

# **LARGE-SCALE ADDITIVE MANUFACTURING OF CONCRETE USING A 6-AXIS ROBOTIC ARM FOR AUTONOMOUS HABITAT CONSTRUCTION**

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## **Abstract**

Layer-by-layer construction of concrete through additive manufacturing allows for greater design freedom in concrete construction compared to conventional casting methods. This has led researchers to pursue a variety of potential system solutions to enable the creation of architectural-scale additively-manufactured concrete structures. One of the most common approaches is through the extrusion of concrete patterned via a six-axis robotic arm. However, while the use of a six-axis robotic arm can offer significant geometric advantages in the printing of architectural-scale concrete structures, it also suffers from significant challenges that must be addressed. In this paper, the authors discuss potential methods to address such challenges associated with (1) minimizing travel moves in toolpath design, (2) expanding the achievable build volume, and (3) inserting pre-fabricated components in a structure being printed. These solutions are then demonstrated through the context of NASA's 3D-Printed Habitat Challenge.

## **Introduction and State of the Art**

Architectural-scale additive manufacturing (AM) is rapidly becoming a crucial facet of the AM landscape. While the majority of modern construction still relies on filling formwork with concrete to create a final structure, researchers have begun to investigate whether material-extrusion AM can offer a more flexible and responsive approach to the creation of low-cost concrete structures. For viable extrusion-based AM of concrete, the material needs to be workable during extrusion, then rigid enough after extrusion to hold itself in place as well as hold weight from subsequent layers without significant deformation [1]. Through ongoing materials research, concrete is becoming more and more capable of meeting these needs. This has the potential to transform the way that architects and engineers approach the design and implementation of habitat-scale structures, especially in remote or austere environments, which include impoverished regions, areas subjected to natural disasters, or even extraterrestrial bodies such as Mars.

Concrete construction can uniquely benefit from AM due to the high labor costs associated with construction along with the high cost of custom formwork. By reducing the cost of labor and allowing for custom designs without the need of producing formwork, AM could drastically reduce the cost of custom concrete construction. Additive construction will allow for new design methods that will be able to take advantage of the shape and hierarchical complexity AM provides.

However, in order to take advantage of AM in construction and the new materials being developed, a physical system needs to be designed to deposit the material, which brings a host of new challenges to be addressed.

Currently, there are three main architectures employed in the design of printing systems large enough to produce architectural-scale structures: gantry systems, cable-driven systems, and robotic-arm systems. The gantry system is common and has been used to print both in-place buildings as well as printed-for-assembly structures. The company ICON and the U.S. Army Corps of Engineers have been able to develop gantry systems that can be used to print entire structures with no assembly required [2,3]. Their system uses a large frame that moves a nozzle in each axis within the frame. Concrete is then pumped to the nozzle by a concrete pump positioned next to the gantry frame. This method is a scaled-up version of the common gantry-based small plastic printers. This makes for a simple printing system design as well as a simple control system [4]. However, a key downside to gantry-based systems is the required scale for the frame. The frame must be larger than the structure to be built, which can require a massive system along with costly transportation and setup and teardown processes. This can hurt the overall responsiveness of a gantry-based printing system in remote environments. Additionally, the gantry system only allows for movement in the X, Y, and Z directions, which generally limits their capability to extrusion of simple 2D layers. While researchers have added unique capabilities to such systems, such as rotating nozzles, angling nozzles, or automated reinforcement placement [5], gantry-based concrete printing systems are still relatively disadvantageous when compared with other approaches to large-scale printing.

A cable-based system strung between multiple fixed points allows for a system that is more compact and easier to transport as compared to a gantry-based system. By making the long bulky components of the system into cables rather than rigid as in a gantry system, there is less of a setup process. Oak Ridge National Laboratory (ORNL) has demonstrated the use of such a system, which uses a series of five fixed points combined with cables to hold the nozzle assembly [6]. By manipulating the five cables, the nozzle can be positioned within a 3D space. This allows the system to be scaled up without increasing the cost significantly. However, this system shares some of the limitations of the gantry system, such as the constraint of the three axes, which limits the system's ability to execute complex maneuvers or perform multiple processes. Additionally, while not requiring a large direct footprint for the equipment, these systems do require large areas for the equipment to be sufficiently separated such that the cables do not interfere with the structure being printed.

Finally, robotic-arm printing is third method currently being pursued for concrete printing. These can take the form of off-the-shelf six-axis robotic arms or custom-made arms like Apis Cor's cylindrical coordinate system arm [7]. This approach offers several benefits when compared with gantry or cable-based systems, specifically due to the potential flexibility of robotic arms along with their compact form factor. Their size simplifies transportation to remote environments when compared with gantry-based systems, while the decreased assembly requirements can reduce deployment time compared with cable-based systems. The advantage of having six axes of

freedom also increases the achievable geometric complexity compared with the three axes of the cable-based and gantry-based systems. For example, robotic arms can achieve out-of-plane deposition or deposit printed layers in sections, rather than requiring the entirety of the layer to be printed at once. They also allow for multiple processes to be performed by a single robot. By adding tool changes to the process, the arm can deposit concrete, embed components, and perform post processing to the structure. The main issue with robotic printing though, is the limited scale; robots have limited reach and must be moved to print structures larger than their reach [4].

Ultimately, while these three different system approaches to concrete AM have their advantages and challenges, we contend that the opportunities enabled by six-axis robotic extrusion of concrete makes this method ideal for agile, on-demand printing of architectural-scale structures in remote environments. As such, this paper provides an overview of a concrete AM system created in response to NASA's 3D-Printed Habitat Challenge, along with crucial modifications made in order to improve the system's capabilities while also accounting for its shortcomings.

### **System Design**

The system pursued for this research was a robotic extrusion platform. This choice was made, in part, to take advantage of the multi-process capabilities of robots, in addition to the size advantages discussed earlier. The physical system is comprised of two parts. The first is a concrete mixer-pump (m-tec Duo mix 2000) used to pump the concrete through the system. The material for the mixer-pump is supplied from a silo via one of two methods: (1) through pneumatic feeding from the silo to the mixer-pump or (2) gravity fed with the mixer-pump below the silo. In this system, dry concrete powder is added to the mixer-pump automatically as the powder gets low. Water and powder are then added to a mixing chamber where it is mixed and then gravity fed into a progressive cavity pump. The concrete is then pumped through a hydraulic hose. The hydraulic hose then feeds the concrete into an extrusion nozzle held by the second part of the system, in this case, an ABB six-axis robotic arm. The robot being used to print is an ABB IRB 6640 with a 2.8-m reach. It is a six-axis robotic arm with a quoted absolute accuracy of  $\pm 1$  mm. The robotic arm is used to position the nozzle for material deposition. The nozzle used has an internal diameter of 25.4 mm, which results in an extruded bead of approximately 25 mm in width and 15 mm in height. An image of the overall system can be seen in Figure 1.

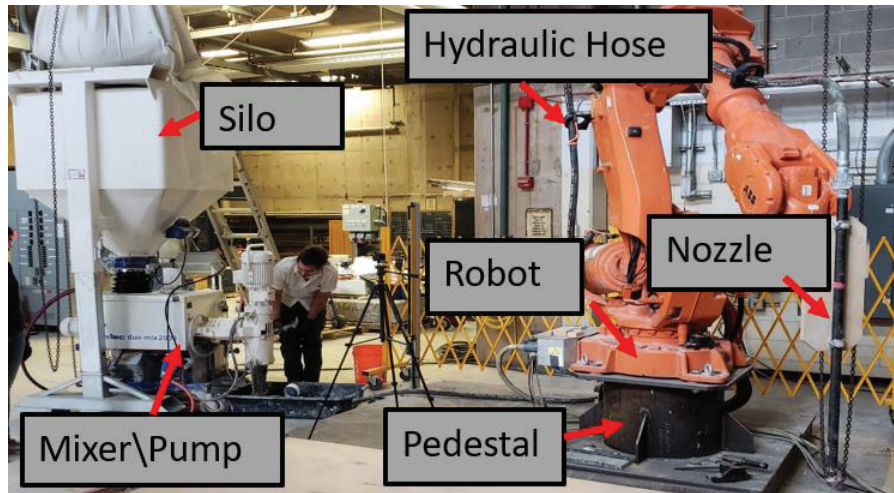


Figure 1: Robotic concrete printing setup

In order to prepare and process a structure for printing with the robotic arm system, a typical AM digital thread is followed, with some added steps required after toolpath generation. This starts with the digital model (.STL) of the intended print. The model is then sliced and a toolpath is generated for the print. The toolpath for this system can be generated using slicing software such as Cura, or by manually coding the toolpath using a software such as MATLAB. However, at this point, it is necessary to modify the toolpath to fit with the six-axis robotic arm, rather than a traditional three-axis gantry. Generated toolpath points are imported into Rhino's Grasshopper using an extension called HAL. Once in Grasshopper, point orientations are then assigned, which is necessary to take advantage of more complex deposition paths, such as printing off-axis. Once the toolpath points and point orientations are generated, the code is converted into the ABB robotic language, Rapid. The Rapid code is then loaded onto the ABB robot controller for printing.

### **Addressing the Challenges and Opportunities of Robotic-Arm Printing**

While the use of a six-axis robotic arm can offer significant geometric advantages in the printing of architectural-scale concrete structures, it also suffers from significant challenges that must be addressed. In this section, we discuss potential methods to address such challenges associated with (1) minimizing travel moves in toolpath design, (2) expanding the achievable build volume, and (3) inserting pre-fabricated components into the structure being printed.

#### *Toolpath Design to Reduce Travel Moves*

Due to the distance from the pump to the nozzle, toggling the pump on and off results in a significant delay to start and stop the flow of concrete. However, the concrete material also cannot simply be retracted as is common in filament-based material-extrusion systems. This means that, to print most consistently, few-to-no travel moves should be employed during a print. This means the development of the print toolpath is a non-trivial step that is required to prevent over-extrusion or unnecessary travel moves.

The most common approach to toolpath generation in extrusion AM is to deposit a series of shells defining the outer perimeter of a slice first. Once the shells are deposited, the system deposits the infill, which results in the final solid or semi-solid printed layer. However, depending on the approach taken to shell and infill deposition, a single slice may require numerous travel moves. Travel moves require the extrusion nozzle to move from one point in a layer to another without depositing material. Due to the challenges with accurately stopping the flow of material as mentioned earlier, it is crucial that any given toolpath for concrete deposition be designed in such a way as to minimize or eliminate the need for travel moves. Figure 2 demonstrates the conceptual difference between the traditional approach (Toolpath A), in which a shell is first deposited followed by an infill, and the approach required for concrete deposition (Toolpath B), in which one continuous bead of material is used to complete the entire layer.



Figure 2: Toolpath A is an example of a toolpath only achievable using travel moves. Toolpath B is able to be printed with no travel moves.

In some cases, depending on the geometry of the printed layer, travel moves cannot be avoided. For example, when a layer does not have continuous cross section, travel moves are required between different sections of the geometry within that layer. An example of one such geometry is shown in Figure 3. In order to print the layer in this figure, travel moves are required to span the gaps on the right side of the structure. One possible solution for reducing the number of travel moves in this situation is to print multiple layers of a single section between travel moves. In conventional printing, each layer is fully printed at a single height before the nozzle is raised to deposit the subsequent layer. However, this method requires travel moves between each section on each layer. By traveling to a section and printing several layers before traveling to another section to print another set of layers, travel moves are drastically reduced. Figure 3 (left) shows how printing in sections can reduce the travel moves in this case to two travel moves, whereas conventional slicing as represented on the right would have many more travel moves. This approach is only achievable due to the flexibility of the six-axis robotic arm. The use of a gantry-based system would result in collisions with the previously printed sections. By printing sections further away first, then printing sections closer to the arm, collisions can be avoided. The robot also has the ability to reach over printed sections where necessary.



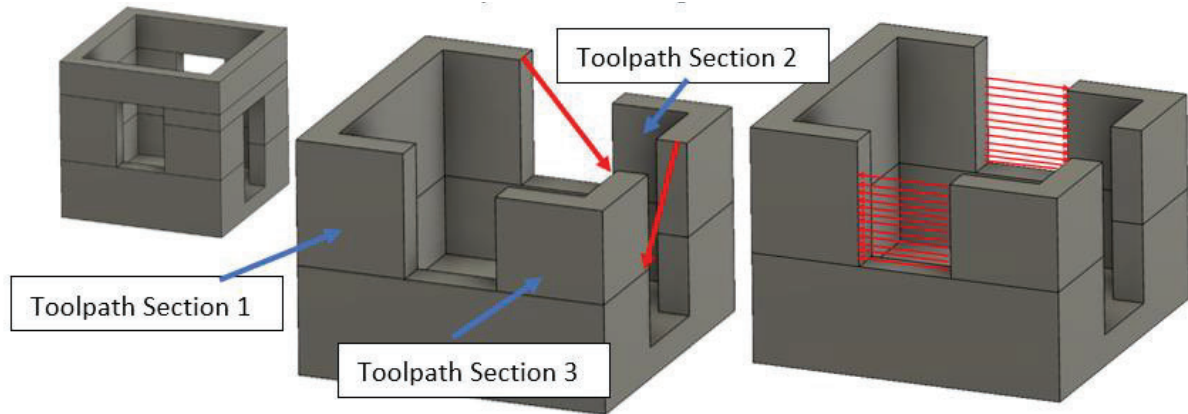


Figure 3: Example of non-continuous geometry and resulting toolpath sections reducing travel moves (in red) on the left and using conventional slicing on the right.

### *Increasing the Achievable Build Volume*

One of the most significant drawbacks of a robotic arm is its limited reach. Whereas conventional gantry systems have been demonstrated to be capable of scaling to construction-size structures, achieving similar deposition sizes with robotic arm systems is challenging. To address this limitation, the robotic arm used in this study was strategically modified to increase the achievable build volume. Specifically, whereas the nozzle is held in a vertical orientation during the printing process, not all of the axes are being used at their full potential. The fourth and sixth axes, in particular, do not play a major role in the printing process when the nozzle maintains a constant orientation. Noting this, an extension was designed to be controlled by the unused axes. By adding this extension to the unused axes, it becomes possible to print significantly larger structures than were previously possible in the robot's default state.

In the case of the system used in this study, the extension added to the robotic arm expands the printing volume in both the X–Y plane, as well as the Z direction. By adding the extension arm perpendicular to the sixth axis, the reach on the X–Y plane is increased. By using a 0-degree angle on the sixth axis, the robot's reach in the X direction is increased by the length of the extension. Conversely, by using an axis angle above 90 degrees, the nozzle can also reach closer to the robot. By doing so, the robot was able to extend its range without just shifting the print away, but keeping the print area close to the robot.

By using the fourth axis, the reach of the robot can be extended in the Z-direction. Adding an extension parallel to the sixth axis allows the robot to reach farther down than in its default state. While the fourth axis is at 0 degrees, or in the down position as shown in Figure 4, the robot reaches down the length of the Z extension. When the fourth axis is at 180 degrees, as in the Figure 4 in the up position, the robot reaches up the distance of the Z extension. This maneuver requires the nozzle itself to be rotated 180 degrees, in order to keep the direction of extrusion downwards. In doing so, this extends the print volume height by double the length of the extension in the Z direction. However, this enables the robotic arm to reach down below its base. This requires the robotic arm to be raised by a height at least equal to the height of the Z-extension. By combining

both the XY-extension and the Z-extension methods, a build volume can be achieved at a scale far beyond the standard reach of the robot. The full extension setup as implemented can be seen in Figure 5.

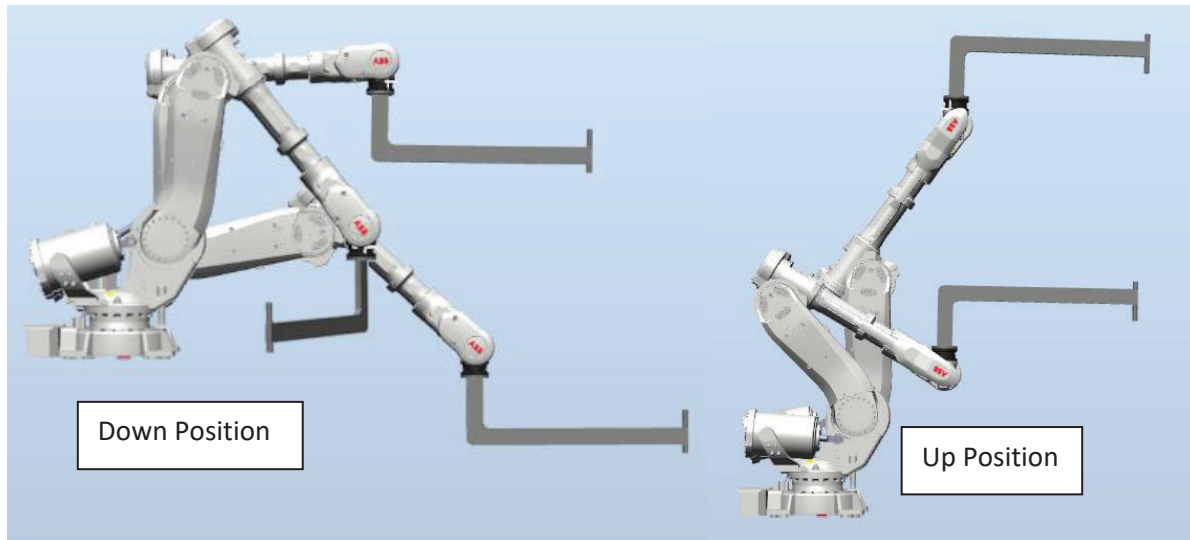


Figure 4: The extension in both the down position on the left and up position on the right.

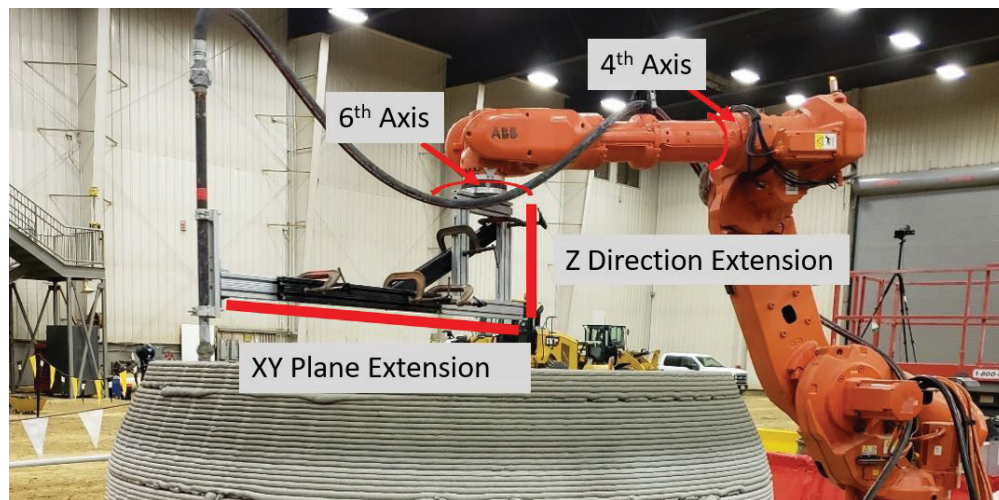


Figure 5: Extensions on the robotic arm to increase the build volume.

The use of extensions does come with limitations. For example, they sacrifice much of the freedom of nozzle orientation, as well as the X–Y plane reach when the fourth axis is in its 180-degree position. When using the X–Y plane extension, a much larger robot movement is required in order to angle the nozzle forward and backward. This can cause such maneuvers to be out of reach of the robot or may cause collision with the printed structure. As discussed, when printing with the flipped fourth axis, the base of the extension is below the extrusion point of the nozzle. This can cause a collision when the cross section of the print is longer than the length of the X–Y plane extension. Figure 6 shows the extension in the fourth axis flipped position with the red line representing the maximum depth of a layer's cross section the robot is able to print. Ultimately,

the design of the printed structure must take these limitations into consideration in order to prevent a collision with the structure.



Figure 6: Extension on the fourth axis to extend reach in Z direction. The red line represents the maximum depth of a layer in this orientation.

#### *Incorporating Multifunctional, Embedded Components*

Concrete used alone does not make for useful structures; in concrete construction there are often many pre-fabricated components that are embedded to increase the strength of the concrete as well as add more functionality to the manufactured structure. For example, the tensile strength of normal-weight concrete in flexure is 10–15% of concrete's compressive strength. This means that, while concrete is very strong in compression, it is unsafe to use concrete alone under significant tensile loading. This is why modern concrete construction must use reinforcement; without it, concrete can crack and crumble [8]. Similarly, in a concrete wall in a building, there are often windows, electrical wiring, plumbing, and various other embedded components. In conventional concrete construction, workers must manually install these components after the concrete cures. This often involves cutting the concrete to place the prefabricated components.

When using a robotic arm to additively manufacture concrete structures, reinforcement and multifunctional pre-fabricated components can be directly incorporated during the printing process. This is further enabled by the flexibility of the robot's end-effector. By either adding a tool change to the robot, or by integrating a multi-process tool to the robotic arm, it can gain the ability to lay the necessary reinforcement (e.g., rebar) as well as the concrete. This can eliminate the time-consuming process of assembling the reinforcement prior to pouring the concrete in conventional construction. Similarly, a tool change or second robotic arm can be used to grip and place larger, more complex pre-fabricated items within the concrete structure during printing. This requires a designer to incorporate a cavity to accept the foreign component in the digital model of the desired concrete geometry. An example of this is shown through the mid-print, robotic placement of a window seen in Figure 7





Figure 7: Robotically embedded, pre-fabricated structure in mid-print

One consideration that must be made when embedding into concrete is the potential error in geometric accuracy of the printed structure. During the printing process, vibrations in the system, imperfect extrusion speed and material properties, and deformation due to the weight of stacked layers can affect the geometric exactness of the manufactured structure [9]. As such, the potential for geometric error must be accounted for when designing the structure's toolpath for embedded components. This compensation takes the form of X–Y tolerances in the embedding cavity; for the system described in this paper, the cavity is designed to be significantly larger than the component so that the pre-fabricated part can be lowered into the structure without interference.

### **Case Study: NASA's 3D-Printed Habitat Challenge**

Based on the robotic arm system and the considerations discussed in the previous section, we were able to successfully print the first fully-enclosed, self-supporting concrete structure at an architectural scale. The structure seen in Figure 8 is the result of our participation in NASA's 3D-Printed Habitat Challenge; this challenge's requirements dictated some of the decisions made regarding the design of the structure. Specifically, the challenge required the printing of a 1/3 scale model of a habitat designed for use on Mars. The total floor area and height required for the full-scale model was 100 square meters with the ceilings of at minimum 2.25 meters. The resulting printed structure printed was 3.7 m tall and consisted of two cylinders, each topped with a cone printed at the concrete's self-supporting angle (approximately 70 degrees from horizontal). The walls of the structure were 20 cm thick and included three pre-fabricated windows (defined by competition rules) embedded within the printed concrete structure.

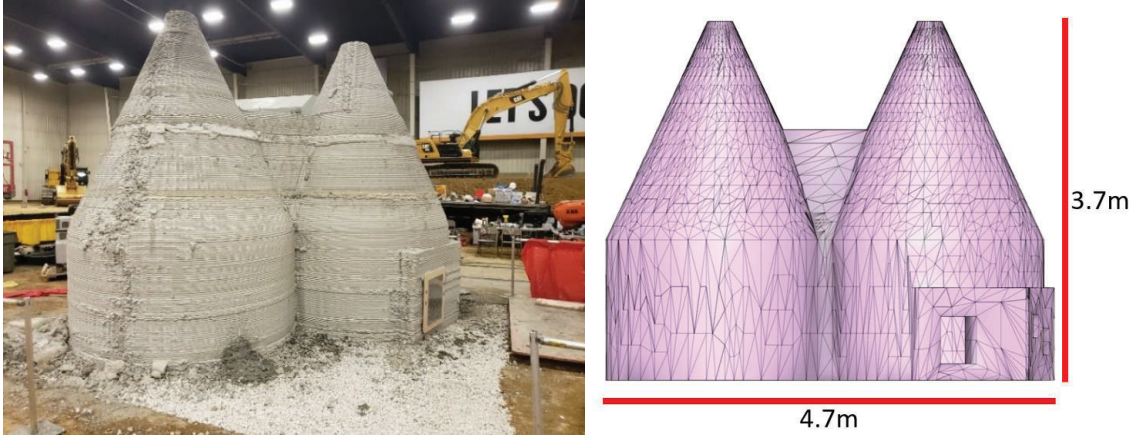


Figure 8: First fully-enclosed, architectural-scale, self-supporting, concrete printed structure built at NASA's 3D-Printed Habitat Challenge.

To successfully print this structure, the three considerations of toolpath moves, build volume, and *in-situ* embedding had to be employed for the robotic arm system. The first consideration involved the tool path design around each of the required windows. Each of the windows resulted in a discontinuity in the wall's toolpath. To reduce the number of required travel moves, the cross-sectional area was broken into three distinct regions as seen in Figure 9. Each section was then printed for the height of the window before moving to the next section. This minimized unwanted material extrusion by completing the entire windowed portion of the structure using only four travel moves. If each layer had been printed in its entirety before moving to the next, over 50 travel moves would have been required to print the windowed section.

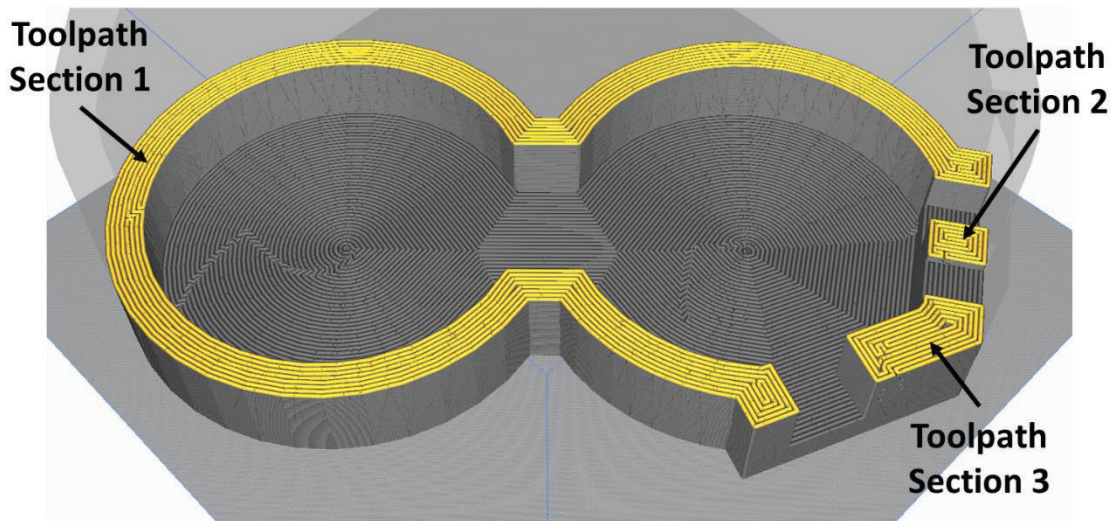


Figure 9: Sections of toolpath made to reduce travel moves for the competition print.

Due to the large volume of the required structure, the printing system also needed to incorporate the use of both XY- and Z-extensions as detailed earlier. Without these extensions, the robotic arm would have been incapable of reaching every point of the toolpath while still maintaining the nozzle's vertical orientation. The necessary self-supporting angle for the conical

sections in particular required the structure to be much taller than the robot could reach in its default state. By adding an extension to the end of the arm, the print volume was expanded enough to print the entire structure. The extension had to be 1.5-m-long along the X–Y plane and 0.5-m-tall on the Z axis. By using the sixth axis to rotate the extension in the X–Y plane, the robot could reach each full layer; by flipping the fourth axis, the robot was able to print the upper layers of the conical structure.

Finally, the placement of the prefabricated windows required the robotic arm system to be capable of secondary operations. However, while six-axis robotic arms are generally capable of performing multiple tasks through tool changes, the need to maintain continuous extrusion did not allow the same arm to be used to both extrude concrete and place the windows. As such, a second robot, an ABB IRB 6600 with a 2.8-m reach, was used and coordinated with the printing arm to embed the windows within the structure mid-print. By positioning the printing robot at the locations of the bottom vertices of each window, the position and orientation of the windows could be found before the print took place. Once all three window positions were found, the second robot could be taught how to place each window by manually controlling the robot to place the windows into the determined position. The robot could then automatically repeat these maneuvers during the print. To compensate for any potential geometric errors in the concrete structure surrounding the windows, the window cavities were designed to be wider than the actual pre-fabricated window. Through previous experimentation at a smaller scale, a gap of 2.25 cm was added on either side of the window. However, during the final print, it was found that this added tolerance was not sufficient, likely due to the larger scale and additional unforeseen vibrations in the added XY-extension. A failed automatic window placement can be seen in Figure 10. This demonstrates the need for robust closed-loop control in the printing system to ensure that foreign components can be reliably embedded as needed.



Figure 10: Failed placement of window due to geometric errors in the concrete

### **Conclusion and Future Work**

This paper addresses the system used to print the first fully-enclosed, self-supporting, architectural-scale concrete structure. Through this discussion, it also details the use of robotic arm

as a viable platform for large-scale deposition of multifunctional concrete structures. However, to achieve this, it is necessary to consider the opportunities and limitations of the system. These include minimizing travel moves in toolpath design to account for the flow of concrete material, expanding the achievable build volume through the addition of XY- and Z-extensions on unused axes, and inserting pre-fabricated components into a structure by coordinating with a secondary robotic arm. By accounting for these considerations, robotic-arm deposition of concrete can be an advantageous alternative to gantry-based systems, especially in remote or austere environments.

Next steps will involve integrating a closed-loop system to allow for better process control with less human input into the system. This will include the integration of sensors for *in-situ* monitoring of print quality and adjustment of print parameters to maintain consistency throughout the print. In addition to a closed-loop printing system, other methods for adding embedded components into the print are being developed. This includes automated placement of reinforcing elements by using the multi-tool capability of the robotic arm. Finally, we will seek to more thoroughly leverage the potential for out-of-plane deposition that the robotic arm enables, as this is one of its key advantages when compared with traditional gantry-style systems.

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