Objective: To create the first autonomous underwater construction system capable of building human scale structures out of modular components in real world environments.

Introduction Autonomous underwater vehicles (AUVs) fitted with specially designed grippers will build concrete retaining walls and artificial reefs with modular blocks. Blocks will be designed to provide passive error correction on both pick up and placement, making the system robust to noise from localization and control. Localization will be achieved with specially designed infrastructure partially embedded in the blocks themselves to provide certainty near assembly areas.

Underwater construction is both dangerous and expensive because specially trained human divers must build and maintain structures by hand. At moderate depths, extreme measures must be taken to protect divers including the use of hyperbaric chambers to treat decompression sickness. Small mistakes or equipment failures during a dive are disastrous, often resulting in death. At extreme depths building in person is effectively impossible due to the reduced capacity of pressurized air tanks at high pressure. The substantial cost and risk of using divers on site leads us to favor assembly on land and then transportation to the final location which constrains the types of structures that can be built.

Though autonomous underwater construction technology could open a frontier of possible applications, no autonomous system exists to date. Teleoperation based solutions have received attention in the literature including a rubble leveling robot [2] and a back hoe [1]. Teleoperation eliminates the need for accurate localization, but it requires that large amounts of data are passed back to the human operator at a high rate. Communication underwater is often achieved using either a physical tether or acoustic networking. Managing long tethers is difficult and acoustic communication is low bandwidth, limiting the possible range of teleoperation based solutions.

Research Plan My initial system will be built around a BlueROV2 underwater robot which is available in the Dartmouth robotics lab. The BlueROV2 is a 10 kilogram, 0.5 meter long robot with 6 degree of freedom motion. It is an attractive robot to base the system on because it includes a well maintained code base and several sensors for localization including two inertial measurement units, pressure sensors, two compasses, a low light HD camera, and a short baseline acoustic positioning system. I will utilize visual markers called ARTags for visual positioning information.

Research Question 1 How can we best exploit accurate localization information when it is available, and smoothly switch to coarse grained techniques when it is not? *Approach* My preliminary experiments on localization suggest that sensor accuracy varies depending on the robot's position and velocity. I will empirically model the noise and accuracy of the sensors under relevant circumstances, then design a sensor fusion algorithm which exploits the most reliable information at every instant. **Research Question 2** Given some desired structure, how can we design a feasible and robust build plan for the structure? *Approach* To design a feasible build order for a structure, it will be necessary to consider the physical constraints of both the building blocks and the robot's maneuvering capabilities. I will model the build ordering constraints induced by the structural and maneuvering constraints as a constrained optimization problem. The objective function of this problem will encode the ability of the robot to exploit localization information throughout the build. My initial work on build order optimization in 3D printing can be generalized to suit this application [3]. **Research Question 3** How can we automatically react to build errors caused by changing environmental circumstances? *Approach* To gain insight into the failure modes of the system, I will test it repeatedly on a selected few build plans in both the pool and Lake Sunapee, NH. During each test, I will record and categorize the failures that occur. Based on the most common types of errors, I will develop automatic recovery mechanisms. For example, if a block is not fully seated on another block, the robot could gently nudge them into place. If the robot passes through a cloud of silt, it could stop and wait for the cloud to settle before continuing the build.

Experiment Plan First, I will isolate each sensor and determine its accuracy limitations. To establish the accuracy of the IMU and ARTag readings, I will utilize an industrial robotic arm available in the lab to collect accuracy and noise data based on known programmed motions. To evaluate the positional accuracy of the sensor fusion algorithm on land, I will utilize a highly accurate VICON positioning system as ground truth. With the sensor quality models in hand, I will begin iterating on the sensor fusion algorithm. Preliminary debugging style experiments can be conducted in a 6 foot diameter water tank in the lab. Frequent field tests in the athletic pool and nearby lakes such as Lake Sunapee will inform further iterations. Simple tests such as repeatedly moving a block back and forth on a platform in calm clear waters will help isolate the quality of localization data. Build order and error recovery algorithms will be tested by selecting several simple build plans and repeatedly testing them in varying environmental circumstances. The ultimate goal will be to successfully execute a build plan near the shore of the Carribean sea during one of the lab's yearly trips to the Bellairs Research Institute in Barbados.

Intellectual Merit Underwater construction will require the co-development of localization infrastructure and sensor fusion strategies to rapidly instrument a build site. Rapidly deployable localization infrastructure will have applications in any autonomous robotic system attempting to achieve manipulation tasks in a remote or harsh environment. Rather than attempting to jump to unaided manipulation in totally unstructured environments, I will be taking the realistic approach of exploring the minimal amount of additional infrastructure required to complete manipulation tasks. This work will also advance the evaluation of the trade offs between computational and physical complexity in autonomous robotic systems. For example, designing blocks which more successfully correct for error could allow manipulation behaviors to be more simple while requiring a more complex block geometry. Developing techniques to rigorously evaluate trade offs between computational and physical complexity for computational-physical systems is an important step in designing robust robotic systems for real world environments.

Broader Impacts A system which can robustly place modular components on one another could enable the mostly autonomous creation of retaining walls or artificial reefs. As ocean levels continue to rise, retaining walls will be increasingly important in developed coastal areas. By stacking components of artificial reefs, we could enable larger scale reef restoration activities. As the technology advances, it could enable more subtle applications as well. It could enable us to more efficiently build offshore energy infrastructure or enable us to scale underwater agriculture.

This project is a valuable opportunity for young researchers to gain hands on experience with robotics and software development, preparing them for a productive career in an exploding field. During the conduction of the preliminary study, I worked with two high school students who contributed directly to this research. The students gained exposure to robotic software design and mechanical modeling. I will continue using this work as an opportunity to mentor driven young researchers.

[1] Taketsugu Hirabayashi et al. "Teleoperation of construction machines with haptic information for underwater applications". In: *Automation in Construction* 15.5 (2006). 21st International Symposium on Automation and Robotics in Construction.

[2] T. S. Kim et al. "Underwater construction robot for rubble leveling on the seabed for port construction". In: *2014 14th International Conference on Control, Automation and Systems (ICCAS 2014)*.

[3] S. Lensgraf and R. R. Mettu. "An improved toolpath generation algorithm for fused filament fabrication". In: *2017 IEEE International Conference on Robotics and Automation (ICRA)*.