Extended abstract: Towards the autonomous underwater construction of cement block structures with free-floating robots

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***Abstract*— This paper presents StoneClaw, our custom-made free-floating autonomous underwater vehicle that plans for an efficient use of two complementary energy sources (battery and compressed air) and exploits self-correcting features on our designed manipulator, for constructing structures with interlocking cement blocks.**

I. Introduction

Infrastructure development in coastal areas has long been essential to supporting the most populous cities on earth. Randomly stacked piles of stone have been used for centuries to create artificial areas of calm. Artificial reefs such as those used in the Grande Anse Artificial Reef Project in Figure 1b have long been built to restore damaged reefs. In the modern age, attention is increasingly paid to offshore infrastructure due to the twin factors of sea level rise and increased need for green energy production. While automation for inspection and intervention tasks has been well explored, little attention has been paid to using autonomous underwater vehicles (AUVs) to directly construct infrastructure.

In this abstract, we present preliminary results on the StoneClaw freefloating AUV construction system shown in Figure 1a. The StoneClaw AUV system is a holistically-designed system featuring a custom designed AUV and error correcting cement blocks. It is, to our knowledge, the first free-floating AUV system for building small-scale structures from practical materials. In addition, it is the first free-floating construction robot to explicitly utilize buoyancy to minimize battery usage.

While free-floating robots on land (e.g., drones) have long been identified as an attractive option for building structures on land, their scale has been limited in practice due to the energy cost required to transport building materials. We exploit the relative ease of changing buoyancy underwater to develop the first planning algorithm for balancing the use of two finite and complementary energy sources while transporting heavy objects: one for changing buoyancy and one for powering thrusters. We defined a convex program which allocates varying amounts of buoyancy to each block based on a calibrated approximation of the cost to hold a block aloft. Preliminary results suggest that our convex-optimization-based procedure for allocating buoyancy can improve vehicle life as compared to a simpler, naive buoyancy strategy. Buoyancy changing drones which combine air heated by a torch and thruster power to manipulate blocks could utilize the same type of approach on land.

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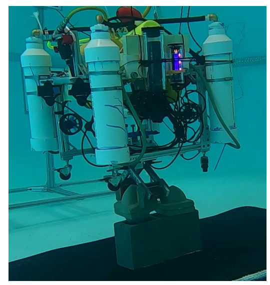


(a)

(b)

Fig. 1: (a) StoneClaw placing a cone insert. (b) Artificial reefs from the Grande Anse Artificial Reef Project.

StoneClaw is designed to build structures out of interlocking cement blocks. The bulk of the structure is made up of standard, low-cost cinder blocks. StoneClaw drops molded cement cone inserts into the cores of the cement blocks which allow passive error correction when placing the next layer of cinder blocks. We envision a new class of robust, yet temporary coastal infrastructure enabled by systems like StoneClaw. Fleets of AUVs could be deployed to erect the foundation for a bridge in an emergency, then disassemble it when the emergency has passed.

II. Related Work

A. Underwater Manipulation

Existing underwater manipulation systems used in practice are often tele-operated, but autonomous approaches have been a recent research focus. Existing approaches tend to use expensive and complex AUV systems mounted with high degree-of-freedom manipulators such as the TRIDENT project in the EU [1]. These AUVs, called "Intervention AUVs", focus on tasks such as retrieval or turning valves in submerged panels [2]. Our AUV features a relatively simple, passively strong manipulator specifically designed for picking up flat-sided stone blocks which allows simpler control.

B. Autonomous assembly on land

Our work is the closest to initial steps taken on the autonomous assembly of masonry structures with drones [3]. The authors explore the development of drone-compatible masonry units and present non-autonomous tests with a drone. The problem of battery usage for transporting the blocks is left as future work. Robotic dry stacking of found stones has been explored more thoroughly [4]. Our focus on stones of known geometry allows the system to more easily execute assembly operations with imprecise localization and grasping position inherent to a free-floating robot.

C. Energy constrained planning

To our knowledge, our system is the first to explicitly balance two complementary energy sources during manipulation tasks. Minimizing energy consumption by mobile robots has been widely explored. In particular, energy conservation has been explored for robots intended to operate for long missions such as autonomous sail boats [5], or UAVs [6]. Energy constrained planning specifically has received less attention. When it has been explored, it is often in the context of exploration [7], but the robots are limited to a single on board battery.

D. Variable ballasting

Compressed air has been used to accommodate the payload of a ROV for manipulation [8], but the source of compressed air was fed into the robot through an umbilical and the system was designed specifically for a single known manipulation target. Our system focuses on working reliably with major changes in payload and varying amounts of water in its ballast tanks.

III. StoneClaw AUV

The StoneClaw AUV is a tetherless AUV featuring a two power sources: compressed air canister for active buoyancy control, and a LiPo battery to power the thrusters. StoneClaw's active ballasting system is driven by a 3 liter SCUBA pony bottle pressurized up to 3000psi which feeds four vertical PVC ballast tanks. Using four vertical thrusters, the AUV can supply up to 26.2kg of thrust. The ballast tanks are vertically oriented to limit the effects of sloshing as the AUV positions itself and are located as far apart as possible to limit the pendulum effect created when repositioning with a cinder block.

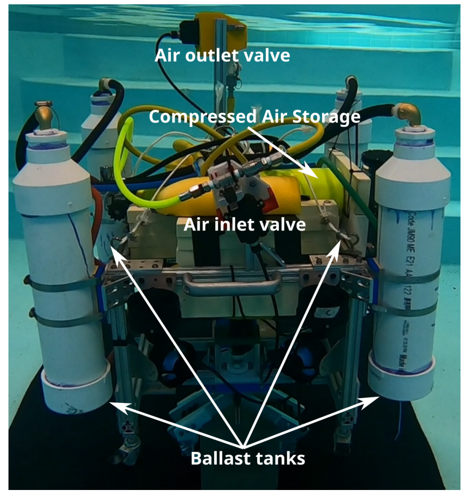


Fig. 2: Active ballasting system.

Instead of directly sensing air flow or pressure changes, StoneClaw uses change in depth to sense its buoyancy. This allows a uniform policy for defining buoyancy in terms of the amount of battery power used to hold the vehicle at depth despite variations in what it grasps. To control buoyancy, we specify $b \in [0, 1]$ which is mapped to an intensity of downward or upward thrust. When increasing buoyancy, b is mapped to a downward thrust applied by the four vertical thrusters. The air inlet valve pulses until the thrust is enough to lift the AUV. When decreasing buoyancy, the thrusters push down while the air outlet valve is pulsed. Figure 2 shows the location of the air inlet and outlet valves.

A. Manipulator

Our primary guiding principles in designing a manipulator for StoneClaw were simplicity and passive strength. This is in contrast to other AUV systems where generality and flexibility are core concerns. Lacking the passive strength present in our manipulator, other more standard manipulators could require large energy expenditures to keep the blocks in hand.

The manipulator's linkage, based on stone grabbers, uses the weight of the block to draw itself closed passively. No sensing of the position of the fingers is required. Instead, a relay powers the actuating servo down when the fingers are commanded to stop, preventing the stalled servo from consuming power.

The fingers are actuated using a high-torque underwater servo which drives a lead screw. The lead screw

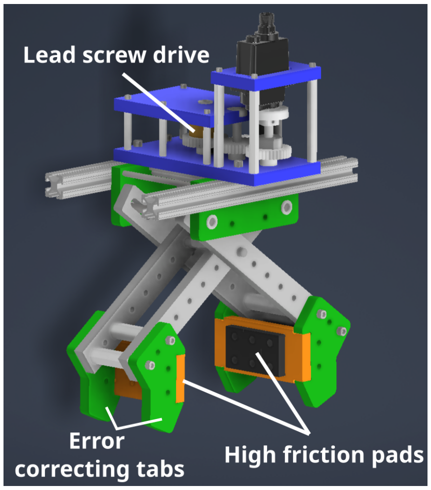
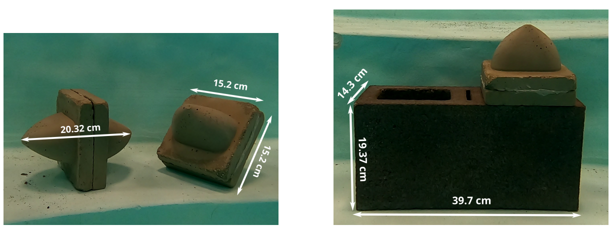


Fig. 3: 3D rendering of 1DOF manipulator.

nut is given room to travel between two spaced plates. When the nut is driven against the top plate, the lead screw extends downwards, preventing opening while preserving a passively strong grip. Tabs on the fingers guide StoneClaw into place as it approaches a block or cone insert. Figure 3 shows the manipulator in detail.

IV. Cinder Blocks & Cone Inserts



(a) (b)

Fig. 4: (a) Cone inserts. (b) Cone insert in block.

We designed our cement building system to help overcome the unavoidable pre-drop and pre-grasp position errors. Standard cinder blocks (9.5kg in water) form the bulk of structures and molded cement cone inserts (3.17kg in water) guide the blocks together. The base of the cone inserts is slightly wider than the cement blocks to facilitate disassembly. To passively correct error while falling, the cone inserts are weighted to bias their center of gravity towards the tip of the bottom cone.

Based on their geometry, the cones can provide up to 4.5cm of error correction along the length of the block and 2cm along its width. Taller, pointer cones with steeper sides can correct more error but are more likely break when dropped or pushed against the sides of the blocks. We selected our current cone geometry to balance strength and error correction.

V. Planning Buoyancy during Construction

Any weight not offset by the vehicle's positive buoyancy must be made up by the thrusters. When the AUV is not loaded with a block, any positive buoyancy must be overcome by the thrusters on the return trip.

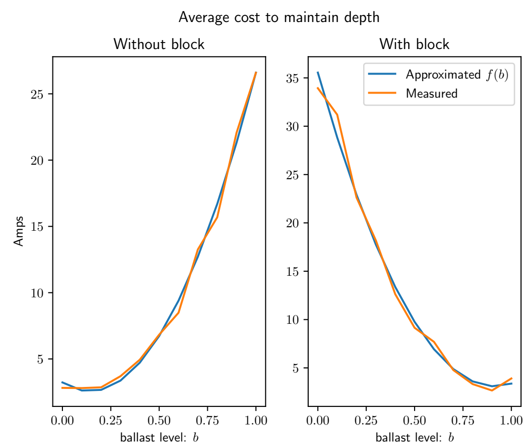


Fig. 5: Calibrated instantaneous cost curves.

For long motions in which the AUV is sufficiently far from neutrally buoyant, we expect that the dominant battery cost will be holding the AUV at depth while moving between points. We model the average instantaneous energy consumption $f(b)$ where f is a polynomial function in the level of buoyancy $b \in [0, 1]$. Figure 5 shows our calibrated instantaneous cost curves with a best fit two-degree polynomial for positive and negative buoyancy changes. The cost of completing a motion is proportional to the distance travelled during that motion. Specifically $\mathbf{E}(\hat{b}) = \sum_{i=2}^{n} f(\hat{b}_{i-1})||x_{i-1} - x_i||$ where x_i is the i-th location in the construction process and b_i is the ballast level for motion i.

A. Convex Program for Allocation

The AUV first grasps a block, transports it, then deposits it, then moves to grasp the next block. Our goal is to allocate the amount of buoyancy for each hop which minimizes battery consumption while limiting the compressed air use to a reasonable level. Let $\mathbf{x} = [x_1, x_2 \ldots, x_n]$ be the set of locations the AUV must travel between in order. The AUV grasps a block at x_1, transports it to x_2 and deposits it, then travels to x_3 to grasp the next block. Our optimization variable, $\Delta = [\delta_1, \ldots, \delta_{n-1}]^T \in [0, 1]^{n-1}$, tracks the changes in buoyancy after each leg of the trip. δ_1 corresponds to adding air into the ballast tanks and δ_2 corresponds to releasing air. To map Δ into $\hat{b}$ we can define a matrix, $\mathbf{M}\Delta = \hat{b}$, a lower triangular matrix composed of columns of ones of alternating sign.

Given $\mathbf{M}$, we can define linear constraints for our convex program. $0 \leq \mathbf{M}\Delta \leq 1$ ensures the ballast tanks are never more than completely full or empty. Let $\mathbf{M}'$ be $\mathbf{M}$ with its negative columns set to zero. $\mathbf{M}'\Delta \leq C$ constrains the amount of compressed air used by limiting positive buoyancy changes. Collecting all of these definitions, gives the convex optimization problem in Equation 1.

$$\begin{aligned} \min_{\Delta} \quad & \mathbf{E}(\mathbf{M}\Delta) \\ \text{subject to} \quad & 0 \leq \Delta \leq 1 \\ & \mathbf{M}'\Delta \leq C \\ & 0 \leq \mathbf{M}\Delta \leq 1 \end{aligned} \tag{1}$$

VI. Preliminary Results & Next steps

For preliminary trials of the StoneClaw system, we deployed the AUV in a 1.6 meter deep indoor pool. For localization, StoneClaw utilizes a fiducial marker mounted near a rubber mat. Assembly actions are described in terms of the state machine described in our previous work [9]. Fixed waypoints defined relative to the fiducial marker guide the assembly process.

A. Buoyancy optimization

As a preliminary trial of our ballast optimizer, the AUV grasped a block, moved it 6m, grasped the next block 1m away then carried that block 5m before depositing it. In terms of the convex program in Section V, we set $\mathbf{x} = [(0,0),(0,6),(0,5),(0,0)]$ and $C = 1$. Solving the convex program in Equation 1 yielded $\Delta = [0.73, 0.27, 0.26]^T$. Multiplying out $\mathbf{M}\Delta$ gives us $\hat{b} = [0.73, 0.46, 0.72]^T$. To compare the effectiveness of the optimized allocation strategy with the obvious strategy of evenly allocating buoyancy, $\hat{b} = [0.5, 0.0, 0.5]^T$, we used both strategies to move a cinder block. The optimized strategy consumed 1.55 Ah while the naive allocation used 3.54 Ah, showing that preserving air for small motions can increase battery life.

B. Construction trials

In preliminary trials of the construction process, the AUV grasped the cone inserts and moved them to a pre-placed cinder block. With proper tuning of the waypoints, the AUV was able to place the cone inserts 60% of the time in a small scale trial. The AUV was able to place the second cinder block on top of the two cones but failed to detect it should release it.

C. Next steps

a) Compliant insertion behaviors: Noise in the AUV's pre-drop position can cause the cinder blocks to become jammed on the cones as it falls. We plan to develop compliant sliding motions in which the AUV guides the cement blocks into place without dropping, allowing control of falling speed, trajectory, and angle.

b) Full construction planning: The problem of planning the full construction sequence is yet-unaddressed. It is possible that building intermediate structures such as creating a stack near the structure could improve efficiency. To allow the exploration of this problem, we plan to develop a high-level construction planner based on Monte-Carlo Tree Search.

c) Insertion success detection: While the AUV is attached to a block, it forms a single rigid body. This fact could be exploited to indirectly sense the status of the insertion process. For example, using the vehicle's gyroscopes, we could detect whether a block is jammed at an improper angle.

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