lost in a theme park and security for the park sends out a quadrotor-based search team to look for the child. The quadrotors may be able to fly over the park’s walkways and above open areas searching for the lost child, but might determine that the child may have entered an area that they are unable to investigate. In this case the search team should be able to recruit the help of other agents in the area, like concession service robots on the ground or park employees, to search the areas inaccessible to the quadrotors. Then when the search is over, the recruited agents can return to their previous assignments.

Background: This question of dynamic team building is largely unexplored in robotics, but represents a necessary functionality as the diversity of robot systems increases. Previous research in this problem domain has focused on defining this challenge and presenting assessment metrics [1]. However, formal methods for coordination of these types of teams are limited.

In 2017, I worked with researchers at Oregon State University on the design and testing of a novel distributed coordination and task planning algorithm for heterogeneous robot teams called Distributed Monte Carlo tree search (Dist-MCTS). By generalizing the tasks, reward functions, and agent abilities, Dist-MCTS remains agnostic to the type of agents in the team, enabling coordination of teams composed of agents with different abilities. Simulated trials showed that Dist-MCTS teams earned 47% more cumulative team reward than teams coordinated using a distributed auction-based approach. While it is effective at organizing complex teams, this algorithm does not allow for dynamic team formation.

Research Proposal: I propose to explore the challenge of creating dynamically formed teams by modifying the Dist-MCTS high-level planner and implementing it in a larger framework for the dynamic formation of heterogeneous multi-robot teams. Two essential extensions must be made to the Dist-MCTS algorithm before it can be used for dynamic formation of teams. These focus on *scalability* and *policy estimation.*

A primary restriction of the current Dist-MCTS algorithm is scalability. If too many agents are added to the team (20+) or the number of tasks increases beyond a certain threshold (100+), the planning space becomes too high-dimensional and the solution quality declines. To address the challenge of scalability, I will incorporate autonomous sub-teaming and task space segmentation into the existing algorithm. This adaptation reduces the complexity of the planning operations for all agents across the macro-team. Extensibility is a key requirement for applications to dynamically formed teams because the planning space has the potential to expand rapidly during complex missions.

The second I will make to Dist-MCTS is the incorporation of an adaptive task selection model for inclusion of independent agents like humans or unknown robots in the team. Previous work [2] has demonstrated preliminary results for a method to estimate the policy of an independent agent like a human and use this to inform the actions of multi-agent teams. This is necessary because it cannot be guaranteed that the recruitable agents in the operating environment of a dynamically formed team will be able to communicate with the team. Policy estimation for these independent agents will allow the existing team to coordinate itself around agents without requiring direct communication and enable teams to be formed of robots that are not built by the same research group or manufacturer.

Methods: I plan to develop a novel algorithm for coordination of dynamically formed teams in three phases: *algorithm design*, *simulation testing and refinement*, and *hardware validation*.

I. The first phase will focus on integrating the modified Dist-MCTS in a larger software framework and developing the components necessary to facilitate dynamic team formation. This will include creating a method for assessing newly discovered tasks and determining a functional set of protocols for recruiting new agents to the teams.

II. With the new planner in development stages, I will test and refine the system with a modified version of the simulator used to assess the Dist-MCTS algorithm. A key point in this phase will be investigating how teams should recruit and release members as tasks are discovered and completed.

III. With a refined result, I will apply this high-level planner to multi-robot teams in a real-world hardware trials in unknown, dynamic environments to assess its validity in application. For a complete test of this algorithm, these hardware trials will be focused on not only validating the team's basic functionality, but in testing its applicability to complex multi-robot task domains like collective construction.

Broader Impact: This proposal addresses a key challenge in the design and operation of collaborative multi-robot systems, and will provide a platform for a variety of other potential research topics including rapid deployment of heterogeneous teams, and optimization of agent structures in such teams. Dynamic formation of multi-robot teams will revolutionize robotics by increasing the versatility of the multi-agent teams and the complexity of possible missions.

As advances in robotics continue and more robots become integrated in everyday life, these types of teams will become increasingly useful in a wide variety of application domains. One application for these types of teams could be in STEM education, where students learn about how robots interact with both the real world and each other through demonstrations involving these teams, allowing them to draw parallels between human teamwork and robot teamwork.

[1] Jones, E. G., Browning, B., Dias, M. B., Argall, B., Veloso, M., & Stentz, A. (2006). Dynamically formed heterogeneous robot teams performing tightly-coordinated tasks. In Proceedings 2006 IEEE International Conference on Robotics and Automation, ICRA 2006 (Vol. 2006, pp. 570-575). [1641771]

[2] L. Milliken and G. A. Hollinger, "Modeling user expertise for choosing levels of shared autonomy," in Proc. Planning for Human-Robot Interaction Shared Autonomy and Collaborative Robotics Workshop, Robotics: Science and Systems Conference, 2016.