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An Autonomous Vault-Building Robot System for Creating Spanning Structures

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***Abstract*— Research in autonomous robots for construction has largely focused on ground-based robots whose reach constrains the size of what they can build, or on climbing or aerial robots that build solid or unroofed structures. Autonomous construction of larger, multistory buildings, or bridges spanning unsupported distances, would require robots that build sturdy structures supporting their own weight. In this paper, we present VaultBot, a system of autonomous robots that build a load-bearing spanning vault using identical modular blocks. The custom blocks employ mechanical and other features to facilitate robotic manipulation and locomotion, and can be removed from and replaced in an assembled structure as a way of repairing damage. We characterize the system's performance and failure modes, and demonstrate reliable autonomous assembly for a structure composed of 46 blocks. Blocks can be made collapsible and deployable as a way of reducing mass and volume that must be transported to a construction site. Such a system could be used to help enable construction of protective shelters in challenging environments, such as disaster relief scenarios, arctic settings, or extraterrestrial habitats.**

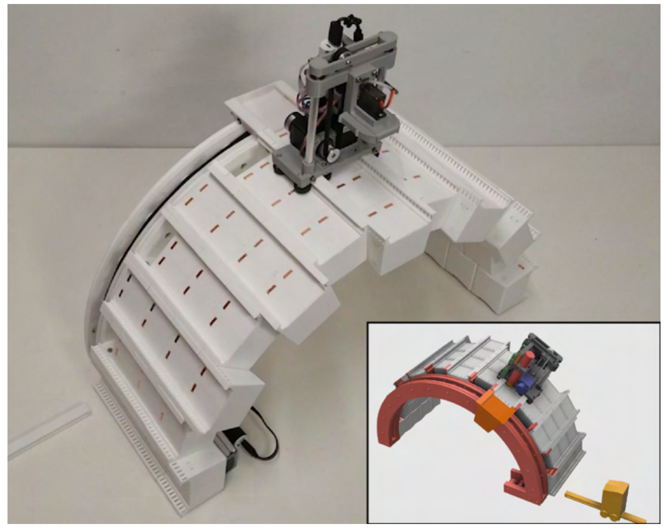

Fig. 1. A diagram of the VaultBot system, consisting of an "ArchBot" (inset: red) to provide initial scaffolding and circumferential locomotion, and a "RailBot" that is responsible for linear locomotion as well as manipulating blocks. The RailBot is transported by the ArchBot's carriage (inset: orange); a feeder shuttle (inset: yellow; manually operated in this implementation) supplies the RailBot with new blocks.

I. Introduction

Increasing autonomy in construction can confer benefits of increasing safety, reliability and speed of building. Full unsupervised autonomy could potentially also enable construction projects in environments where they are otherwise prohibitive or infeasible, such as disaster relief scenarios, arctic bases, or extraterrestrial habitats.

Industry developments in construction automation tend to prioritize incremental improvements to legacy tools and techniques (such as conventional heavy equipment) which may be difficult to transport to remote environments where unsupervised construction would be most attractive [1], [2]. Conversely, researchers focused on robotic construction in remote environments have recognized the advantages of small, agile, custom-purpose-built robots that could operate with less site disturbance while incurring considerably lower transportation costs than conventional heavy equipment.

Some academic researchers have taken the approach of co-designing robots and the building material they work with in coordination with each other (sometimes called "material-robot systems"), as a means of reducing complexity and facilitating robot operation [3]–[5]. While many such material-robot systems have demonstrated full autonomy, none has previously demonstrated an ability to build load-bearing spanning structures such as roofs or bridges, as would be needed for many relevant real-world projects.

In this paper we present a novel material-robot system capable of autonomously building a vault structure composed of a single repeating module. The assembly process is reversible, to facilitate repair through replacing modules.

II. Related Work

Autonomous robots for construction have received increasing attention from both the robotics and construction fields [2], [6], [7]. This work can be characterized in terms of several different considerations; a few relevant here follow.

One broad distinction that can be drawn is based on the relative scale of the robots and the structures they build. Some work considers ground-based robots (e.g., gantries erected over a workspace [8], fixed arms [9], or mobile platforms [10]–[15]), for which the scale of what can be built is limited by the robot's reach. Other work considers robots which climb or fly over what they build, in order to be able to reach new places as building proceeds, thereby removing that limitation [3]–[5], [16]–[21].

Most work in this area considers manipulation of discrete building elements [3]–[5], [9]–[12], [14], [16]–[18], [20], [21]. Some considers building with continuous materials,

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typically through extrusion as an additive manufacturing approach [8], [13], [15], [19].

Much of this work is relevant to building 2- or 2.5-D structures: material is directly supported by other material, and the result is solid throughout or open at the top, not suited to creating elements like roofs or bridges [4], [8], [10], [14]–[16], [18], [19]. Some work has addressed building structures with elements that span a distance unsupported, with robots either large [9], [12], [13] or small [5], [11], [21] compared to the size of the structure; these elements could be considered as constituents of roofs, but not of bridges or floors of higher stories, in that they could not structurally support the robots that do the building. A few studies have discussed systems that could in theory provide spanning structures that support the robots that build them, though this has not been demonstrated in hardware [3], [5], [21].

The system described here is one where robots build spanning structures that support the robots' weight, allowing them to travel over the surface of a much larger structure to reach otherwise unreachable locations, and to extend the structure indefinitely in principle. To our knowledge, it is the first such system.

III. Hardware

A. Robot Design

Overview: VaultBot is a material-robot system that relies on simplified building operations to assemble a spanning structure. The structure begins with a pre-deployed arch that will constitute one end of the vault. A robot on the arch is provided with modular blocks from an external source, travels along the curve of the arch to a given angle and then along the row of blocks at that angle, adds the block at the end of the row, and returns to the origin for the next block.

In its demonstrated form, VaultBot (Fig. 1) splits its 4 degrees of freedom (DoFs) between a 3-DoF "RailBot" responsible for linear locomotion along the vault axis and for block attachment, and a 1-DoF "ArchBot" that moves the RailBot along the arch as well as providing the scaffolding to initiate the structure. The blocks (or voussoirs) form a barrel vault with 13 rows arranged in a running bond (half-offset) pattern. Separating the system into two parts frees the RailBot from needing to carry the power source and actuation for circumferential locomotion when it is not being used.

ArchBot: The ArchBot includes a rigid structural frame (made of acrylic) and walled cavities to contain each of the first 7 blocks, which contact the arch (odd-numbered blocks in Fig. 5). The ArchBot incorporates a stepper motor that advances a timing belt, pulling a carriage (Fig. 1 inset; orange) along the arch. This carriage transports the RailBot to any row along the arch. The exceptions are the outermost rows, which rest on the ground: the blocks incorporate rails that let the RailBot move along a row, but the geometry prevents locomoting along the ground-resting rows. In an implementation of a fully autonomous system, we envision that the blocks in these rows would be placed by another, external robot system (likely the same one that delivers new blocks to the RailBot); it may also need to stake them to the ground to anchor against lateral forces. In the implementation here, the ground-resting blocks are anchored with magnets.

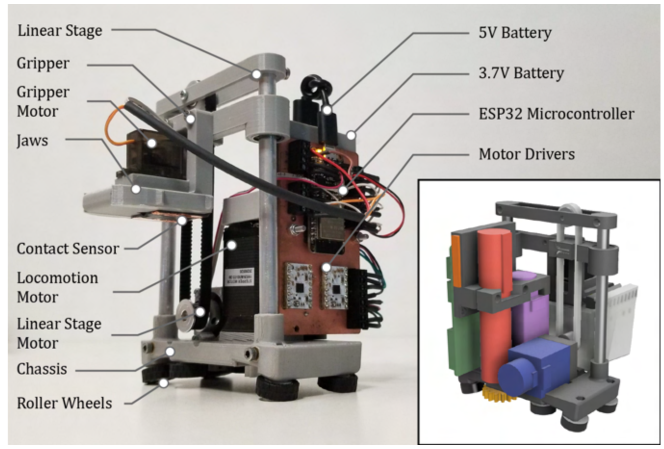

Fig. 2. A diagram of the RailBot, highlighting its salient features. The inset shows a rendering of the opposite view, highlighting the motor for the linear stage (blue), locomotion motor (purple), pinion gear (yellow), 5V battery (red) and 3.7V battery (orange). Not shown is the position of the Hall effect sensor (installed underneath the linear actuator motor).

The ArchBot is commanded by the RailBot and controlled by an ESP32 microcontroller, which communicates with the RailBot using the 2.4GHz protocol ESPNOW. The microcontroller is powered by a 3.7V LiPo battery. The stepper motor is powered by an 11.1V LiPo battery and controlled with an A4988 motor driver. The stepper motor is equipped with an encoder to enable closed-loop control. If the motor skips steps during a commanded operation, it will attempt to make up those lost steps before continuing to the next command. If it is unable to do so, it will report an error.

RailBot: The RailBot (Fig. 2) is an untethered 3-DoF robot capable of locomoting along a row of the vault in addition to carrying blocks and adding them to the structure. The RailBot sends commands to the ArchBot using radio communication. It locomotes using rack gears (i.e., tracks) embedded in the blocks (Fig. 3A), and its gripper holds blocks by interfacing with the same feature (Fig. 3B).

A 3.7 V LiPo battery powers the microcontroller and logic supply, while a 5 V USB battery powers the robot's motors. A 0.11 N·m Nema 11 stepper motor provides locomotion by turning a gear system that engages with the toothed rails formed by blocks in a row (similar to a rack-and-pinion system). A 0.13 N·m Nema 11 stepper motor operates a linear stage that raises and lowers the gripper. A timing belt advances the stage along a frame composed of linear bearings running along two aluminum rods, which provide support and stability. The linear stage has a range of motion of $\sim$60 mm, allowing for clearance for the robot to carry the 50 mm-tall blocks as it locomotes over the vault.

A 9 g servo motor operates the gripper, which expands its jaws to engage a block by its rails (Fig. 3) and retracts its jaws to release it. A pairwise rack-and-pinion system converts the angular motion of the motor to symmetrical linear motion of the jaws. Each jaw features 2 teeth that engage with the gaps in the block's gears, which facilitate repeatable alignment between the block and the robot and prevent the block from sliding off of the gripper. The edges of the jaws are chamfered to prevent catching on the block. The bottom of the gripper is equipped with a contact sensor, consisting of two electrical contacts mounted on a compliant pad; blocks have matching contacts connected internally. The robot supplies the logic voltage (3.3 V) to one side and measures the return voltage with the other side; successful grasping of the block results in a completed circuit.

The electronic components of the robot are contained on a custom-milled board, allowing for robust electrical connections to be made with screw terminals. An ESP32 microcontroller controls the RailBot. In addition to performing radio communication with the ArchBot, the microcontroller is also capable of communicating with a computer terminal over Bluetooth. A custom simple command-line interface allows an operator to either initiate an autonomous building routine, or to control individual degrees of freedom for homing, calibration and debugging.

The stepper motors that are responsible for locomotion and the linear stage are each controlled by a dedicated DRV8834 motor driver. By efficiently operating at lower voltages than A4988-type motor drivers, the robot can avoid the need to carry a high-voltage battery. Each stepper motor is also equipped with a rotary encoder, which allows for closed-loop control. Additional odometry is achieved with the use of a Hall effect sensor installed on the chassis, which verifies the robot's position relative to the magnets in the blocks.

The robot is designed to minimize mass and to keep the center of mass as close to the vault as possible, which reduces the torque needed for locomotion along the arch. The chassis is made of 3D-printed PETG, and has filleted corners and edges to avoid catching on blocks. The chassis is equipped with roller wheels installed at the appropriate angles to engage with the rails of the adjacent rows.

B. Block Design

The block design used in this demonstration features a keystone profile that tapers at 13.8 degrees, such that 13 blocks compose a self-supporting 180-degree arch (Fig. 5 inset). Blocks are arranged in a staggered (half-offset, or running bond) pattern, such that 3 adjacent blocks form a 3-walled cavity to receive a 4th block. In this way, the vault remains self-supporting throughout its assembly without requiring aids like jigs, templates or scaffolding. While the vault is supported by the pre-deployed arch during the demonstration, only lateral reinforcement is required to maintain structural integrity (Fig. 4).

Blocks feature concave indentations on their angled faces, which enforce alignment with neighboring blocks and provide additional structural stability. The same faces incorporate magnets in a pattern of alternating polarity (Fig. 3A), such that each block connects with up to four diagonally adjacent neighbors. Magnets serve the purpose of facilitating alignment, not bearing structural loads. As with any masonry vault, load transfer occurs primarily through face contact.

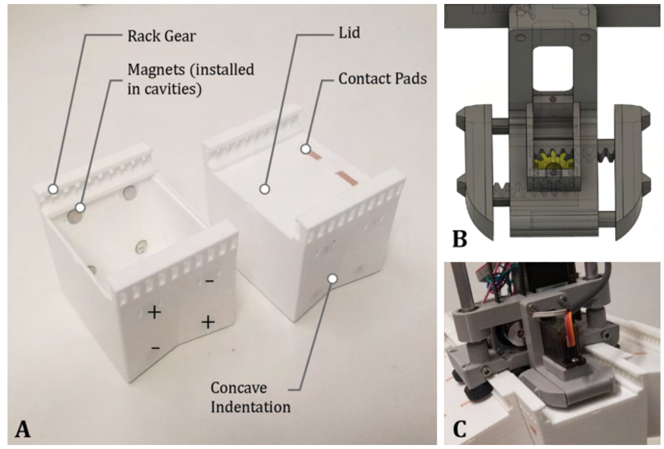

Fig. 3. (A) The blocks used in the demonstration measure roughly 50 mm × 68 mm × 57 mm and are 3D printed with embedded features like rack gears to facilitate robot locomotion, shaped faces to facilitate alignment and enhance structural stability, a channel to hold a lid, and cavities to mount magnets. Magnets are installed in a pattern of alternating polarity (the same pattern is mirrored on the reverse side). (B) Detail of the RailBot's gripper with the motor removed, showing the pairwise rack-and-pinion mechanism. (C) Detail of the robot's gripper, having just retracted after placing a block.

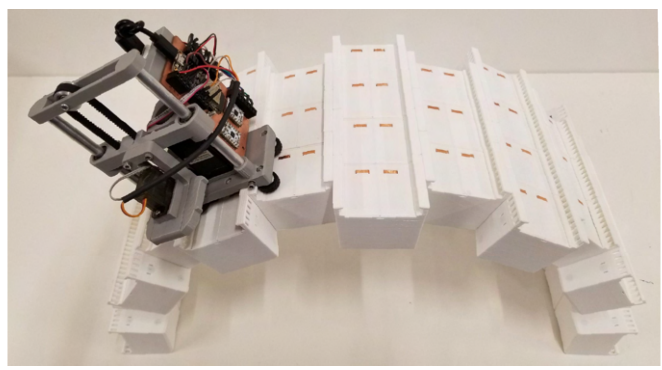

Fig. 4. Structural integrity of the vault does not require the scaffolding arch, only lateral reinforcement (i.e., blocks on the ground fixed in place).

C. Building Routine

The sequence by which the VaultBot system installs a block is as follows: (a) The ArchBot carries the RailBot to row 2, where a new block is waiting atop the feeder shuttle. (b) The RailBot lowers its linear stage, positioning its gripper between the opposing rails of the block. The gripper's contact sensor confirms correct positioning. (c) The gripper expands, engaging with the block. The linear stage retracts slightly, lifting the block off of the feeder shuttle. (d) The ArchBot transports the RailBot (and the block it carries) to the desired row. It sends a radio signal to the RailBot to acknowledge correct positioning. (e) The RailBot locomotes along the row of blocks until it reaches the targeted vacant position. Its linear stage then lowers the block into position. (f) The gripper retracts, disengaging from the block. The linear stage lifts the gripper to its maximum height. (g) The RailBot returns to the ArchBot's carriage. Meanwhile, the feeder shuttle, carrying the next block to be placed, is moved (by hand) into position.

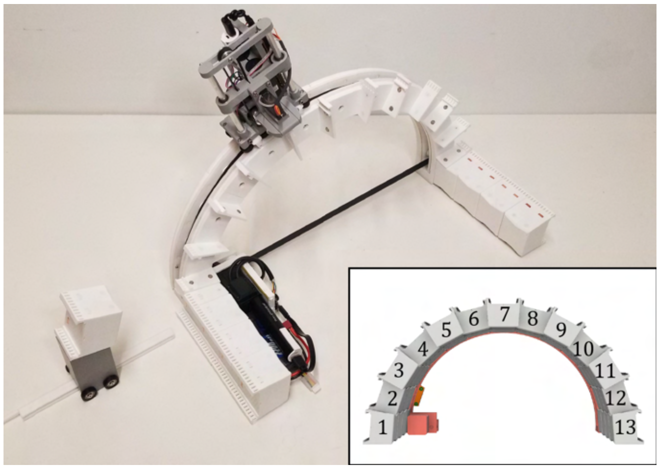

Fig. 5. The sequence begins with a pre-deployed “ArchBot” and two rows of four ground-resting blocks. The inset shows the numbering of rows.

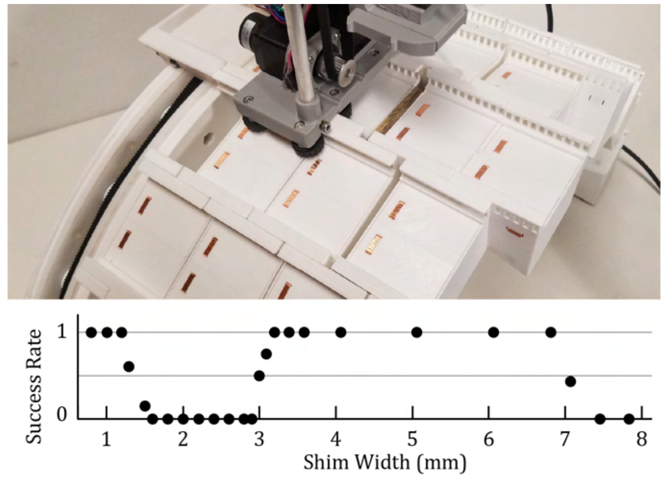

Fig. 6. Testing robustness to block misalignment by inserting a shim. Successively smaller gaps appear in adjacent rows. (Below) Gaps of 1.3–3.2 mm (∼3–6% of block width) can disrupt locomotion.

A typical building routine begins with the pre-deployed arch (ArchBot) in place, which provides a properly-spaced template in which to install the first blocks. Rows are numbered 1–13, with row 1 being the row of ground-resting blocks closest to the ArchBot’s motor and battery, and row 13 being the opposing row of ground-resting blocks. The building routine begins with up to four ground-resting blocks on each side of the arch in place (Fig. 5A).

Because each row is offset from its neighboring rows by half the width of a block, a set of 13 blocks spanning the arch from one side to the other proceeds not in a direct line but instead staggered. This arrangement can be considered as the union of an “odd arch” (7 blocks indexed as odd numbers) and an “even arch” (6 blocks indexed as even numbers). The building routine begins with an “odd arch”, with ground-resting blocks already in position (rows 1 and 13), and the rest added in sequence from the outside toward the center (i.e., blocks 3, 11, 5, 9, and finally 7, in the row along the top of the arch). Next, an even arch is installed in a similar way (blocks 2, 12, 4, 10, 6, then 8). The demonstration model consists of up to 4 odd and 3 even arches, totalling 46 blocks.

IV. Performance

The presented demonstration model allows for structures consisting of up to 46 blocks (8 ground-resting blocks placed in advance and 38 placed by the robot). Performance trials measured the reliability of continuous building sequences. Any time a failure to successfully place a block occurred, it was manually repaired and recorded, and the robot was allowed to continue on to place the next block. For each of three trials, the robot was able to complete the 38-block installation but required human intervention to recover from 1, 2, and 4 failed block placements, respectively. Failures typically occur when a block in the robot’s path is slightly tilted in a way that raises a corner of the block to create an obstacle. In most cases, the RailBot can traverse such an obstacle, even knocking the tilted block into better alignment with its filleted chassis as it passes. In some cases these kinds of obstacles cause a minor error (i.e., skipped steps) which the robot is able to recover from at the end of the move. However, on rare occasions a tilted block presents enough of an obstacle to halt the robot entirely, requiring manual intervention. Over the three trials (114 block placements total), 7 such failures occurred, resulting in an average success rate for block placement of 107/114 (94%).

Overall, this prototype system was designed to prioritize reliability rather than speed of operation. A complete sequence (38 blocks) requires approximately 19 minutes.

The ArchBot carries the RailBot along the arch at an average speed of 16.5 mm/s. In subsequent trials, it was found that the speed could only be increased to 18 mm/s before the ArchBot began to regularly skip steps. While the closed-loop control allows for the ArchBot to reliably make up steps that were lost during a command, this compensation requires additional time. With the mass of the RailBot and block together totalling 644 g, the nominal torque required to move the ArchBot’s carriage from a fully horizontal position is 0.3 N·m, exclusive of the resistance imposed by the timing belt or by friction. The motor used to operate this DoF is rated for a maximum torque of 0.72 N·m.

The RailBot’s average speed down a row is 24 mm/s. In subsequent trials, it was found that this speed could be increased to 45 mm/s without compromising the reliability of the DoF (i.e., causing the motor to skip steps).

Because of the increasing distance the RailBot must travel along the vault axis to add blocks as the structure grows, the time required for such a system to build a long vault of length L scales as L^2.

The gripper requires 2.5 s to raise or lower a block, and 0.5 s to expand or retract. During a typical block-placing routine, time spent performing gripper operations represents only a small fraction (3–10%) of the total elapsed time.

Experiments were conducted to characterize the system’s ability to accommodate induced errors. We first tested the effects of errors in block spacing (e.g., if a foreign object were to prevent two blocks in a row from being in contact), by introducing shims of incrementally increasing widths between adjacent blocks in a row, thereby disrupting the regularity of the running bond pattern and the rack gear formed between blocks (Fig. 6). The bottom panel shows the effect of these shims on the locomotion success rate (each dot represents the average of 10 attempts). For the hardware presented, the RailBot was able to move past the discontinuity without difficulty for gaps less than 1.3 mm as well as for gaps from 3.2 up to 6.8 mm (14% of the block length). Up to 1.2 mm, the rack-and-pinion system continued uninterrupted, with the teeth of the pinion gear engaging with the expected teeth in the rack; for gaps of 3.2–6.8 mm, the pinion gear skipped one or more teeth, re-engaging with the rack gear in a way that was offset from its expected odometry but without causing an interruption in locomotion. Shims 7.1 mm and wider caused misalignment prohibitive to locomotion.

Introducing shims between two blocks in a row will not affect the spacing between other blocks in the same row. It will, however, introduce smaller gaps in adjacent rows, due to both the geometric alignment features (concave faces) and the magnetic attraction between blocks. The relationship between the width of a gap w in one row and the width of the gap induced in a row i rows offset from it w_i was empirically measured as $w_i = w - 1.67i$.

Another experiment characterized the system's ability to recover from robot positioning errors during block placement (Fig. 7). The RailBot was commanded to place a block in locations increasingly further from its intended position (adjacent to the last block in the row). Placement attempts were repeated 5 times for each location (Fig. 7, bottom panel). It was found that the block would self-correct to achieve precise alignment when the robot positioned it anywhere from 0–23 mm past the edge of the previous block (up to ∼50% of block length). The success rate falls to 0 by 24 mm, beyond which the block fails to physically engage with the cavity formed by the adjacent blocks. (In routine operation, the RailBot takes advantage of this range of tolerance by placing blocks 4mm past their intended position, then locomoting 4mm backward with the block still in its gripper, thereby pulling the block tight against its neighbor in the same row.)

As reversible assembly was a guiding principle of this work, trials were conducted to evaluate tolerances for block replacement. In each of 30 trials, a single block was chosen at random to be designated as "damaged". (Note that while it is possible to remove more than one block at a time from a given row, the RailBot is unable to locomote past missing blocks.) The robot was commanded to locomote to the damaged block, extract it from the vault, and return it to the feeder shuttle; it waits for the feeder shuttle to return with a new block, which it then carries and installs in the vacant position. The robot was able to complete this block replacement sequence without intervention in all 30 trials.

An architectural-scale version of such a system would need to handle blocks of correspondingly greater mass. Limitations in robot carrying capacity could be addressed by reducing the relative size of individual blocks along any of their three dimensions, and by using larger gear reductions, in both cases increasing the total building time accordingly.

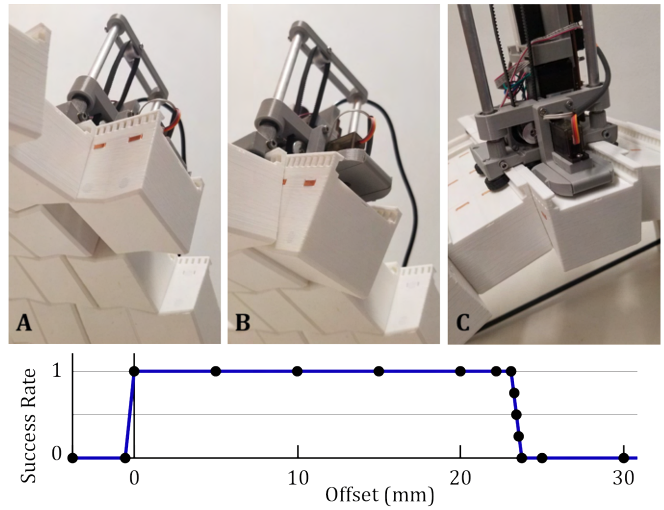

Fig. 7. The system is capable of self-correcting even large positioning errors. (A) When placing a block into the vault ∼22 mm past its intended position, the insertion forces neighboring blocks out of its way. (B) After the RailBot retracts its gripper, the magnetic forces attempt to pull the block into alignment, but the robot's body blocks its path. (C) The RailBot locomotes back toward the arch, allowing the block to settle in its intended position. (Below) The success rate when placing blocks an offset distance from the edge of the previous block in the row (0mm).

V. Deployable Blocks for Transportation

The prospect of unsupervised robotic construction would likely hold the greatest value for construction in environments that are too hostile or remote to support human labor. For building in such environments, the transportation of raw materials to the construction site is likely to incur considerable costs. Therefore, it seems advantageous for a material-robot system intended for unsupervised operation to be designed with mass and volume constraints in mind.

In-Situ Resource Utilization (ISRU) is a term most often used in space applications, but which more broadly describes the practice of minimizing the cost of material transportation by maximizing the use of materials already found on site. For example, stacking stones found in a field to build a fence or building a structure with rammed-earth construction could be considered examples of (terrestrial) ISRU.

ISRU-based proposals for planetary space habitats generally fall into one of two categories: (1) additive manufacturing (architectural-scale 3D printing) or (2) piling regolith on top of a habitat to provide shielding. Additive manufacturing is challenging because it is dependent on the physical and chemical properties of the regolith, which can be variable and difficult to know in advance, and because it can entail potentially infeasible demands regarding supplied mass and/or energy [22], [23]. Piling regolith on top of a habitat requires the habitat to be capable of supporting the weight of large masses of regolith (accordingly increasing the mass needed for the habitat itself), and introduces maintenance issues associated with accessing the habitat surface.

In order to avoid such challenges, loose regolith could be used to fill hollow containers like the blocks in our system, which could then be arranged into a vault to provide

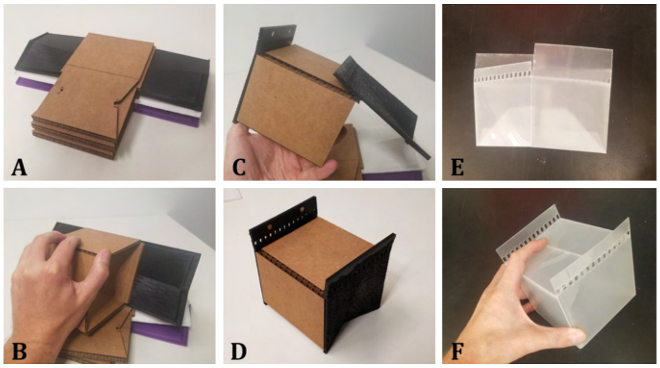

Fig. 8. Study models for collapsible blocks made of sheet materials like cardboard (A–D) and polypropylene (E–F). The dimensions of the expanded models (taken to be at ∼1:10 scale) are ∼10 cm on each side. The cardboard model (which features 3D printed concave faces) collapses to ∼40% of its expanded volume while the polypropylene model collapses to ∼10%.

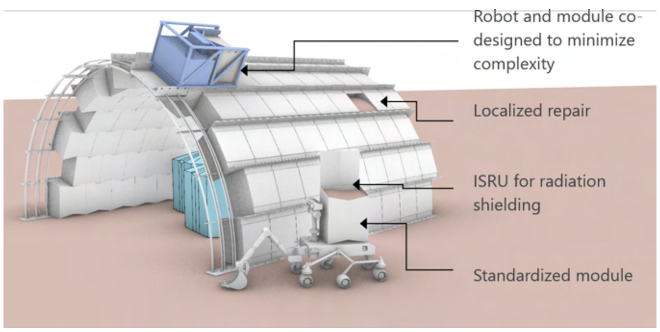

Fig. 9. An autonomous vault-building robot system could create shelters in environments inhospitable to human construction workers, e.g., to provide a shield for a Martian habitat. Key features of the approach are highlighted.

shielding against hazards like radiation and micrometeorite impacts. While using hollow blocks reduces the mass needed for transportation, volume remains an issue. Using a collapsible block design instead would allow for a considerable reduction in the transportation volume needed.

While collapsible blocks at the scale of our prototype robot system were not feasible due to fabrication limitations, we designed and fabricated larger-scale blocks showing how hollow boxes of the same shape could be folded from nearly-flat materials (Fig. 8).

A challenge for designing a collapsible building unit is that its folding mechanisms need to be compliant enough to pack flat but also strong enough when locked into place to withstand the forces acting on the structure. Future work will look at larger-scale prototypes that can more comfortably accommodate hinges and locking mechanisms, rather than relying solely on folding sheet materials like the cardboard and polypropylene in the model of Fig. 8.

VI. Discussion

The proposed system demonstrates a framework for building spanning structures with climbing robots, which need not be limited to the specific choices made with this particular prototype. Other variations are possible and may be chosen according to the demands of a particular scenario: e.g., geometric parameters like the depth of blocks (thickness of the vault) and the number of rows in the vault can be varied, overall scale can be changed, and so on. Other variations could increase redundancy and speed by using multiple RailBots, multiple shuttles on an ArchBot, and/or building in both directions along the vault axis. Alternatively, a modified ArchBot could potentially be removed from a completed vault and re-installed elsewhere to enable building in a different location.

One potential application of the proposed system is the construction of protective shields to shelter assets in harsh environments (remote equipment, extraterrestrial habitats, etc.) (Fig. 9). Blocks could be collapsible for transportation, and filled on-site with found materials such as regolith (as described in the previous section). In the example of planetary space habitats, an instantiation approximately 25 times the scale of the demonstration model would correspond to a regolith shield roughly 1m deep, providing an appropriate thickness for radiation shielding [24].

For a full-scale deployment, it may be difficult or impossible to transport and install a rigid prefabricated arch to use as scaffolding to begin the structure. Instead, it may be desirable for this element to be collapsible, for instance by telescoping or as a tensile element that could be coiled and released on site (much like a pop-up tent). The design of such an element will be the topic of future work. Regardless of the scale of the deployment, load transfer occurs primarily through face contact (i.e., blocks bearing on one another). While this is sufficient at the model scale in a controlled laboratory environment, threaded fasteners or other mechanical connections between blocks may be required to preserve structural integrity in challenging outdoor environments. Magnets could improve alignment regardless of the scale of the blocks (their strength would not need to scale proportionately to be useful, as they serve no structural function in the vault). Finally, the rack-and-pinion features employed in this demonstration would likely not need to scale proportionally for a large-scale version (they are of an exaggerated size to facilitate working at the scale of the demonstration). Rather, a full-scale deployment could employ a modified version of a commercially available linear actuation system, taking care to design the track system in a way that avoids collecting dirt and debris.

Future work in this area will seek to address challenges toward more complete implementation scenarios. In addition to the development of a deployable arch scaffolding mentioned above, attention will be given to the design of a large-scale deployable block unit capable of folding flat for transportation and making mechanical connections to its neighbors. Future work will also consider the full lifecycle of the proposed building system, including fabrication, transportation, deployment, decommissioning and reuse.

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