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CONCRETE ADDITIVE MANUFACTURING SYSTEM DESIGN FOR EARTH AND MARS

A Thesis in

Additive Manufacturing and Design

by

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ABSTRACT

This work explores additive manufacturing of concrete using a six-axis robotic arm and its use in large scale, autonomous concrete construction. Concrete additive manufacturing uses an extrusion method to deposit concrete beads in layers to create a three-dimensional shape. This method of construction has been found to have many uses and advantages in both terrestrial and extraterrestrial applications. The lack of formwork and the autonomous nature of this manufacturing method allows for new geometries and materials to be printed where it may not be safe for humans to go. Autonomous construction has been suggested as a method of creating habitats for humans on Mars and on the moon using *in-situ* materials.

This thesis presents research towards systems that could be used on the surface of Mars as well as on Earth, which required increasing the capabilities of a six-axis robotic arm along with overcoming system challenges to achieve deliverables for the NASA's "3D Printed Habitat Challenge". The system designed increased the build volume, integrated embedding, printed non-coplanar sections, and addressed issues with continuous extrusion and implications of toolpaths that minimized travel moves. The system was demonstrated by printing a one-third-scale Martian habitat for which the team printed the first fully enclosed structure at an architectural scale without the use of support.

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Chapter 1

INTRODUCTION AND MOTIVATION

1.1 Motivation for Concrete Additive Manufacturing

Concrete is an ancient material that dates back millennia and is still the most used human-made material today [1,2]. The inexpensive composition and abundance of concrete, along with its strength and the form-fitting nature of wet concrete, has driven its ubiquity in the world. The material has proven itself over the millennia, but current construction methods using concrete limit its full capabilities. Formwork, into which wet concrete is poured, gives the concrete its final shape. This means that a negative mold needs to be made in the shape of the desired concrete structure, which limits the possible shapes of the concrete structure to what formwork can be made or afforded. Formwork contributes significantly to the cost of concrete construction and can cost between 35–60% of the overall cost of construction [3]. Formwork's cost structure of is that of increased cost for increased complexity. This makes mass customization expensive and, therefore, leads to simpler designs, a vast majority of them being comprised of straight walls and 90-degree angles.

Additive manufacturing (AM) is a method of manufacturing that makes a three-dimensional (3D) object by building it in layers. These layers are formed through the deposition of material or the fusing of existing material in layers. The significance of this method is that is does not require molds or formwork for a part's fabrication. Concrete AM uses extruded concrete that is deposited in layers without the use of formwork, which affords a number of benefits. The cost of formwork is eliminated along with the cost penalties of complexity related to formwork.

This also reduces or eliminates labor associated with concrete construction. These attributes of concrete AM make it a candidate for both mass customization as well as use in hazardous conditions.

Construction sites here on Earth can be hazardous and concrete AM can be a good option to prevent injury. Extraterrestrial construction, however, can pose hazards far too dangerous for humans to be on site at all. NASA and SpaceX both have plans to put humans on the surface of Mars [4,5], but as plans move forward there are questions about the safety and cost of such missions [6]. It is important to be able to find a solution that is safe and cost effective, such that the many benefits can be gained of conducting a manned mission to Mars [7]. One of the major cost drivers of sending missions to Mars is the mass of the launch vehicle and payloads required. This means finding methods that can use materials available on Mars for construction, which will reduce the amount of mass needed to be launched from Earth. Autonomous construction through concrete AM could be a unique fit to allow for the construction of the habitat before humans arrive on Mars or the Moon by using materials found on their surfaces.

1.2 Advantages of Additive Construction on Earth

Concrete AM or, more broadly, additive construction brings unique capabilities that enable new ways to envision construction. Construction has several different motivators, i.e., safety of the construction workers, needs of the client, and cost of construction. The decisions made on construction sites must take all three of these into consideration. When introducing a new construction method, these motivators remain but costs and benefits of the methods can be very different. Concrete AM changes the human interaction with construction, which creates new possibilities for the client as well as different cost structures as compared to conventional concrete construction.

Concrete AM uses a machine that controls the deposition of concrete. The removal of a human at the point of extrusion allows for less strict safety protocols and a reduced risk of human injury. The robustness of the machine allows for construction on sites that otherwise would not be accessible to humans [8], which could be due to hazardous conditions such as where chemical or radioactivity risks are high, or within a conflict zone. This may be most helpful, though, on everyday construction sites where mistakes are common. In 2018, an U.S. construction sites there were over 1000 deaths associated with construction, 70 of them associated with concrete construction [9]. Human involvement with construction adds risk; by removing the human element, lives can be saved.

The next motivators that concrete AM addresses are the needs and desires of the client, with one of the most important being cost. Increasing the design freedom and decreasing the cost of custom designs creates more options for the client within their price range. The lack of formwork eliminates the cost and time associated with formwork, but the concrete AM machine is an added cost. Concrete AM removes the requirements to have identical (or only a few different) designs for concrete structures, as each print can be different, which allows the client to have full control and enables mass customization. The machine's cost can be justified by the need for mass customization or the need for short lead times. If a client wants a non-repeating aesthetic element or non-straight walls, the cost of the custom formwork—along with not being able to reduce the cost by the reuse of formwork for multiple elements—often increases the costs beyond what the client is willing to pay. However, concrete AM can reduce many of the costs of construction [10]. It allows for custom prints for every print at no additional cost beyond the cost of the designs.

Without the need to build formwork, time can be saved. If a mistake is made on a job site, if the client changes the design, or if spatial geometries on the jobsite are different than planned, it can take weeks to change or replace the formwork for the concrete structure or acquire new precast elements. Designs must be provided well in advance for these long lead-time concrete parts [11]. Concrete printing has no lead time, allowing for design changes just hours before constructing the concrete structure. The automated nature of concrete AM also reduces the possibility of human error as machines do what they are programmed to do.

1.3 Advantages of Additive Construction in Space

The advantages of automated construction become even more critical in space, especially on a planet like Mars. The unique challenge of creating a habitat on the surface of Mars goes beyond the measures taken in the past to keep humans safe in space. Missions to the Moon have been relatively short and missions on the International Space Station (ISS) are relatively close to the Earth [5]. A mission to Mars will stretch both of these aspects with the additional challenge of landing on another planet. The long distance to and limited communication with a Mars base pose a serious risk to humans as there will be no way of returning to Earth quickly if a mission becomes too risky. This will require precautions to be made, such as preparing for the mission as much as possible without humans being in harm’s way. This means making autonomous missions to these sites to prepare safe habitats before humans arrive, such that construction failure does not jeopardize crewed missions [6].

Another challenge of building habitats on Mars is the quantity of the materials needed to build there. The habitat pieces to be assembled must be either brought from Earth, or a manufacturing method needs to be developed that uses *in-situ* resource utilization (ISRU). As with construction on Earth, cost is a driving factor for construction in space. To meet the needs of astronauts on Mars, a certain habitat size is required, in addition to radiation protection [12]. This requires a large amount of materials, which must either be brought from Earth or gathered on Mars. Using concrete AM, material can be used *in situ*, which drastically reduces the launch mass, which reduces the cost of the mission [13].

1.3 Research Contributions

This research designed a system to print concrete using a six-axis robotic arm for Earth use as well as to demonstrate the system as part of NASA’s 3D Printed Habitat Centennial Challenge, which focused on systems that could demonstrate how printing a habitat on Mars could work. The research also tests a hypothesis of printing a raised slab without the use of support. The 3D Printed Habitat Challenge specified a set of deliverables that the system should be capable of making. This meant stretching the capabilities of a six-axis robotic arm as well as overcoming the issues faced with the design of the required deliverables. The scope of my work included design of the printing system, control of the system, as well as helping other team members design structures that were compatible with the printing system. Then, with the system that was developed, the goal was to test the system’s capability to print raised slabs without support.

The 3D Printed Habitat Challenge set out multiple challenges that involved physically printing geometries as well as designing what a printing system and habitat could look like on Mars. In order to accomplish these tasks, they had to be done within the constraints of major system elements that had already been purchased for previous levels of the competition. This included the robotic arm and pump system used in previous levels of the competition.

The next contribution tested the hypothesis of being able to print on a mesh laid autonomously by a wire-reinforcing system. This included multiple tests to find the different possible parameters for printing an overhanging concrete feature. These parameters include wire spacing, deposition height, and the effect of drooping of the mesh.

1.4 Overview of Thesis

In this thesis, Chapter 1 introduces concrete additive manufacturing through a discussion of concrete's use today and the benefits and shortcomings of concrete construction. It then speaks on the motivations for the developments of concrete AM by talking about the uses of it, both improving standard concrete construction as well as its ability to enable novel uses of concrete, on earth and on Mars.

Chapter 2 presents how others have approached both concrete AM as well as creating habitats on Mars. It lays out all the work that has been done and discusses what is missing and how this thesis fills some of those gaps.

In Chapter 3 the printing system is described along with system improvements that were made as a contribution of this thesis. This chapter present the basic concepts of a concrete printer and how the system addressed those elements. The system control is discussed along with the improvements made to the system to address the reach of the robot, the toolpath limitations, and the embedding capability of the system.

Chapter 4 presents a case study performed with the system along with how system improvements were implemented and allowed for the completion of NASA's 3D Printed Habitat

Centennial Challenge. The case study included multiple required deliverables, which required new improvements to the system as the challenges progressed.

Chapter 5 also shows a use of the system through testing of a hypothesis that raised slabs can be printed without the use of support. The hypothesis was broken into questions that were then tested.

Chapter 6 concludes this thesis by summing up what was accomplished and provides recommendations for is next in concrete AM and in the future of AM for use on extraterrestrial planets.

Chapter 2

LITERATURE REVIEW

2.1 Concrete Additive Manufacturing

For producing architectural-scale structures with concrete AM, there are 4 main printing system architectures: gantry systems, cable-driven systems, robotic arm systems, and swarm printing 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 print entire structures with no assembly required [14][15]. Their systems use large frames that move a nozzle in each Cartesian 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 small gantry-based plastic printers. This makes for a simple printing system design as well as a simple control system [8]. However, a key downside to gantry-based systems is the required scale of 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 processes. This can detract from 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 [16], 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 Lab (ORNL) has demonstrated the use of such as system, which uses a series of five fixed points combined with cables to hold the nozzle assembly [17]. By pulling on the five cables, the nozzle can be positioned in 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 three-axes movement, 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, the system does require a large area for the equipment to be sufficiently separated such that the cables do not interfere with the structure being printed.

Finally, robotic-arm printing is another 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 [18]. This approach offers several benefits when compared with gantry or cable-based systems, due specifically to the flexibility of robotic arms along with their compact form factor. Their size simplifies transportation to remote environments when compared with gantry-based systems, whereas limited assembly on site 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 [8]. 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 more limited scale; robots have limited reach and must be moved to print structures larger than their reach [19].

Robots that are mobile can then be paired with more robots which can print simultaneously which is called swarm printing. This method uses robots, often robotic arms, to print at multiple points simultaneously. This approach allows for better scalability as well as efficiency as compared to a single robot. Although accurate positioning of the robots are a challenge, especially on uneven terrain [20].

2.2 Automated Construction in Space

Many ideas have been proposed over the years for automated construction in space because of the benefits of safety and the ability to build before the arrival of astronauts. While the concept is simple, there are countless ways that this problem can be approached. Each has different costs and benefits and requires further research and a better understanding of the context of these solutions. Solutions depend on mission size, duration, and mission objectives. A plan to start a space colony of 500 people on Mars and a four-person mission with no plan for future missions will lead to very different solutions. Each proposed approach will have an amount of mass needed for construction on Mars—this mass is equipment and material—and the scale of the mission will determine how to balance the ratio. The balance being considered is that of bringing more equipment enabling greater use of Martian materials, or bringing material rather than equipment to remove material processing steps.

Cesaretti et al. [21] propose a strategy for construction on the Moon that would use a combination of Lunar regolith, as well as an inflatable interior shell. This method proposes inflating a pressurized structure that could be brought from Earth in a compact form factor. The inflated structure would then be covered using Lunar regolith that is bonded together using the additive manufacturing technology used by D-shape, which uses droplets selectively jetted onto the surface of each powder layer to provide strength to the regolith piled on top of the inflatable structure. The additional layers of bonded Lunar regolith would then protect the occupants from radiation, micrometeorite impacts, and the thermal environment. While bringing material from Earth is necessary for habitat construction, it is best if the consumable portion of what is brought is minimized [13]. Within this plan a large component of what needs to be brought is a consumable, that being the binder integrated into the structure.

Other plans also require large construction equipment sent from Earth, but the equipment is reusable for a modular construction as Kading and Straub propose [22]. Their plan uses a fused deposition modeling (FDM) approach, in which basalt, found abundantly on the surface of Mars, is melted and extruded layer by layer into the 3D shape of the habitat. First triangular sections are created within the spacecraft to make a large geodesic dome in which the printing operation takes place. Then a large gantry is assembled in the dome to print the habitat modules. While this approach also uses large equipment transported from Earth, it is not a consumable, which allows for scalability as it can be used multiple times. However, a large amount of energy is needed to melt the basalt for extrusion and the equipment seems to be single purpose, which increases the amount of equipment needed to be brought from Earth.

Another gantry approach intended for implementation on the Moon is proposed by Khoshnevis et al. [23]. This method uses *in-situ* resources to create a cement through the processing of lunar regolith. Water would then be obtained from the Moon through chemical methods, although more recent findings suggest that water may be obtained from the poles. The gantry system would be on tracks to make the movement of the gantry simpler for construction of large habitat structures. While the processing of the material will use considerable amounts of energy, this is a relatively low energy process as compared to a thermal extrusion process, which would likely require high energy storage.

A different binder method was explored by Buchner et al. [24], which uses phosphoric acid as the binder. While it would have to be transported to the extraterrestrial body, the rest of the regolith would require minimal processing. This would also require a small amount of water, which may be difficult to find on the Moon and Mars. While this method seems promising, more testing is needed to develop the best methods for printing the material, as well as to gain an understanding of how the proposed binder could work with materials on the Moon and Mars.

As is common within early research and work towards a lofty set of goals, such as autonomous habitat construction on a different planet, there are many unknowns and ideas that are only a first step. The research presented herein works to increase the technology readiness level (TRL) of some concepts most of which are currently TRL 1–3. This is done by identifying specific solutions that can be adapted from automated construction techniques being developed for Earth [25].

Chapter 3

SYSTEM DESIGN

3.1 Concrete Printing System

A concrete printing system design must include a method of preparing material to be printed, a method of transporting that material to a nozzle, and a method of moving that nozzle in the pattern needed to print the object. The system designed and used had additional motivations behind it, primarily, printing for construction on Earth, but it was also designed to demonstrate what autonomous construction on Mars could look like. These motivations led to a system that is primarily a concrete mixer/pump connected to a robotic arm (Figure 3-1) [26]. A silo gravity feeds or pneumatically feeds material into the mixer/pump, which is an m-Tec Duo Mix 2000. The Duo Mix adds water and mixes the concrete before pumping it through a hydraulic hose. The hose is then attached to a nozzle that is carried by an ABB IRB 6640, which is a 2.8-meter-reach industrial robotic arm. This allows for a printing process that continually mixes dry powder into wet concrete and pumps it to the nozzle. The material is then able to cure within minutes as it is deposited soon after it is mixed with water, which activates the accelerant. The quick cure time along with its viscosity allows for the system to operate without formwork.

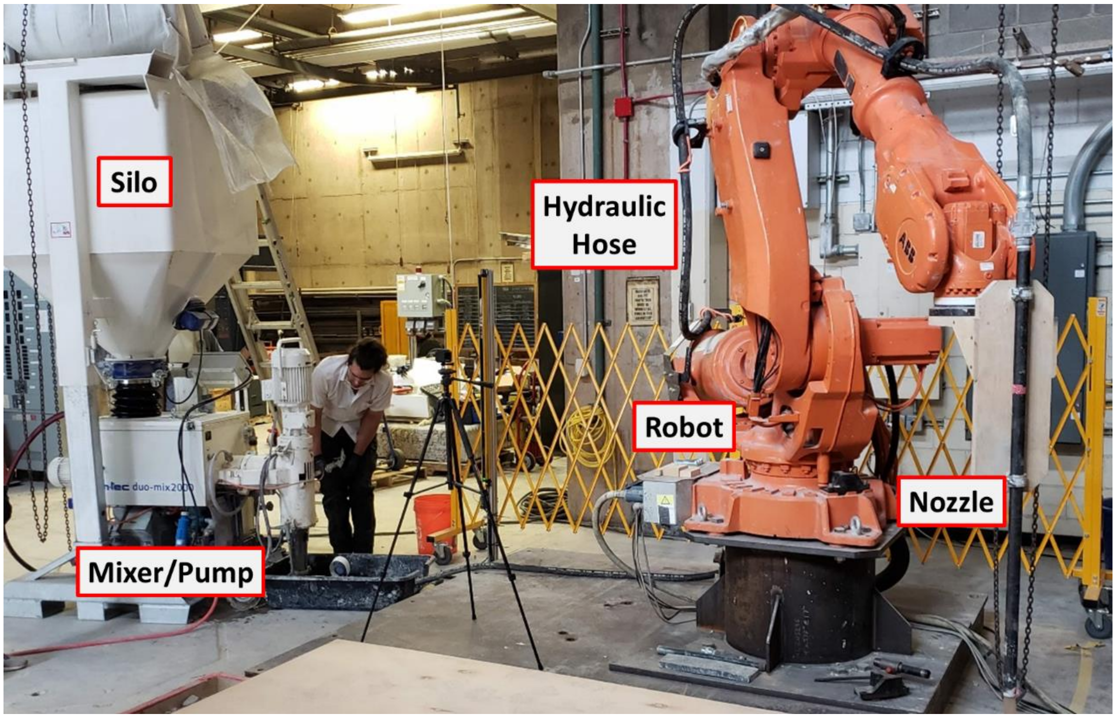

Figure 3-1: Robotic printing setup

The lack of formwork is a key driver for use on Mars because none needs to be assembled, especially since this is often done by hand. It also eliminates the need to bring the formwork from Earth, which would increase the launch mass. The next key factor is the ability to use resources found on the surface of Mars. Members of the team developed a building material, named Marscrete, which mainly uses materials available on Mars to make up both the aggregate as well as the binder of an extrudable and fast-setting geopolymer concrete. This material uses fine basalt aggregate along with metakaolin and some activating solution, which includes primarily water with Na_2O and SiO_2. For this material, over 98% of the materials can be sourced on Mars [27]. This drastically reduces the amount of material needed to be brought from Earth. This material is also able to be printed using concrete AM.

While this system is able to print concrete, there are limitations to the system. The pressure required to pump the concrete is generated at the base of the hose, which causes the hose to be under relatively high pressure and also makes the hose stiff. This pressure means there is a certain amount of potential energy stored within the hose. This and the short curing time make stopping and starting of the pump difficult. The length of pressurized hose causes delays in the extrusion response to the stopping and starting of the pump. When the pump stops, the hose will continue to extrude momentarily, then once the pump starts again, the extrusion is delayed and inconsistent for the moments after the extrusion begins again.

The continuous printing process allows for the printing of quick setting concrete. The concrete must be viscous enough to hold its shape as soon as its extruded as well as set fast enough to hold the weight of subsequent layers without significant deformation or failure. By continuously mixing and extruding concrete, the time between water being added to the cement powder mix and the concrete being extruded is minimized. This allows for use of a quick-curing mix, which is what makes concrete 3d printing possible without the use of formwork. This fast-setting nature of the concrete also creates issues when pausing the printing process. Printing cannot be paused for too long, or else the concrete within the hose and mixer/pump will start to set and create a blockage within the system, potentially ruining parts of the hardware. This creates the necessity to print nearly continuously without long pauses. Depending on the concrete mix, a pause can be considered too long in as little as 10 seconds or, in slower curing mixes, several minutes. This requires a more complex toolpath as the nozzle should not move without extruding concrete.

3.2 Robot

The choice of a six-axis robotic arm was motivated by the availability of a capable system to hold and move the nozzle as well as the ability to demonstrate a solution that could be deployed on Mars. Deploying a system on Mars or the Moon requires that it is able to be transported to the surface of the foreign body, then set up and operated autonomously to harvest, process, and produce material and then subsequently build the habitat. This requires a compact and light system that is able to unpack autonomously and self-assemble. Large format printing systems generally fall into a few categories as discussed earlier: gantry solutions, cable-suspended solutions, swarm solutions, and multi-purpose robotic solutions [8]. A key mechanism for reducing the overall launch mass is to consolidate functions into fewer pieces of equipment. A gantry system is a scaled-up version of most standard desktop plastic extrusion printers and its print volume is limited to what can fit within the dimensions of the printer. This means that a large structure needs an even larger gantry in order to print it. This requires a system larger than the size of the habitats to be printed to be sent to the surface of Mars. Also, because of the required size of the system and the limited size of the rocket, the gantry system will require assembly before use, which may add additional challenges to the system's deployment.

Cable-suspended solutions share some of the challenges of gantry-based systems. While there is not the need for structural elements to run the length and width of the build space, the height needed for the cable connection points are very tall and would require assembly of the anchor points along with placing and securing them in place [17]. This system is also very limited in its capabilities and can only perform the single function of construction.

Swarm solutions use multiple mobile robots that are able to print simultaneously by knowing where each robot is relative to other robots as well as the structure being built [28]. This holds many advantages for construction on other planets because of the limited volume and mass that can be sent from Earth. These swarm robots can vary in size, but they are capable of printing within a theoretically infinite build volume. Depending on the size of each robot, they may have to climb what was recently printed in order to reach the top to continue printing [19]. This solution would both have the scalability required as well as be a low mass system for transportation. While this system appears to have potential, there are technological challenges that are yet to be overcome to build an entire habitat, including 3D positioning and mobility of the robots.

A multi-purpose robotic arm uses multiple axes and is able to move each joint accurately to move the end-effector. The end-effector can hold different types of tools to perform multiple functions. The ability to perform tool changes along with its multi-axis design allows for use in multiple stages of construction as well as embedding items into the build. Robotic arms have been used extensively for many types of AM methods because of its ability to produce a wide range of geometries and ability to perform in different environments [29]. A robotic arm also does not require assembly due to its compact size when folded. This allows for ease of transportation as well autonomous system setup as the robotic arm can assist in the setup process. The arm would then have multiple tool attachments for the different steps of both the construction process as well as post construction needs of the astronauts. The reusability of the robotic arm will allow for the consolidation of hardware needed, ultimately reducing the needed launch mass [13]. For these reasons the robotic is the platform this work chose to focus on.

3.3 Digital System

The digital control of the system produces robot instructional code to move it along the tool path of the print. The first step in creating the tool path is actually to consider the design of the part to be printed. When designing the model, it is important to understand the dimensions of the bead that is laid down when printing. Wall widths should be divisible by the bead width, as then the wall can be printed without over or under extrusion to compensate for the remainder of the wall width that cannot be printed without over extrusion. Also, when designing walls that are not continuous, but rather have dead ends, it is important to have the wall width divisible by two times the bead width so that the nozzle does not have to travel from the end of the wall to the rest of the structure. When designing parts of the structure that are not continuous single width walls, it is important to understand the limitations of the system when printing that part. Some amount of over extrusion will not cause the structure to fail as long as the dimensional tolerances are large enough to account for it.

Once the model is made, then the toolpath can be generated. When generating the toolpath, the nozzle must extrude material in the entire geometry while minimizing travel moves due to the difficulty of starting and stopping the material extrusion. Some travel moves are unavoidable, although it is possible to minimize their number. In the case of a cross section geometry that is not continuous, a travel move must be made from one part of the geometry to the other. Toolpaths are often generated such that a travel move is made between the non-continuous geometries on each layer printed. By instead printing multiple layers of each section of the non-continuous geometry, travel moves can be reduced to only one travel move per section. In Figure 3-2, a structure is represented where a portion of the print has three sections in a portion of the print. Using conventional toolpath generators, the travel moves would look like the image to the right. By printing each section separately like in the images to the left, the travel moves can be reduced to just two.

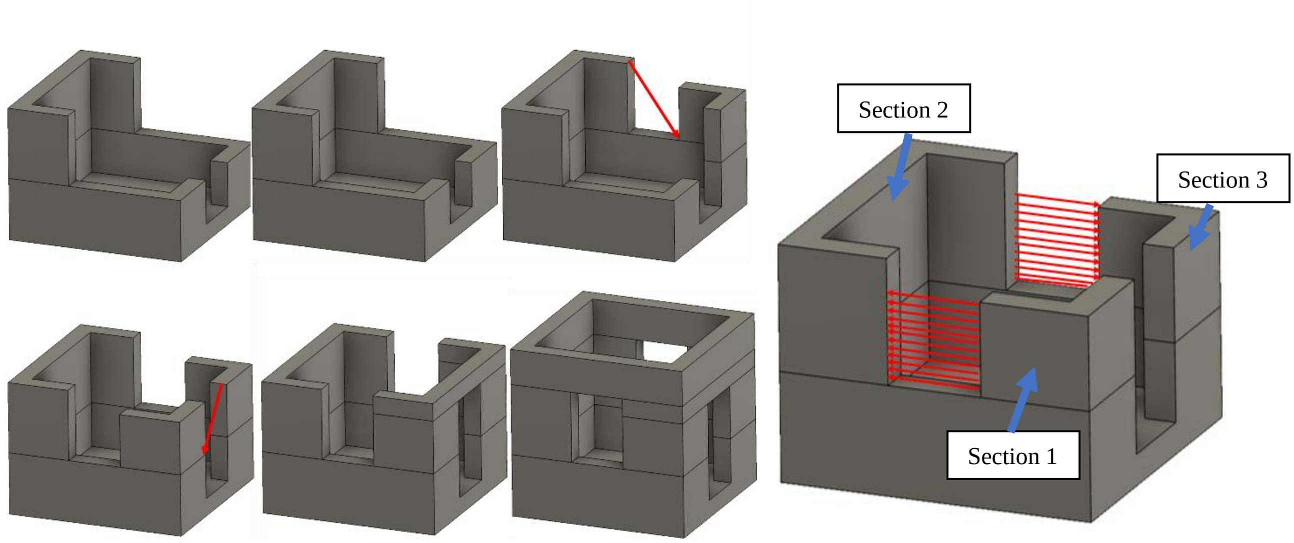

Figure 3-2: Sectioning to reduce travel moves from one travel move on each layer as shown on the right in red to only between each section (two total) as shown in red on the left

Within each section, it is also important to reduce or eliminate travel moves. Figure 3-3 represents two methods of creating a toolpath for a two-dimensional layer for a beam, the top image shows a beam with a parallel line infill, which is common in AM. This infill method uses travel moves to get from one line to the other along with traveling from where the parameter ends and the infill starts. This creates many unnecessary travel moves within the layer. Additional travel moves, even short ones will lead to over extrusion. Tight turns of the nozzle also can lead to over-extrusion. As the nozzle turns, there is overlap of the extruded beads as illustrated in Figure 3-4. By limiting the amount of tight turns and trying to include primarily continuous beads, this over-extrusion can be limited. This method allows for the pumping at a constant rate through the turn as well as the robot moving at a constant speed, rather than speeding up in the turn causing increased vibrations.

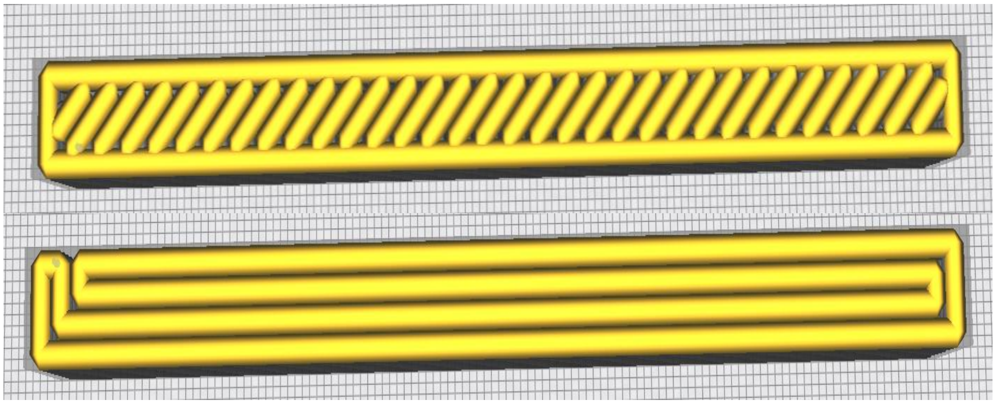

Figure 3-3: Two toolpath design methods, the top one requiring many travel moves and the bottom one without travel moves

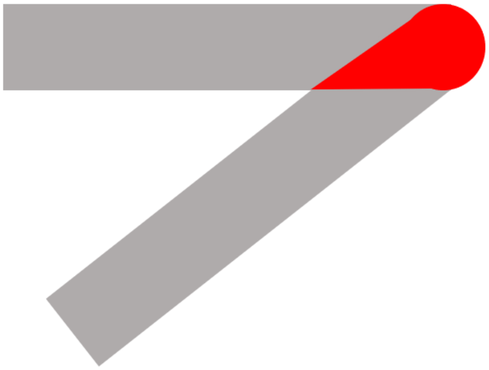

Figure 3-4: Material over extrusion overlap when the nozzle corners

3.4 System Limitations

One of the most significant drawbacks of a robot arm is in its limited reach. While conventional gantry systems have been demonstrated to be capable of scaling to construction-size structures [8], achieving similar deposition volumes with robot-arm systems is challenging. To address this limitation, the robot arm used in this study was strategically modified to increase the achievable build volume. Specifically, as the nozzle is held in a vertical orientation during the printing process, not all of the robot’s six 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 print significantly larger structures than were previously possible in the robot’s default configuration.

For the robot-arm system used in this study, the extension expands the printing volume in both the XY plane, as well as in the Z-direction. By adding the extension arm perpendicular to the sixth axis, the reach in the XY 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 the range of the robot without 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 configuration. When the fourth axis is at 0 degrees, or in the down position as shown in Figure 3-6, the robot reaches down the length of the Z extension. When the fourth axis is at 180 degrees, as shown in Figure 3-7 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 far beyond the standard reach of the robot. The full extension setup as implemented can be seen in Figure 3-6.

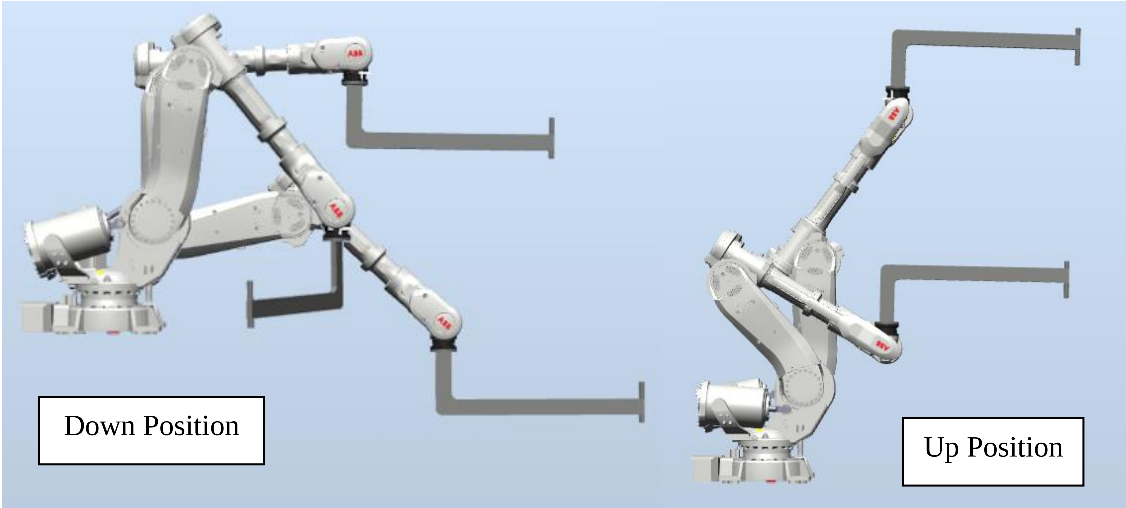

Figure 3-5: The extension in both the down position on the left and up position on the right. By using both positions, the height of the print can be greatly increased.

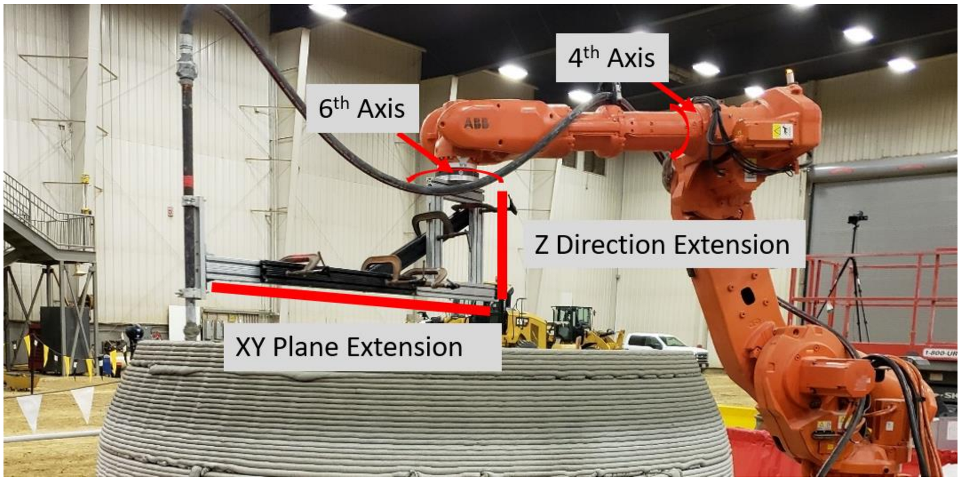

Figure 3-6: Extensions on the robotic arm to increase the build volume.

The use of extensions does come with limitations. For example, they sacrifice much of the freedom of nozzle orientation, as well as the XY plane reach when the fourth axis is in its 180-

degree position. When using the XY plane extension, much larger robot movements are 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 XY plane extension. Figure 3-7 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.

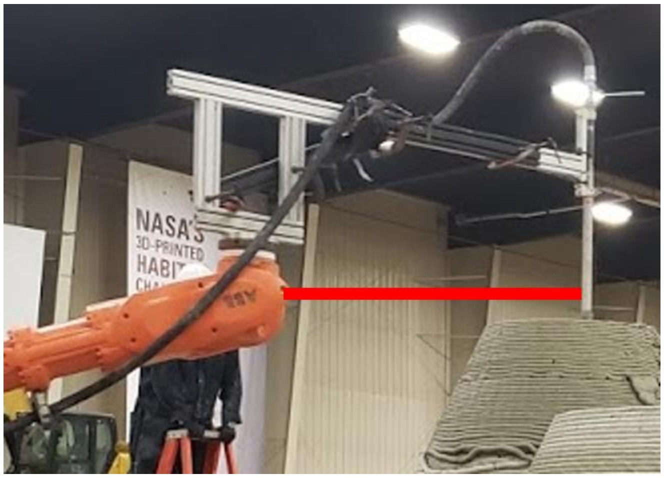

Figure 3-7: Extension on the fourth axis to extend reach in Z-direction. The red line represents the maximum depth of a layer in this orientation.

3.5 System Opportunities

While many of the limitations of a robotic system are able to be overcome, there are also opportunities within construction to take advantage of a six-axis robotic arm, for example, embedding. Concrete 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 element 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 3-8.

Figure 3-8: Robotically embedding a pre-fabricated structure mid-print

One consideration that must be made when embedding into concrete is the potential error in geometrical 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 [27]. 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 XY tolerances in the embedding cavity; for the system used in this research, the cavity is designed to be 2 cm larger than the component so that the pre-fabricated part can be lowered into the structure without interference.

Chapter 4

CASE STUDY

4.1 Research Motivation

One of the primary motivators of this research into system design and system use in the context of both terrestrial as well as extraterrestrial construction was participation in NASA’s Centennial Challenge called “The 3D Printed Habitat Challenge” [30]. This NASA Centennial Challenge was designed to incentivize the development of technology that can be used to create habitats on the surface of Mars. The competition included three phases with multiple virtual and physical construction levels within the phases as seen in the chart in Figure 4-1. The physical construction challenges laid out increasingly challenging tasks to print out different aspects related to making a habitat on the surface of Mars. These aspects started with small cylinders and beams for testing purposes, to complex shapes with overhangs, embedded objects, and large-scale structures. All of this had to be demonstrated with a high level of autonomy to help recreate Martian conditions. Research then continued to better understand how the system built for the 3D Printed Habitat Challenge could be used for applications on Earth.

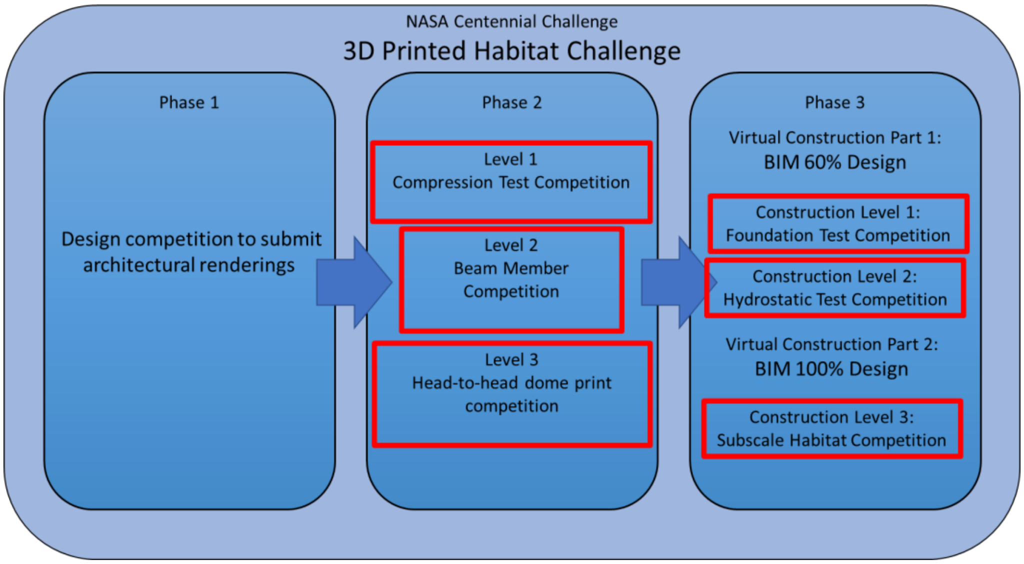

Figure 4-1: NASA Centennial Challenge: 3D Printed Habitat Challenge, three phases of competition with progressing complexity physical construction levels marked in red

4.2 System Application: Dome

The concepts discussed about the system were demonstrated in the 3D Printed Habitat Challenge. In Phase 2 Level 3 of the Challenge, teams were tasked to create a dome shape as seen in Figure 4-2 with a diameter of 1.5 meters and a height of 0.5 meters. This geometry combined a much larger scale as compared to previous geometries in the competition along with the challenge of printing three separate columns that combine into one horizontal overhang. The team chose to print this geometry using the geopolymer Marscrete, which was designed for this Challenge.

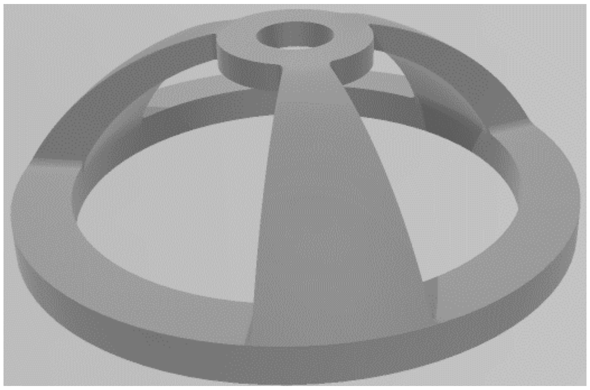

Figure 4-2: Dome design for Phase 2 Level 3 of the 3D Printed Habitat Challenge

The printing was done using an ABB IRB6640 six-axis robotic arm, which held the nozzle that had concrete fed through a 1-inch hydraulic hose supplied by an m-tec Duo Mix 2000 mixer/pump. This allowed for continuous mixing with water of the dry material from a silo, the resulting concrete was then immediately pumped through the hose. All of the dry ingredients were mixed together in the hopper such that only water needed to be added. This meant that the material started its setting process immediately. Marscrete was designed to set within minutes in order for the printed layers to support subsequent layers without deforming. The accelerants caused the material to heat up, which further accelerated the setting process. At the relatively high temperatures of printing on Earth as compared to Mars, the material had to be actively cooled in order to not cure before being deposited. For this reason, dry ice was packed around the spiral pump and pipes along with sections of the hose.

The horizontal overhang required the use of a support structure, as printed concrete cannot be printed with a horizontal overhang. In order to maintain a high level of autonomy, a support structure was developed that could be placed, printed on, and then removed using the robot. The robot was fit with a secondary tool to remove the support structure, which was able to be removed by pulling it through the gap between two pillars. In the case of a habitat being built on Mars, the removal of any support structure will further complicate the system, so designs should avoid the use of support systems.

The robot was programmed using a slicer that developed the toolpath for the robotic arm. Due to the difficulty in travel moves, they were reduced to two travel moves by breaking the geometry into three sections [26]. This was done by printing the initial bottom ring first, then the first arm within one continuous path. Then after the first arm was finished, one travel move was performed to the second arm and again to the third arm where the print was finished. The third arm of the print can be seen printing in Figure 4-3: Dome printing one arm at a time on the support frame

Figure 4-3: Dome printing one arm at a time on the support frame

The dome was successfully printed and passed the minimum strength requirements, which earned the team 2nd place in the competition. The robotic printing approach allowed for the print to be performed in sections, as it was able to reach over the support structure to print as well as be used in a secondary function of removing the support structure. The fast curing rate of the Marscrete material at the high temperatures in which it was being extruded prevented the print from stopping for even brief troubleshooting sessions during the print, which caused over extrusion and a poor surface finish, but the overall structure met all requirements including a minimum pressure of a crush test performed within 24 hours of the print. While the print was completed successfully with the setup used, the dome took up a large portion of the build volume. The build volume of the robot had to be expanded to continue to scale up the prints. This was done by including the extension arm on the robot as discussed earlier.

4.3 System Application: Sub-Scale Habitat

The third construction level of the third phase of the competition used a similar system to print a one-third-scale Martian habitat, which included a rover hatch, a suit hatch, and a circular window near the suit hatch. The full-scale habitat had to have 93 m^2 of floor area with a ceiling height of at least 2.25 m. The design of the habitat was designed using the same methodology as a virtual design that was designed for an earlier stage of the competition. The design included two cones that connected such that the larger habitats could be created in a modular fashion with a mobile robot. However, in order to print with a fixed-base robot, the print was completed as one unit. The limited reach of the robot also dictated the diameter and height ratio needed to meet the internal area requirements. The material used in the construction was a Portland cement–based mix rather than the Marscrete. This was due to the challenge of manufacturing the quantities of Marscrete material required. A Portland cement–based mix was chosen to act as a type of functional simulant of the Marscrete mix. The scoring system for Phase 3 of the Competition also changed to emphasize less the material and more the printing process.

Based on experiments that determined the minimum overhang angle that was printable, 65 degrees from horizontal was possible for the cones and the straight wall portions were found to support 70 degrees from horizontal. These overhang experiments were done by holding a constant wall thickness for the structure, i.e., 20 cm. Although they were not comprehensive, the experiments found that the minimum overhang angle is affected by the radius of curvature in the XY plane, especially when comparing a cone to a straight wall. The angle of the cone along with the inside diameter of the cone dictates the height it needs to be. By adding cylindrical vertical walls below the cones, the height of the area below the cone could be increased to provide more usable space. The internal usable area was then calculated by finding the amount of space within the structure as if a second floor was in the structure, where the ceiling would have been at least 2.25 meters divided by 3, which would be 0.75 meters. The area in the habitat was then added up to be at least $93/9 \approx 10$ m^2.

An additional requirement of the printed habitat was to have penetrations, i.e., a rover hatch, suit hatch, and a circular window. These needed to be set into the structure during printing. A second robotic arm, also an ABB IRB 6600 2.8 m, was used to place wooden frame inserts into the printed voids. The second robotic arm was programed to pick up the wooden frame from a designated point and then to place it into the concrete void such that the top of the frame was flush with the top of the void so that the printing system could then print over the top of the frame and wall surrounding it with flat layers. For the circular window, the wooden frame was used as a shape converter to match the flat walls surrounding it such that the printer did not need to print while it stuck up out of the print. Although the second robot was programed specifically to place the windows exactly where they needed to go, dimensional tolerances made the task challenging and led to mixed results including both successes and failures [26]. One window was successfully placed, but geometric inaccuracies caused by vibrations in the system prevented the other two windows from being inserted completely autonomously.

The resulting structure stood 3.7 meters tall with a maximum width of 4.7 meters as seen in Figure 4-4. The one-third-scale habitat was the first fully enclosed concrete structure without support printed at an architectural scale. The print would have taken 12.5 hours to complete if it was performed non-stop. The 10-hour daily printing limit along with time troubleshooting the printing process caused the print to span over 2 days. The resulting structure showed in the print itself where troubleshooting took place at the different layer lines. The print was able to demonstrate designing to maximize the volume within the print area using an extension on the robotic arm along with the ability to embed using a robotic arm [26]. Despite the successful print, the system was not robust enough to print fully autonomously, the toolpath planning challenges proved difficult to fully negate the issues caused by the lack of travel moves. Moving forward it will be important to incorporate a method to complete travel moves. Another important note is that this structure was built without the use of reinforcement, which makes for an unsafe concrete structure. Concrete structures often crack when exposed to tensile forces. In future builds, reinforcement will need to be added.

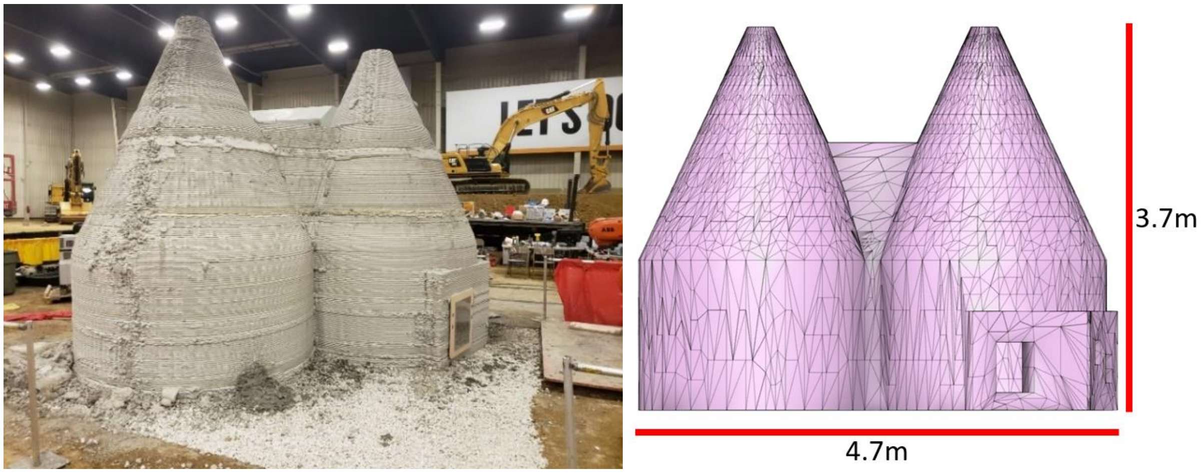

Figure 4-4: One-third-scale habitat printed in Phase 3 Level 3 of the 3D Printed Habitat Challenge

Chapter 5

RAISED SLAB PRINTING

5.1 Introduction and Motivation

As a part of the 3D Printed Habitat Challenge, the habitat had to be an enclosed structure and be built autonomously. By exploiting the concrete's self-supporting angle, the habitat was able to be fully enclosed without the use of support. This resulted in a cone-shaped roof for the habitat, which created a tall structure with a limited amount of floor space. This makes for an inefficient use of material if the goal is simply to make a roof over a given area. Within conventional concrete construction, roofs and additional raised slabs within a concrete structure are made by pouring concrete into formwork built up in place where the roof needs to go, or it is precast and is assembled. Slabs also need reinforcement as there are tension forces in the middle of a beam or slab when held on the sides. Concrete has one tenth of the compression strength when under tension [31]. This requires reinforcement to be laid anywhere there is tension in a concrete structure. Printed concrete is not able to print beyond the self-supported angle of concrete, which was found to a minimum of 60 degrees from horizontal. This means that printing a raised slab requires a system that is able to both reinforce and support a concrete slab. Concrete reinforcement within AM has been achieved using embedded cables run in the print [16]. This has been shown to increase the tensile strength.

A hypothesis was proposed that running cable into a mesh between the walls of a concrete structure would allow concrete to be printed over the mesh. The mesh would be created using the reinforcement system, but without concrete being extruded during the mesh construction, the resulting mesh would be strung over the area to be enclosed as seen in Figure 5-1. The following layers of concrete would have embedded reinforcement from the same system, which would help counteract the tension experienced in the center of the concrete slab. The printed concrete would bridge between the wires of the mesh, which would then support the subsequent layers of the slab. To test this hypothesis, the bridging limits, or the span that the concrete beads can bridge over without breaking, of the concrete printing system was needed to be found along with the response of the concrete beads being placed on the tensioned wires.

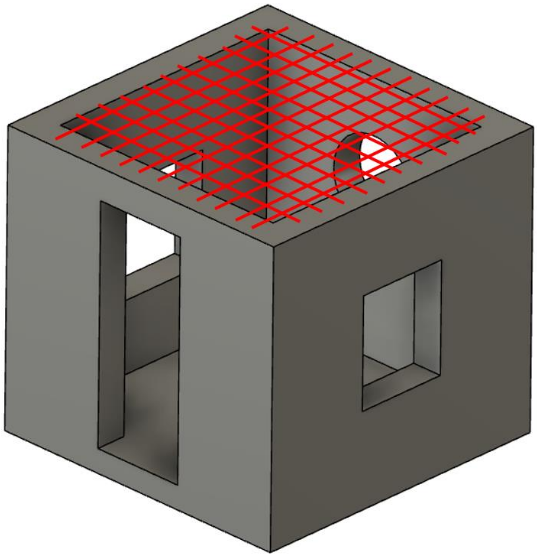

Figure 5-1: Mesh for raised slab on which the concrete is to be printed

5.2 Testing

First, the bringing limit was explored along with the relationship between the height of the nozzle above the previous layer or the printer base for the first layer, also known as deposition height, and the bridging limit. The first bridging limit tests used two plywood bases with increasingly larger spaces between the two surfaces. Tests were done using consistent material and material extrusion parameters while the bridging distance and deposition height where changed. Whereas in each given test the extrusion parameters were set such that there would be consistency when changing the other variables, the parameters did change between tests. The water flow rate was always between 875 to 950 liters per hour, and the pump speed for the m-tech Duo Mix 2000 was set at 7 (arb. unit). The bridging limit was tested between 1 and 12 cm at each centimeter mark. Each bridging distance was then tested three times by printing three beads across the span with each bead not touching the other. The results of the test were gathered by determining if the bridging was a success or failure as well as qualitatively observing the droop of the wet concrete. Success was determined when the concrete bead was continuous and not touching the surface below the bridge and failure was when the bead broke or sagged so much it touched the surface below. In the tests, none of the beads were able to sag low enough to touch the surface below.

Figure 5-2: Bridging limit test, 1–4 cm bridging

The next test sought to understand the relationship between the concrete and the steel cable. While the bridging test can identify the potential bridging limit when the two sides were two solid ledges, it was unknown how the wire would affect the bridging of the concrete. The three variables addressed in this test were the distance between wires that the concrete could bridge, the diameter of the wire, and the deposition height. The distance bridged is meant to see the difference between bridging on mesh versus solid ledges, the diameter of wire will also affect bridging by increasing surface area to support the wire as well as preventing the wet concrete from slicing itself on the wire. Again, the deposition height is meant to find the ideal deposition height for bridging. For bridging, there were 3 sets of 6 wires spaced 4, 5, and 6 cm apart. The two wire diameters used were 1/8 in and 3/32 in. Deposition height was 15, 20, and 25 mm.

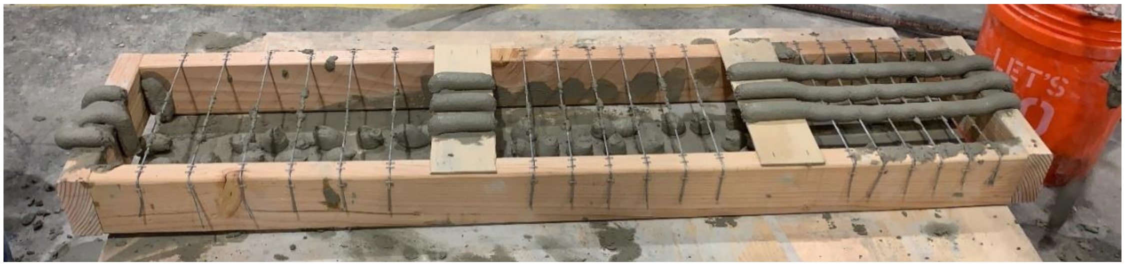

Figure 5-3: Bridging wire test

The last test sought to understand how tension affected the printing on a mesh and was run at three different tension levels. Each tension level was set using a constant weight and measuring the displacement. The 3 different tensions were set at a deflection of 1, 2, and 3 cm. The spacing of the wires was set at 4 cm with perpendicular wires. Two layers of concrete were printed on each mesh and the deflection from the concrete was measured after the first and second layers. Each of the measurements was made using a measuring tape beneath the printed mesh and was rounded to the nearest half centimeter.

Figure 5-4: Variable tension 1×1 meter mesh as built on left and on second layer on the right.

5.3 Results and Discussion

The first bridging test between the two solid ledges gave useful results showing the critical effects of deposition height. When printing concrete, the layer height that has been used has been 15 mm, the deposition height has also been 15 mm, which means that the concrete simply comes up to the opening of the nozzle as it prints. While printing with a deposition height of 15 mm gives a desirable result when not bridging, it is not the best deposition height for bridging. The maximum bridging limit found using the 15-mm deposition height was 2 cm. Changing the deposition height to 25 mm allowed for up to 8-cm bridging with some drooping (i.e., in which the concrete did not span as a straight line across the gap) and up to 4-cm bridging with no drooping. This deposition height difference created a drastic difference in bridging limits. This is because the higher deposition height allows for more concrete to be carried by the tensile strength of the wet concrete. A tension is created in the wet concrete as the material laid pulls back on the material and the material in the nozzle pulls up on the bead that has just been extruded and yet to be laid. The material creates a curve between these two forces, which creates an amount of material that is able to span large gaps. The gap spanned is limited by the tensile strength of the concrete as well as its elongation under tension. Under tension, the material can elongate, which causes the droop in the longer distances. If there is too much tension, the material can break. It was found that at deposition heights above 25 mm, such as 30 mm, the material broke off as the tension on the wet concrete was too much to be supported.

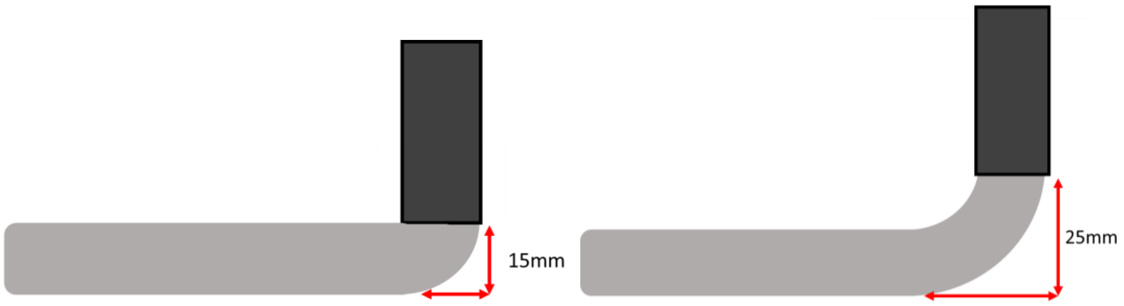

Figure 5-5: Diagram showing effect of deposition height to bridging distance by allowing for more material to be carried by the tension of the wet concrete

The next test that combined bridging with the effect of the wire with the three different wire spacings and different wire diameters showed that the concrete can be held by a wire mesh. The concrete was deposited perpendicular to the wires with three beads at different deposition heights. It was found again that the higher deposition height of 25 mm was the ideal height, which was expected. It was clear that the lower extrusion height of 20 mm failed to bridge even at the shortest gap spacing. The concrete was able to successfully bridge the 4-cm gap at the 25-mm deposition height for both wire diameters. The smaller wire diameter did cut deeper into the concrete as shown in Figure 6-5, but it did not affect the results of the two tests as they both succeeded for the 4-cm test and failed on the 5- and 6-cm tests.

Figure 5-6: Wire cutting into concrete, 1/8-in wire in A and 3/32-in in B

For the final test, each of the tests at all tension levels and for both layers were successfully printed. The deflections measured for the prints were 1, 2, and 3 cm for the first layer at each tension level and drooped one additional centimeter for each of the second printed layers. Each layer took 4 minutes and 20 seconds to print, but the second layer was perpendicular to the first such that the second layer printed on both the 4-minute-old concrete as well as the recently printed concrete. The results showed how, despite the increased deflection, the prints were successfully printed, meaning that the concrete did not fall between the wires of the mesh. The weight of two layers of concrete was not able to slice through the 3/32-in wire and the bridging was able to be done without breaking the tension of the wet concrete even when the actual deposition height was increased due to the drooping of the mesh.

An important note is that during the testing there were inconsistent concrete behaviors. Each of the three rounds of testing was performed on different days and on each day the concrete seemed to perform differently despite identical concrete input parameters. The parameters such as water content and robot speed in response to the change in extrusion rate was changed to create more consistent concrete behavior. The concrete behavior that was focused on was the viscosity of the extruded concrete. As the water content changes, the viscosity of the mix also changes. Concrete that is too viscous may clog the hose and concrete that is not viscous enough will not hold its shape. That being said, the actual bridging distances should only be used as a rough estimate of what is possible. The more valuable information lies in the concepts shown especially in relation to other variables such as deposition height, wire diameter, and mesh drooping. The other successes can be seen as a starting point of what can be done in future tests as the system becomes more robust and consistent. Seeing these results as a starting point, it appears to be correct hypothesis as a successful test was performed on a 1×1 meter mesh. Although much more information and system additions are needed for this concept to be implemented. Some of the major needs for this concept is an automated method of mounting the cables to the printed walls. There must be a way to embed anchors into the printed wall which can both hold the wire strung by the robot, as well as tension the wire to an appropriate tension for the span required. As the spans increase, further testing must be done to discover the needed tension of the wire.

Chapter 6

CONCLUSIONS AND FUTURE WORK

This thesis addressed concrete AM and its development and use in the 3D Printed Habitat Challenge case study as well through understanding its behavior in bridging in order to develop a method of creating a raised slab without the use of formwork. These approaches addressed specific system needs to accomplish specified deliverables from the Challenge as well as testing of that system in different bridging tests. The specific parts addressed were the physical system design to reach the entire structure as well as placing the embedded windows and hatches on the final print, along with the software component to allow for control of the system as well as creating compatible toolpath design. The tests then used the built system as well as test rigs to test if the system could be used to create a raised slab between printed walls.

The 3D Printed Habitat Challenge led the system design towards a robotic arm with an extension that was able to print the entire one-third-scale habitat for the Challenge. The robotic system paired with Marscrete was found because of the potential reduction in launch vehicle mass because of the multi-purpose capability of the robot and ISRU. While this system was able to demonstrate basic concepts of how printing could take place on the surface of Mars, there is much more information and development needed to implement this technology. The required printing environment on Mars must be better understood as well as how to scale a robotic arm to the size necessary while still minimizing the packed size of the robot as well as its mass. Material harvesting and processing also is a topic that was not addressed yet requires work to understand how Marscrete can be synthesized on the surface of Mars.

These system solutions have created a stepping stone for future work by making a working system within a lab context. While the system was moved to the competition site, it took days for the system to be set up before printing could start. The future of this printer system is in a new form factor that can be used on construction sites. This also requires added layers of robustness to the system; this includes fail-proof physical and software elements so the system can deal with mistakes and user error without ruining prints. Some of these improvements would be made on the physical side, such as adding the ability to start and stop the robot during printing. On the software side, there needs to be an intuitive and comprehensive user interface to allow for a user to use one piece of software to get from the CAD model to printed structure. As with all construction, there also must be ways to verify that the structure is built as it should be to have the confidence that it will perform as it was designed. This will require *in-situ* monitoring of the material and print quality in order to have the confidence that the structure will stand.

To ensure the integrity and accuracy of a printed concrete structure, both the printing stage as well as the final loading stage must be considered. During printing, the wet concrete is still able to deform until it is cured. During this period, the concrete is limited in its capacity to hold its shape when weight is added above from inserts or subsequent layers as well as from torsion forces from gravity in overhangs. To understand these forces and effects, tests must be done to measure the effects [27], as well as simulations done to predict the behavior given some found parameters [32]. This would allow for an understanding of what geometries can be printed as well as what initial geometries should be printed to gain a correct final geometry.

The future of this preliminary work will include finding a better understanding of the behavior of printed concrete, both on Earth and beyond in different environments. It will also include creating a closed-loop system to allow for adjustments to be made during the print to ensure the consistency and integrity of the print. Concrete printing must also continue to scale up to the built environment, far beyond the build volume in this work. Concrete printing will continue to improve and gain its place in construction as research continues in both the academic and private sectors.

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