1 Technical Area Chosen

The area of multi-robot systems, collections of heterogeneous or homogeneous robots exhibiting collective and cooperative behavior to accomplish a task, is growing at a rapid pace. These systems have potential applications in medicine, planetary exploration, disaster relief, manufacturing, and more. Multi-robot systems is inherently a multi-disciplinary field with many overlapping areas of interest and terminologies. It involves specializations from mechanical engineering, industrial engineering, mathematics, control systems, and computer science. Approaches range from relying on emergent swarming behaviors (such as those of an ant colony) to more centralized coordination between robots.

2 Importance of Chosen Area

Cooperating systems of multiple robots serve as one of the next stages in the development of robotics. They take advantage of the increased availability of small form factor computing platforms and microcontrollers and rapid small scale manufacturing techniques (such as additive manufacturing) to reduce cost. This enables massive numbers of robots to be constructed at low cost, in contrast to most current robotics systems which can cost thousands of dollars. Harvard University’s KiloBot [1,2] and Arizona State University’s Pheeno robots [3] are two such platforms built to study swarm robotics and multi-robot systems.

Additionally, the study and development of such systems can serve both as solutions to existing engineering problems and presents its own set of open problems that can advance related scientific fields. There are numerous applications of cooperating robotics being investigated. These are areas that can see major benefit from the introduction of cooperative robots or are otherwise incredibly difficult to accomplish without it:

1. Planetary Exploration Current robotic explorations of other planets generally rely on a single, high-cost, heavily outfitted robot. To ensure success of its mission, many of its moves are careful, deliberate, and as a result, slow. In addition, the availability of a single robot with a single set of instruments restricts the region of a planet that can be safely explored in any given amount of time. Using a fleet of coordinated robots would vastly increase the amount of a planet’s surface that could be covered. They would also provide a level of redundancy in the case of failure. Additionally, this redundancy would allow greater risks to be taken
by each individual robot, allowing exploration of areas previously out of reach due to fear of total mission failure [4].

2. Construction in Harsh Environments Utilizing robotic swarms may be crucial to building large-scale structures in environments like space and the surface of the moon. These structures may include human habitations, orbiting stations, or space elevators. In these situations, the ability for humans to operate is limited and we will undoubtedly rely on robots to perform much of the work in their construction. Cooperating robots that can perform these tasks with a high level of autonomy will be crucial as human resources and communication will be limited [5,6,7].

3. Search and Rescue Deployable swarms of robots, such as quadrotors, can potentially be quickly deployed to scan, map, and search the site of a disaster for survivors. This would serve to both help save human lives and reduce the risk to first responders [8].

Investing knowledge and resources in this area is crucial as robots become more and more integrated to our society. Robots will no longer be isolated machines operating in predictable environments, but coordinated agents operating and cooperating in uncertain environments with humans and other robots.

3 Problem to be Pursued

A major area of interest within multi-robot systems is methods of planning and decision making. This is the issue of how to best coordinate a group of robots to accomplish a common task. Solutions to this problem are will help to bring multi-robot systems out of the laboratory environment and into real-world scenarios. Coordination is central to the application of multi-robot systems in nearly every domain from exploration to search and rescue. My focus will be on robots that will cooperate, with each other and with humans, on collective construction tasks.

Current approaches to this problem range between two extremes of explicit and implicit coordination [11]. Explicit coordination mechanisms involve centralized or deliberate coordination between robots over resources. Implicit coordination mechanisms rely on coordinated behaviors forming from individual actions of robots. Many approaches take inspiration from nature and
biology, turning to the collective behaviors of insect colonies such as termites, ants, wasps, and bees [12-15]. These approaches assume that implicit behaviors can efficiently organize robots while keeping computational and communication complexity low. Additionally, the element of human operators is also considered. In a real-world scenario, a robot may encounter an unforeseen difficulty or failure that requires the intervention of a human. Some research is directed toward finding the optimal balance between the robot’s autonomy and human judgment. Ultimately, some seek to develop ways to intelligently bridge the cooperation between humans and a multi-robot team [15, 16]. In addition to this, there is a great deal of research into specific data structures, algorithms, and strategies for increasing the robustness of multi-robot systems or standardizing the software frameworks in use [17-20].

I intend to first proceed with intense study of these various approaches, comparing the benefits and trade-offs of each. This wide viewing of the field from a computer science angle may provide different insights into the solutions presented in the area. The problem is difficult and requires careful application of mathematical analysis and a novel approach. Approaches that expand on inspiration from nature have proven effective in the past. One of the the biggest hurdles is overcoming computational complexity constraints when increasing the number of robots in a system. This is where simpler more traditional methods, such as the classic search algorithms, fail and more intelligent, but complex, algorithms prevail [23].

4 Importance of the Problem to be Pursued

The problem of multi-robot coordination and decision making has a wide range of applications to the areas previously described (planetary exploration, construction, search and rescue). In assembly systems involving coordination between multiple robots and humans, these task allocation and planning problems are especially relevant. For instance, Multi-agent systems in factory environments can improve the efficiency and consistency of products [25]. For deep space missions, multi-agent systems can allow a smaller team of humans to control larger teams of robotic spacecraft. This has implications in space structure construction and planetary exploration [26].

5 Relevant Career Prospects

As multi-robot systems is still very much in the research and development stage, very few industry entities are active in the area. Kiva Systems (now Amazon Robotics) produces the Kiva robot platform utilized in Amazon’s warehouse operations. NASA also conducts a wide array of research in the field related to space and planetary exploration across its centers. NASA Ames and the Jet Propulsion Laboratory specialize in robotics and multi-agent robotic system, working on projects such as SPHERES and Super Ball Bot [21], and investigating trade-offs of multi-robot systems in space applications.

Many universities have laboratories dedicated to the study of multi-robot systems and swarm robotics. Only a portion of those are described here. The Georgia Institute of Technology’s GRITS (The Georgia Robotics and InTelligent Systems) Lab researches the control and coordination of multiple robots. They place a heavy emphasis on theoretically provable swarm robotics strategies. The Autonomous Collective Systems lab at Arizona State University focuses on an interdisciplinary and biologically inspired approaches, incorporating research on both biological and engineered collectives. The University of Pennsylvania’s GRASP (General Robotics, Automation, Sensing, and Perception) Lab, and specifically the Kumar Lab group, focus on developing bio-inspired algorithms for collective behaviors and robotic swarms.
6 Approaches: State-Of-The-Art

The cutting edge of this area pulls and combines ideas from both artificial intelligence and control systems.

- A system designed by Harvard University, TERMES, is inspired by termites and describes a method for collective construction under heavy idealizations [5]. The TERMES system uses only local information and on-board sensors to plan a construction sequence, instead of global tracking methods used by some other approaches. TERMES focuses primarily on the mechanical design of the robots, utilizing whegs (wheel legs) and uniform building blocks to build 3D structures. It uses relatively simple path planning, ensuring a partial order of block sequence and assuming an obstacle free environment. It includes methods for building temporary scaffolding when required.
• An approach by Barros Dos Santos [27,28] looks at decentralized planning utilizing reinforcement learning (RL) and heuristic search strategies, based in automata theory. His work focuses on quadrotors that have available actions of moving, loading, and unloading of materials.

• An IPJR and truss structure being built A work by Komendera [29] focuses on highly regular truss structures and heterogeneous robots. This work focuses on the coordination of "Intelligent Precision Jigging Robots" that precisely hold components of a structure in place for welding by a third agent. This approach is readily applied in a 6-DOF environment such as the ocean or space, but seems more difficult to make practical use of in a ground-based environment. Additionally, these agents are limited to truss structures and their algorithms would need to be adjusted to work for general assembly problems (this is discussed in the paper).

• Some approaches come from the industrial engineering domain, focusing on process optimization in assembly lines. These bear resemblance to the classic traveling salesman problem, with one variant being called the assembly sequence problem (ASP). One approach to ASP uses discrete particle swarm optimization to approximate an optimal assembly sequence [30]. Another approach considers human-robot collaborative assembly and emphasizes factors such as operating speed and battery life [31]. This approach utilizes genetic algorithms to find the optimal allocation of assembly tasks to agents.

These assembly approaches are very specific to fixed robots operating in a mostly linear fashion. This limits their solution domain to industrial settings and applying them to more unstructured environments may be difficult.
7 Approach to be Pursued

An approach I may consider is similar to that of Barros Dos Santos, pulling from the domain of artificial intelligence to find optimal policies on-line for a distributed set of quadrotors. I would want to incorporate humans into the policy search, allowing an expert operator to provide input to the policy formulation. Simplifying assumptions can be made, such as the omission of obstacles and limitations on the structures to be built.

![RL architecture proposed by Santos](image_url)

Figure 6: RL architecture proposed by Santos [27]

8 Rationale for Approach

This approach is primarily valuable in real scenarios where the limitations of perfectly crafted algorithms and learning will not be sufficient to handle all given scenarios. In one scenario, an group of robotic agents may survey an area prior to beginning construction of a structure. Their assessment of how to proceed will only be optimal as specified by the input parameters to the algorithms used to determine it. Even a well-trained reinforcement learning system cannot substitute for e.g. a decade of experience in civil engineering and the abstract reasoning of a human. Said agents may also lack certain information not provided to them or gathered by their sensors. This could include conditions of the soil, scheduling restrictions, and As such, it is reasonable to propose task allocation strategies that involve humans in the decision making process when deemed necessary.

For the same reasoning, being able to involve humans in the task allocation policies that are extracted is also important. General purpose robots are not readily available or reliable, and specialized robots capable of accomplishing all given tasks in a construction environment are not feasible for many scenarios.

The use of quadrotors present challenges in the controls domain, but can potentially greatly simplify policy extraction in the artificial intelligence domain. Having full degrees of motion for agents in the system allows structures to be built without the need for temporary scaffolding or avoidance of other agents in only the X-Y plane.

9 Risk-Reward Assessment

The major risk of pursuing this interest is opportunity cost. Putting effort toward the study of the necessary knowledge takes time that could be spent on other relevant pursuits. Since this a relatively sparse field, future specific career opportunities (discussed previously) are slim. There is a (small) risk of becoming too specialized and too engrossed in this one area and having difficulty pursuing a career in a related one if it cannot be found yet. That said, the consideration of that risk is almost eliminated if the general skills and knowledge acquired are kept in mind. Many of the non-domain specific skills, such as programming, controls, algorithm design, research, and other non-technical skills are applicable in an incredibly wide array of engineering disciplines. As such, the rewards in terms of knowledge and skills gained are well worth any risk of not reaching significant conclusions in this area.
Preparing to study multi-robot systems now also prepares me for a future in graduate school on this topic, providing ample space for a thesis project or paper. As mentioned, the skills gained will prepare me for an industry career, whether in multi-robot systems, robotics, or computer science in general. Additionally, it also provides me a solid track to pursue a PhD and to conduct further research on hard problems in the field if I were to so choose later.

The major obstacles are my current lacking in fundamental knowledge necessary and a need for a larger network of professors and students in the area. Filling the knowledge gap mostly requires that I continue my education, both at the undergrad and graduate level. Choosing appropriate elective classes in senior year is critical, as it will be moving into my 4+1 accelerated masters program. Taking note of what appears in relevant research papers will assist greatly in making these choices. Building a network requires that I invest time contacting and meeting with professors, attending group meetings, and seeking out fellow students that share my interest.

10 Preparation To Date

I have prepared to pursue this area of interest through my coursework, summer internship pursuits, undergraduate research, connecting with others interested in the topic, and through side projects to develop technical skills. My field of study, Computer Systems Engineering, is very well suited to allow me to contribute to the multi-robot systems area. I am gaining a strong theoretical background in both algorithm design and electrical engineering. With the flexibility granted to me by course selections, I intend to focus my studies toward areas relevant to robotics such as control systems, machine learning, and artificial intelligence. In the Fall 2018 semester, I have taken an intro to AI course which has already yielded benefits in understanding the fundamental concepts required to proceed into the advanced understanding of this research topic.

In the summer of 2017, I interned at NASA Marshall Space Flight Center. There, I worked on a project helping to design the software for a CubeSat controls prototyping testbed. This testbed would primarily be used for hardware-in-the-loop tests of controls algorithms for proximity operations involving multiple CubeSats. As part of this, I had to learn an off-the-shelf robotics framework, Robot Operating System, as well as how to interface this with controls algorithms designed in Simulink. This internship prepared me immensely, introducing me to some of the difficulties encountered in the design of control systems.

During the summer of 2018, I intered at Ball Aerospace, working on a project with a complex ROS enabled mechanism. This offered me the opportunity to gain skills in visualization of complex mechanisms and systems using ROS, as well as learn about the system engineering process in industry. Along with utilities like rviz and Gazebo commonly found in ROS, I had the opportunity to also connect those with Unity, and see visions for virtual reality enabled systems. All of those look to prove valuable in future robotics endeavors.

I am beginning talks with a professor at ASU who specializes in Muti-Agent task allocation, interested in human-aware collaborations. We have begun regular talks on the subject, reading specific relevant papers in the field and providing guidance on how I can contribute.

11 Special Relevant Skills

The following are special relevant skills that I either posess, am in the process of developing, or will potentially require to pursue this topic of research.

- Robot Operating System (ROS)
• Control Systems (Linear, Non-Linear, Multi-Variable)
• Artificial Intelligence (Filtering/Prediction, Decision Tree Search, Sampling, Monte Carlo)
• Probability Theory
• Theoretical Computer Science (Automata, PSPACE, etc)

In addition, I have strong technical writing and research skills, developed through the ASAP program and FURI. I have had many experiences to improve my presentation skills, which are vital in any area of interest.

12 Required Resources and Budget

• High Performance Computing
  Long-term work will require large computing power to execute simulation and planning algorithms in the research phase (before more optimal calculation methods can be developed). ASU hosts a High Performance Computing center that is available for use by students to this end.

• Robotics Hardware
  Robotic hardware will required for practical implementation of the methods that are developed. Quadcopters, ground vehicles, or a combination of the two could all be utilized.

• Professional Organizations
  The Technical Committee on Multi-Robot Systems of the IEEE Robotics and Automation Society

13 Timeline

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14 Future Plans

My future plans are to continue pursuing research in multi-robot systems. I currently plan to pursue the thesis option of the ASU 41 Master’s Program in Computer Engineering, focusing my work on multi-robot task allocation. I intend to intertwine this work with experience in the aerospace industry. Following the achievement of my M.S degree, I intend to spend a few years working for a relevant aerospace company. This will provide me valuable experience, perspective, and networking with people in this area. Additionally, it will assist me in my long-term financial security. Depending
on what opportunities present themselves, I may return to academia to pursue life-long research in these technical areas.

15 References


