Introduction/Intellectual Merit: Autonomous construction is a quickly growing field with wide-ranging applications. Robotic systems are perfectly suited for repetitive or dangerous construction tasks, from brick laying and creating city infrastructure, to building extraterrestrial or disaster-relief structures. This latter application presents a formidable challenge in robotics: to enter an unknown and uneven environment and autonomously build pre-designed or adaptively designed structures to stabilize the site and prepare it for human presence. Already, there are many designs for emergency relief structures and space infrastructure that are well-suited for this type of autonomous construction, but existing robotic systems are not able to build them.

There are two primary approaches to improving construction capabilities. The first approach is to create complex systems that rely on high-accuracy perception, complete representation of surroundings, and precise movement and control. While this method could be capable of building a greater variety of structures, it has problems with cost, computation, and robustness that current technology cannot address. The second approach relies on distributed systems that absorb high levels of error through mechanisms and control, rather than trying to perform perfect actions.

This second approach can take great inspiration from biology. Termites, which build mounds millions of times their own size to house their colonies, and beavers, which cobble together dams to adapt their environment for their habitation, demonstrate the extraordinary potential of these systems. Additionally, the compliant or underactuated mechanisms that compose many animals show the potential for error-absorption and robustness in material choice and mechanism design.

In this vein, some recent work has explored the use of robot collectives for construction. These systems take control and communication methods from biology, such as distributed decision-making based on the state of the built structure, called stigmergy, and communication through pheromones. In [1], a multi-robot system built simple structures with blocks using stigmergy, and mimicked "tagging" the structure with pheromones by using color-coded LED's. In [2], a multi-robot system relied on a stored blueprint to build complex structures much larger than an individual agent, and relied completely upon stigmergy for representation of the current built structure. Even more similar to termite construction, [3] presents an algorithm for construction of a ramp using amorphous material similar to the soil used by termites. These robotic systems rely upon simple agents and control policies to absorb errors and robustly and efficiently build.

Other work takes inspiration from the underactuated and soft mechanisms present in nature to make compliant robots. These soft robots are extremely effective at absorbing error; their flexibility simplifies control and damps out unwanted perturbations. However, soft robots are presently limited by difficulty of manufacture and poor performance of soft actuators. There exists a large body of work developing soft robots, but these concepts have not been applied to construction tasks.

Research Plan: My aim is to enable collective construction that is robust and effective on uneven terrain. It will consist of a mechanical design phase and an algorithm design phase, supported by a foundation of tools to evaluate system success objectively.

I. Metrics*:* First, I aim to develop a novel metric to quantify error tolerance in a multi-robot construction system. Presently, most metrics that would apply are within the realm of control theory: metrics such as the size of zone of attraction, or the degree to which an action in the system is passively stable. These are effective in characterizing aspects of a collective construction system on the micro-level, in terms of individual actions, but fail to characterize the system on a macroscopic scale. I will create and validate a metric that effectively characterizes the response to disturbances and errors of a collective construction system. This will allow comparison of my future work with its biological counterparts, and will give the necessary basis for verifying a collective construction system.

II. Physical System*:* I plan to create a physical robotic system capable of robust collective construction on uneven terrain. My research group at University at Buffalo, under Nils Napp, is the foremost group exploring autonomous construction on uneven terrain, a broad and applicable subset of the autonomous construction field. One approach that is almost untouched within the field is the use of soft, compliant, or underactuated robots and robot components to increase error tolerance. In the field of behavioral robotics, soft robots are ideal: their simplified control and adaptable structures make them perfectly suited. However, the lack of effective untethered actuation systems make them underutilized. I intend to use soft components in my robotic system, focusing on passive mechanisms and flexible-rigid interfaces to increase error tolerance without relying upon soft actuation.

Additionally, I will extend research I performed in the past year, developing a robotic platform for construction over uneven terrain. I will modify it to be highly modular, allowing soft components to be swapped in and out easily, and enabling new directions of research involving self-charging and even self-healing agents.

III. Control System: I will develop new control methods to improve coordination and efficiency in collective construction applications. Presently, there exist few control systems capable of controlling multiple robots towards a construction objective over uneven terrain. One of the only examples, presented in [3], makes non-navigable terrains navigable through deposition of expanding foam. With the Napp group at UB, I extended this in a paper submitted to ICRA this year, which modified the algorithm to work with a single-agent system and discrete objects: filled bags. I intend to generalize this work to construct any arbitrary structure, by developing new planning policies for the order of voxel construction based upon the structure shell and other parameters. Additionally, I will incorporate policies for a range of materials: continuous materials such as foam, and discrete amorphous objects such as filled bags.

Broader Impact: The broader impact of the project lies in its motivation: autonomous construction can be used to save lives in disaster areas, and to build structures on different planets. Robots can stabilize buildings and make rubble navigable in areas of disaster, build levee walls to prevent flooding, build emergency shelters, and build structures on the moon and mars.

Additionally, the project could have a parallel initiative in educational outreach, by incorporating high school and undergraduate students in important roles. Because the core of the project is small, highly modular robots whose abilities are augmented through collaboration, undergraduates and even high school students can take part in construction of the robots while learning about robotics and experiencing the environment of a research lab.

Further, these modular robots can be easily integrated into demonstrations in schools to foster interest in robots and STEM in general. The coordinated robots could inspire elementary, middle, and high school students to become involved with robotics, and could form the foundation for a program to increase college attendance in STEM fields.

[1] M. Allwright, N. Bhalla, C. Pinciroli, M. Dorigo, M. All- wright, N. Bhalla, C. Pinciroli, and M. Dorigo, "Towards Autonomous Construction using Stigmergic Blocks," 2017.

[2] J. Werfel, K. Peterson, and R. Nagpal, "Designing Col- lective Behavior in a Termite-Inspired Robot Construction Team," *Science*, vol. 343, no. February, pp. 754–758, 2014.

[3] N. Napp and R. Nagpal, "Distributed amorphous ramp construction in unstructured environments," *Springer Tracts in Advanced Robotics*, vol. 104, pp. 105–119, 2014.