Designing for Digital Assembly with a Construction Team of Mobile Robots

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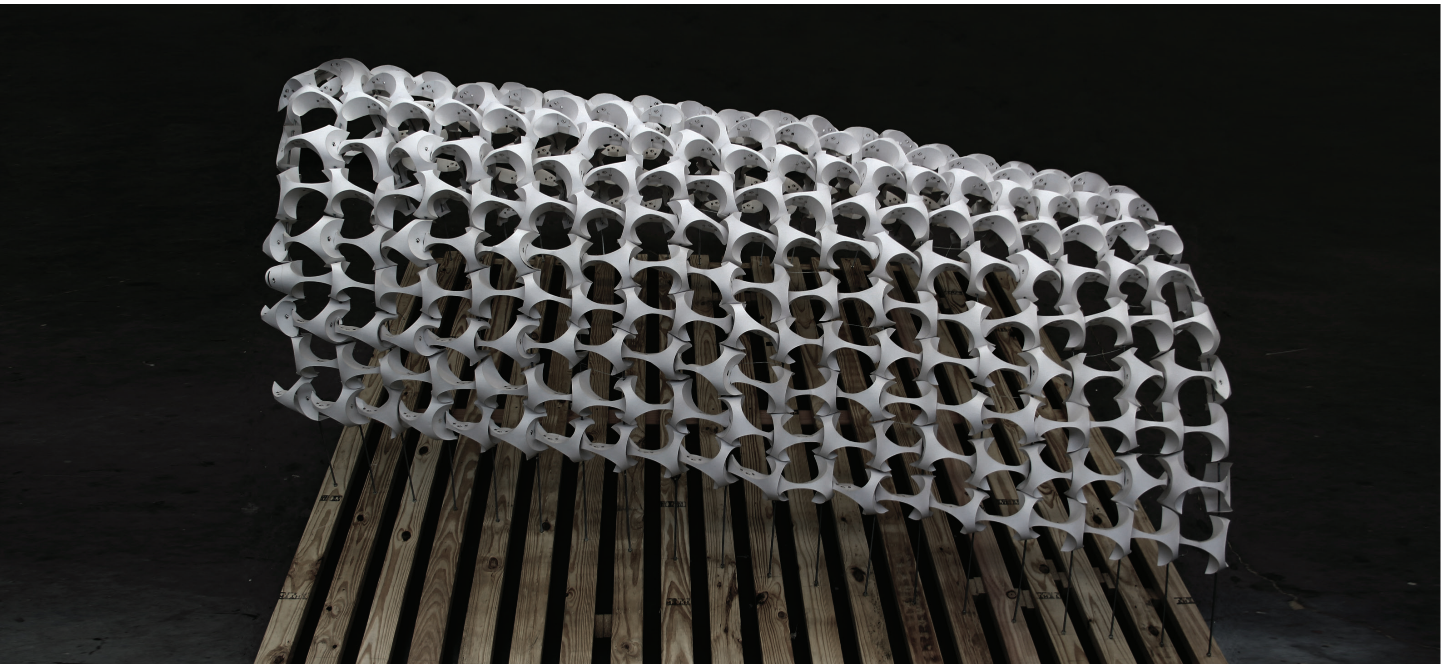

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1 A large-scale structure that was fabricated using the proposed robotic-fleet method (side view).

ABSTRACT
Advances in construction automation have primarily focused on creating heavy machines to accomplish repetitive tasks. While this approach is valuable in an assembly-line context, it does not always translate well for the diverse terrain and dynamic nature of construction sites. As a result, the use of automation in the architectural assembly has lagged far behind other industries. To address the challenges of construction site assembly, this project suggests an alternative technique that uses a fleet of smaller robots working in parallel. The proposed method, which is inspired by the construction techniques of insect colonies, has several advantages over the use of larger machines. It allows for much greater on-site flexibility and portability. It is also easy to scale the operation, by adding or removing additional units as needed. The use of multiple small robots provides operational redundancy that can adapt to the loss of any particular machine. These advantages make the technology particularly suitable for construction in hazardous or inaccessible areas. The use of assembly robots also opens new horizons for design creativity, allowing architects to explore new ideas that would be unwieldy and expensive to construct using traditional techniques. In our tests, we used a team of small mobile robots to fold 2D laser-cut stock into 3D curved structures, and then assemble these units into larger interlocked forms.

INTRODUCTION

Most contemporary manufacturing sectors have adopted cutting-edge fabrication techniques, helping to improve the speed, quality, consistency, and safety of their operations. Until recently, however, the construction industry has remained resistant to this trend. While sectors such as automobile manufacturing and electronics have rushed to embrace robotic techniques, architectural construction continues to rely on traditional labor-intensive approaches. These practices are slow and sometimes unwieldy. They are also dangerous for workers—nearly 17% of all workplace fatalities today take place in the construction industry (Somavia 2005).

Traditional approaches to construction assembly can also limit the creativity of designers. New computational tools are quickly advancing the possibilities of architectural design, allowing for innovative structures, more adaptive designs, and more complex geometries. New digital fabrication technology, including laser cutting and robotic fabrication, supports these developments. However, the on-site assembly of the fabricated materials still relies on traditional, labor-intensive practices, and the assembly of innovative designs can often be convoluted, unwieldy, and expensive using traditional techniques (Gramazio et al. 2014).

In this paper, we propose an innovation in the automated architectural assembly that is based on the use of small, mobile robots. The inspiration for this approach is biological, grounded in observations of how insect hives cooperate in the construction of relatively large and complex structures. Since the architectural construction process often involves many small, interdependent, site-specific, and complex tasks, the usefulness of large scale factory techniques is limited. However, using an integrated "swarm" of small, task-specific robots working together enables exciting new construction possibilities.

BACKGROUND: ROBOTIC ASSEMBLY IN DIGITAL FABRICATION

Throughout human history, architecture has been continuously influenced by new technologies. Innovations during the industrial revolution, such as steel frames, electricity, and elevators, rendered the previous limitations of architecture obsolete and altered the fabric of our cities. A similar revolution began during the second half of the twentieth century when computer-aided design enabled architects to expand the possibilities of the field. Today, robotic assembly techniques are a new frontier for innovation in architecture. Speculation about using robots in architectural construction has existed for several decades, but it is only in recent years that some of these imaginings have started to become a reality.

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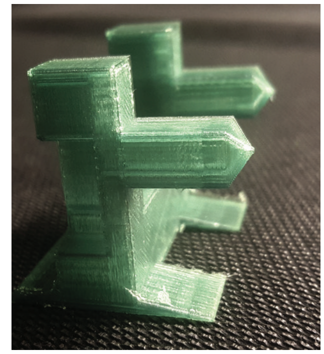

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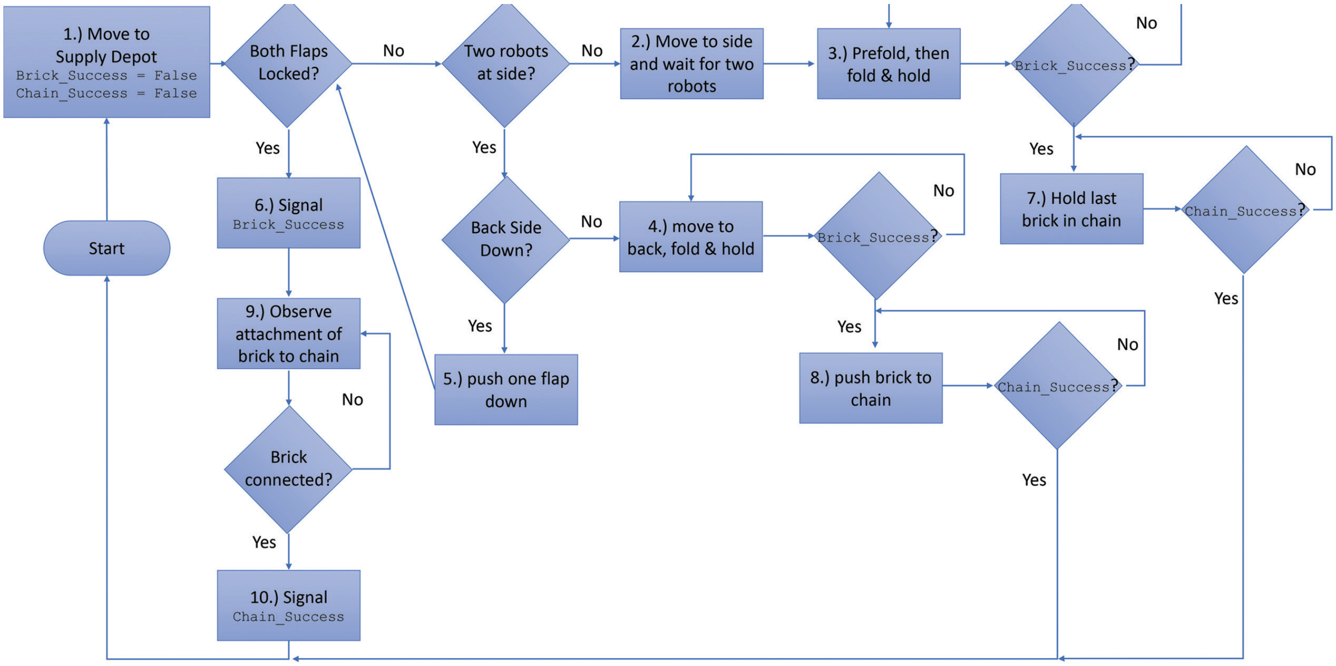
2 A Cozmo robot is 10 cm long. It has tank steering, an accelerometer to measure tilt, a one-degree-of-freedom forklift arm with a maximum reach of 3 cm, a microphone and speaker, and a one-degree-of-freedom head with a camera and mono-chromatic expressive face.

3 A 3D-printed forklift, snap-connected to each Cozmo's lifting bar.

The earliest ideas for using robots in construction were related to the automation of repetitive tasks such as bricklaying and lifting heavy materials (Pritschow et al. 1996). Experimental installations gradually expanded these ideas, leading to automatic assembly systems for large-scale modular structures (Terada and Murata 2004). It was not until 2008 that any of these ideas were used in commercial contexts, and even then the units were more proof-of-concept showpieces than practical industrial applications (Gramazio et al. 2014; Helm et al. 2014). Over the past decade, however, the technology has steadily improved, and new implementations have been explored. In addition to bricklaying/masonry robots (Mekinc 2015), researchers have worked to develop automated systems for paving roads (Tiger Stone 2018), aerial construction robots (Lindsey et al. 2012; Kalantari et al. 2016), and climbing robots that can build and reconfigure trusses (Nigl et al. 2013).

Keating and colleagues (2017) developed an automated construction system capable of customized on-site fabrication of architectural-scale structures using real-time environmental data for process control. The system employs hydraulic and electric robotic arms and an additive manufacturing technique for constructing insulated formwork. A couple of other examples of robot arm applications in construction sites (Institute for Computation Design and Construction 2017; Dierichs and Menges 2012), present interesting solutions to circumventing the workspace limitations of stationary robots. However, the approach is highly dependent on preparing the site in advance for the use of bulky robots, and these automated systems can only be used for very specific subtasks.



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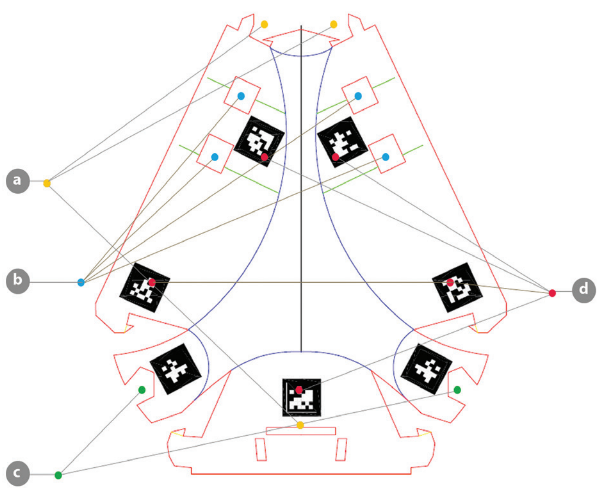

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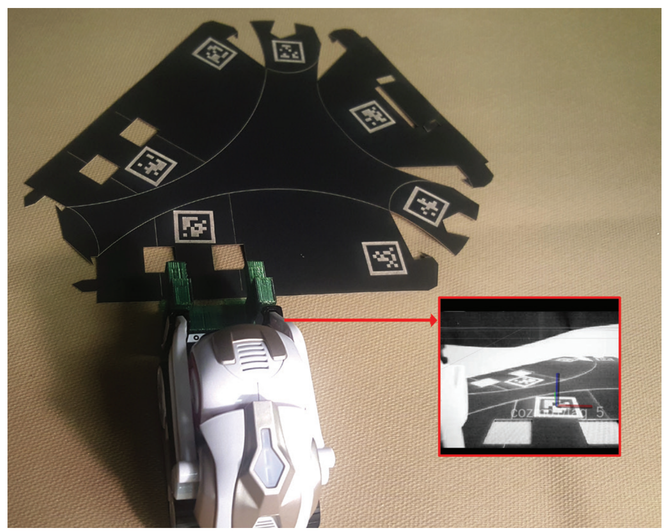

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4 Team construction relies on cues from the environment and the current actions of neighboring robots.

5 A planar construction component designed for automated assembly: (a) interlocking tab and slot; (b) holes for lifting; (c) holes for connecting the system to the structure; and (d) fiducial pattern recognized by Cozmo as landmark for initiating the fabrication process.

6 Image processing with the Cozmo. Fiducial markings are embedded in the planar part and identify key manipulation targets. The inset shows a view from the onboard camera (after processing).

The complex nature of architectural construction and the need to navigate unique on-site environments has proven to be severely limiting. Architectural construction robots require more flexibility than those in other industries, including the ability to respond to obstacles, changing lighting, and cluttered workspaces, endure the weather, and handle diverse terrain conditions. Human/robot interactions in construction sites are also of particular concern—the robots must be carefully configured and/or limited to avoid creating dangers for the human workers that are still needed in many on-site tasks (Goodrich and Schultz 2007).

The current research addresses these problems by suggesting a move toward smaller and agiler construction robots, which can work together as a team. This approach will allow the robots to more effectively accomplish intricate tasks, to exhibit greater on-site flexibility, and to take over more of the construction processes that today require human workers. The inspiration for this approach is drawn from observations of insects that build in coordinated groups, such as mound-building termite colonies. Such insect hives exhibit a remarkable capacity to create structures that are intricately designed and that can grow to a tremendous scale relative to the individual termites (Turner 2002; Camazine et al. 2001). In recent years there has been a growing interest in autonomous robot "swarms" that function on the termite model, using decentralized multi-agent systems rather than a single robotic unit to accomplish tasks (Theraulaz and Bonabeau 1995, Werfel 2007, Werfel et al. 2014). This approach has many advantages, including adaptability, easy scaling (by adding or removing units as needed), and network robustness (the failure of a single unit can be accommodated without significantly affecting the overall process).

When applied to construction sites, the "termite model" offers the promise of finally overcoming challenges that have kept the industry from fully embracing the benefits of automation that have transformed other sectors of the economy. Increasing automation in construction industries has the potential to improve ecological efficiency and resource-use, to allow for the efficient assembly of innovative architectural designs, and potentially to help with significant human problems such as housing shortages and disaster responses. As we begin to move in the direction of greater automation, this approach can be particularly appealing for disaster areas, hard-to-reach terrain, or even extraterrestrial sites—anywhere that the extensive presence of human workers would be particularly expensive and/or dangerous.

METHODS

The goal of this project was to develop a prototype automated construction technology based on teamwork among multiple small robotic units. The central challenges included determining a useful mechatronic design for the system and developing advanced motion-control and navigation schemes for the fleet.

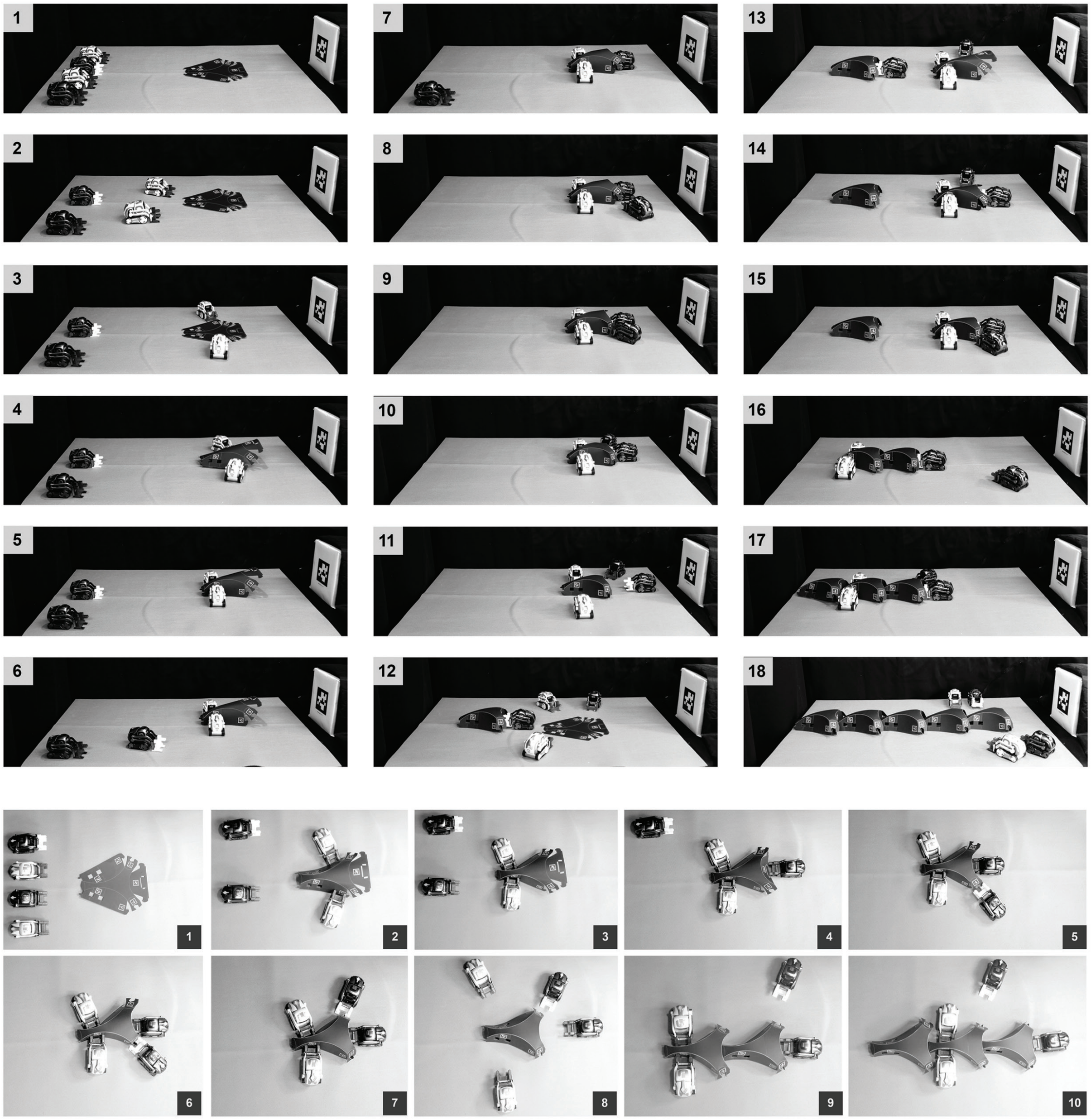
After considering various factors such as software versatility, cost, and built-in sensor technology, we decided to use an inexpensive commercial mobile manipulator unit, called the "Cozmo," as the foundation for our study (Figure 2). This robot is marketed primarily as a children's toy, but it is nonetheless strong and sophisticated enough for use in construction robotics research. The Cozmo is easily portable, weighing just 150 grams, and it comes with built-in motors, accelerometers, and a color camera. The robot has little onboard processing; instead, most of the computation is performed by a smartphone or tablet running the Cozmo app and communicating with the robot via WiFi. The off-the-shelf electromechanical components of this system and its use of open-source software made it ideal for our purposes.

The next step was to develop rules of assembly and navigation algorithms that would allow a fleet of Cozmo robots to create architectural structures. There are two general building approaches that can be undertaken by robot swarms—the fleet may be employed to create a predetermined shape, or it may also be given the autonomy to create variable outcomes based on algorithmic processes under the influence of the local environment. In the latter process, placing objects or markers in the workspace can direct the final design to achieve different objectives. In our tests, we focused exclusively on creating predetermined architectural shapes, but we also designed the system so that it could be converted to produce variable designs by altering the dimensions of the building components and the order in which they are supplied to the construction robots.

Our test used 3D modules constructed from a planar material and curved-crease folding (Demaine 2011). This approach takes its inspiration from a large body of previous origami and robotics work, including pop-up construction (Whitney et al. 2011), self-folded origami robots (Miyashita et al. 2015), and laser-origami (Mueller et al. 2013). For this work, we also used landmark recognition based on fiducial markings (Olson 2011) to determine the configuration of the robot and the objects in the workspace. The onboard camera determined the position and orientation of the fiducials. By placing multiple fiducials on the building blocks, we were able to determine what stage of assembly the current brick is in. For example, if the tags are coplanar, then the brick has not yet been folded. If the tags are co-planar, but at an angle from the floor, then the brick has been lifted.

A similar, but larger, fiducial tag was used to mark the supply depot, the location where the unfolded 2D stock was furnished for the robots. This large tag was visible from a distance and provided all of the robots with a common coordinate frame. In the future, similar fiducials on the four sides of each Cozmo could enable the robots to identify neighboring robots—but for now, the location of each robot is shared wirelessly through the Robot Operating System (ROS) framework.

Our approach to architectural construction draws from the classic, insect-inspired notion of "stigmergy" (Werfel et al. 2014). Under this paradigm, there is only a limited dialogue between the robotic agents. Most communication among the units is implicit via the joint manipulation of the shared environment. Each robot makes its decision about



7 Overview of the assembly process, side view, and plan view.

brick placement based only on the current local state of the developing structure; in other words, based on the existing configurations of bricks. The robots must be programmed in such a way that the eventual correct completion of the target structure is guaranteed, despite the lack of information about distant parts of the structure, and irrespective of the number of robots engaged in the task.

The tasks that need to be carried out by the robot fleet include four fundamental processes: (a) constructing a 3D brick from 2D stock, (b) assembling bricks into interlocked chains in alternating directions, (c) stitching the chains together into a mesh, and (d) lifting the mesh into the desired overall shape. In the current work, we focused on accomplishing the first two tasks, while steps (c) and (d) were completely manually. Future work will continue the process of automating the final two steps.

(a) Constructing a 3D brick from 2D stock.
We assume the planar stock has been cut and scored and is lying in the workspace.

The Cozmo robots must first identify the part and its orientation using the embedded fiducial images. We have tested two methods for finding the part. The first is to apply a distributed spiral search algorithm (Fricke et al. 2016).

The second method is to furnish planar parts at a standard location, called the supply depot (Werfel 2014). Both methods were successful, but the latter method proved to be faster since no search time was required.

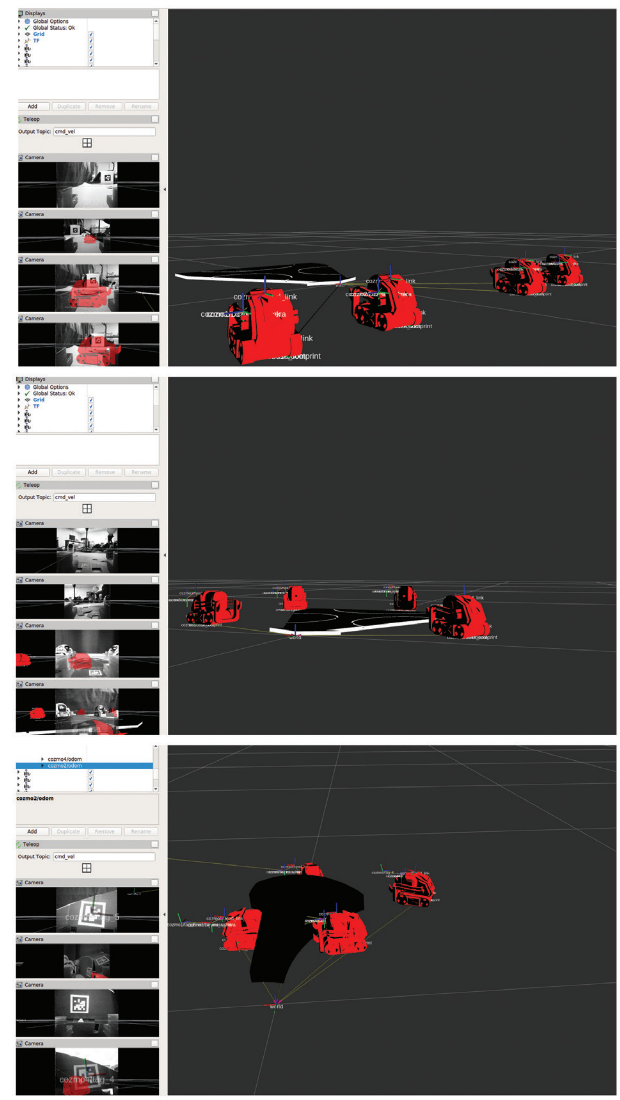
The Cozmos are able to exchange basic information using the ROS protocol, and this allows them to determine when two robots have located the same planar stock component (the fiducial tags on each stock components are numbered). Once two Cozmos have identified the same stock component, they move to opposite push-points along the sides as identified by the fiducials. A curved-crease folding technique (Demaine 2011) is used in the construction materials to generate the desired 3D shape and lock it into place using folding tabs and mating slots. The robots must work together to push the component into its three-dimensional shape.

One potential difficulty we encountered in our design is that the unfolded planar parts can be somewhat stiff, and depending on where the robots are located, bending the scored material may require more force than two Cozmos can supply. However, we were able to identify a specific push-point near the rear of the stock where the required force is reduced considerably. In our tests, two Cozmos using the appropriate push-points were able to "pop" an unfolded, laser-scored part into its intended three-dimensional configuration with an 85% success rate.

The part is now a three-dimensional "brick," but if the robots release the brick, it will collapse back toward its original two-dimensional position. Additional Cozmo robots must now find the part, identify its current configuration using the fiducial tags, and push the component's locking flaps into place. These flaps are designed with a slot that snaps into mating tabs on the sides of the brick. Once all the flaps are locked down the brick will become rigid, and the robots can release it.

To improve the effectiveness of this assembly process, we created a 3D-printed "forklift" that can be snap-connected to each Cozmo's lifting bar (Figure 3). This forklift attachment has two sloped tines that will slide underneath the planar stock, and two alignment pins that passively ensure the part is correctly oriented. The use of this attachment helps a single Cozmo to grip the brick better and partially restrict the brick's movement.

Throughout this process, stigmergy is encoded by the state of the stock part and the number of Cozmo robots that are involved with assembling the part. If the part is planar (determined by onboard cameras), then the robot assigns itself as the pushing unit and waits until another

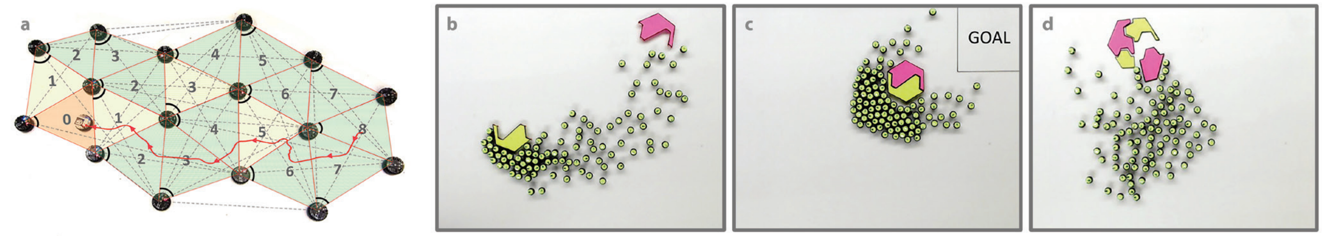


8 A 3D rendering of one Cozmo's beliefs about the world, taken from the Robot Operating System software. Shown in the image are the Cozmo, the planar part identified by its fiducial, the other Cozmo robots, and a large rectangle showing the workspace. The black windows show the current code executing.

robot arrives and takes up an opposing position. They then work together to "pop" the planar component into its 3D formation. If the part is already three-dimensional, then a newly arriving robot checks to see if the flaps have been pushed into place to secure the 3D shape. If the flaps need to be pressed into place, then the new robot assigns itself to this task. If all the flaps are locked, then the brick is ready to use, and the process flow continues to the next step (Figures 4–6).

(b) Assembling Bricks into Interlocked Chains in Alternating Directions.

When an individual "brick" has been prepared and is ready for use, one of the robots that was involved in the previous step is elected to push the brick into place (the selected



9 (a) Using robots to build a map, with individual robots as landmarks (Lee et al. 2014). (b-d) Swarms together assembling and delivering structures too large for one robot (Becker et al. 2013).

robot is the one that previously closed the flap on the opposite side from the direction in which the brick needs to move). This "pushing" robot's field of view will be obscured by the 3D brick, so a second robot needs to serve as the eyes of the operation. The robot chosen for this vision task is the one that is closest to the pushing robot's right-hand side. Together, these two robots steer the brick to the location of the existing assembly chain. The pushing robot attempts to press the brick into place, adding it to the chain by pressing a tab into a mating slot on another brick. The observing robot checks to see if these tabs are correctly locked in place. If there is a problem, then the team steps back and attempts the task again until it is successful (Figures 7 and 8).

The chains of bricks are assembled in alternating rows to create the overall structure. The form of this structure is primarily determined by the design of the individual bricks, but it may have significant variations due to randomness and the contours of the local environment. In our initial test, we did not include any ending conditions—construction continues until the supply of building material is exhausted.

RESULTS

For preliminary testing, we used a team of five Cozmo robots. The modular construction units, or "bricks," were generated from planar stock (heavy-weight cardstock) that was laser-cut to allow pop-up construction into curved three-dimensional forms. The laser cutter was used to inscribe the cardboard along desired folding creases so that applying planar forces at specified points along the perimeter caused the cardboard to spring into a 3D shape. Our system design was motivated by the goal of using relatively simple, independent robots with limited capabilities, so we endeavored to keep the process as streamlined as possible.

The sensory capacities of the robots were limited to perceiving only objects labeled with fiducials. They were also able to query nearby robots to obtain the robot's ID and to verify that they were working together on the same brick (these processes were also carried out using fiducial numbers). A large fiducial tag at the supply depot was used to give the robots a common coordinate frame and help them navigate from the supply depot to the building site. However, we noted during our tests that the accuracy of the robot's localization decreased with distance from the depot, particularly when the robots were moving and/or temporarily lost sight of the depot.

Future work could potentially use the robots themselves to maintain a more reliable coordinate frame. Even without global position information, it is theoretically possible for the robot team to maintain reliable paths from the supply depot to the construction area by using some robots as stationary landmarks (Figure 9) (McLurkin et al. 2014, Lee et al. 2014; Becker et al. 2013).

One of the unique aspects of this approach is that neither information about the current state of the overall structure nor the actions of more distant robots was stored by the individual units. Furthermore, the robots obtained information about the available construction options only through direct inspection. After leaving the build area, the memory of the structure's state was not retained since this information was likely to become outdated as other robots continued to make modifications.

Our trial demonstrations showed that the Cozmo robots could be readily programmed to build basic architectural structures in this fashion. One of the structures that we constructed using this approach is shown in Figures 1, 10, and 11. As noted above, only the first two steps of the process are currently fully automated. Future work will be carried out to automate the process of stitching the chains into a mesh and lifting them into place. These movements will require coordinated action from many robots at once (Shahrokhi and Becker 2016; Shahrokhi et al. 2018).

CONCLUSIONS AND FUTURE WORK

This project contributes to the incorporation of new technologies in architectural construction by using a fleet of small manipulator robots instead of a single-task machine.

10 Robotic assembly. (Top) connecting the bricks into a chain. (Bottom) the chain in front of a final 3D mesh.

11 A large-scale structure that was fabricated using the proposed robotic-fleet method (top-down view).

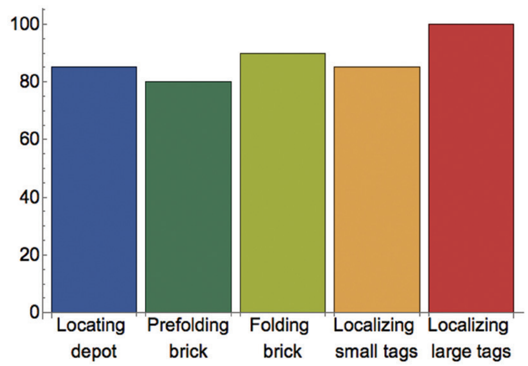
This approach has numerous advantages, including site flexibility, portability, ease of process-scaling, and network robustness that can accommodate the failure of individual units. The aggregated system developed in this work is intended to address central limitations that have so far prevented the construction industry from fully embracing the benefits of automation.

To design a full-scale construction scenario that could be assembled by the use of small, inexpensive robots, we needed to overcome two major challenges. The first was the overall design of the construction components, and the second was the protocol for the robots' behavior during the assembly process. These two components needed to be completed in a back-and-forth manner since they each influenced the other. Our ultimate solution was developed through an iterative, exploratory process that began with investigating simple "brick" designs and became increasingly sophisticated as we learned more about the robots' capacities and developed their behavioral protocols. We fabricated multiple prototypes before ultimately reaching one that led to a successful and reliable assembly. In our tests, Cozmos' success rate to "pop" an unfolded, laser-scored part into its intended 3D configuration was 85%. The rate for Cozmos to find the depot location was also 85%, and to get the paper out of equilibrium state was 80%. The robots could push the cardstock into a 3D state with a 90% success rate and could find the tags by an 85% success rate. Figure 12 illustrates a summary of the Cozmos' success rate. We would like to increase this percentage further, but as it stands this is adequate for the robots to make use of the vast majority of the building materials with limited waste.

With the lessons learned from this project, the goal of creating even more sophisticated swarm-assembly designs become more achievable. It is our goal that the knowledge gained here can eventually be applied to develop a computational platform that will break down any design into the required cutting, tagging, and behavioral protocols that are needed for robotic assembly. Furthermore, by modifying or expanding the capabilities of the component robots (for example by adding 3D printing, additional assembly effectors, or flight capabilities), this method could potentially provide architectural designers with a greatly expanded palette to create structural meshes of any size, anywhere.

There are numerous potential applications of this fabrication approach, but the most exciting and urgent uses involve construction in hazardous or inaccessible areas. The method could be used to fabricate temporary housing or hospitals in disaster areas, to build small-footprint structures in remote terrain, or even to create advance bases on other planets. It also has the potential to encourage a new era of innovation in everyday architectural design, as the creative possibilities of automated construction extend far beyond conventional fabrication and assembly techniques.

Future projects based on this research will include looking at other, more complete implementations of hardware and assembly protocols. In the area of hardware, we intend to expand our robotic platform and enhance the limits and size of the Cozmo robots. We expect that better results could be achieved by using a custom-made robotic platform designed for automated assembly. Customized robot designs would allow us to expand the number of potential tasks for the robotic construction team, and to develop more complex fabrication scenarios. This will lead us closer to addressing real-world construction problems and to working with standard construction materials such as brick, aluminum, and concrete. In the area of software, we expect that better results could be achieved by certain



12 Cozmos' success rate in different functions designed for digital assembly.

modifications to the agent behavior—for example, using a robot's location as a benchmark in their navigation instead of relying purely on cameras. Taken together, these advances can help to fulfill the promises of safe and effective robotic architectural construction.

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IMAGE CREDITS

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