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Project Number: P21652

CONCRIT 2.0: 3D CONCRETE PRINTER

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Abstract

In recent years, multiple Multidisciplinary Senior Design (MSD) teams have needed to prototype concrete objects. This process involves expensive, time-consuming, and inaccurate molds. Concrete was used in their projects due to its low cost and high durability. The rapid prototyping capabilities of a 3D printer and reduced waste of additive manufacturing methods would remedy these problems; therefore, a medium-scale concrete 3D printer was requested by Rochester Institute of Technology (RIT) staff member, Sarah Brownell. P21652 (or ConcRIT 2.0) builds on the work of the previous team. The print area of 36"x36"x18" allows for a variety of objects to be printed. An extruded aluminum frame supports the Cartesian motion system. The axes consist of ball-screws driven by stepper motors that move the gantries along ground guide rods. Mounted to the motion system is a novel mortar extruder featuring a vertical auger inside a PVC shell powered by a windshield wiper motor. A Duet Wi-Fi control board simultaneously moves the axes while controlling the flow rate of the mortar. Sakrete Type-S mortar was selected for its fine powder consistency and low cost. The final product featured precise movement in three axes, a solid structure, removable print beds, a mortar extruder, and more. This paper presents the technical design, prototyping processes, progress achieved, and future plans.

Background and Motivation

Prototyping has always been a critical phase in the product development process. Prototypes are an early sample or model of the product being built. A tangible object can aid stakeholders in identifying the product's strengths, weaknesses, and opportunities in question. Many Multidisciplinary Senior Design (MSD) teams have projects that require prototyping. In the past, teams have struggled with expensive processes, time-consuming mold making, and inaccurate final prototypes.

Figure 2: Mold Attempt Two

Figure 1: Mold Attempt One

An example of this time-consuming and laborious process is P19414, a previous MSD team tasked with developing an Arborloo—a simple type of composting toilet in which feces are collected in a shallow pit and a fruit tree is later planted in the now fertile soil. This team first attempted to shape parts by hand around a bucket to make a ring, but this resulted in rough surfaces that did not meet their customer's requirements. When attempting to use plastic as a mold form, the concrete ring broke after the removal of the plastic casing. Several casts had to be made before they could get a single sturdy prototype.

The students needed an effective and efficient way to create prototypes quickly while working with a limited budget. A mid-size 3D printer was deemed a viable option for future teams and clubs to utilize for school projects. The customer provided specified requirements for the printer to meet. These are listed below.

- Prints objects using inexpensive and accessible material
- Prints objects up to 3' diameter and 18" tall
- dimensionally accurate within .5"
- Print beads retain shape
- Reservoir can hold one bag of concrete
- Adjustable flow rate
- Printer must be able to be used indoors
- The printer must be able to be disassembled for storage.
- Tension and compression strength be at least half the strength of standard concrete

This project is a continuation of a previous team that was cut short due to Covid-19. The previous team, P20652, provided a rough draft CAD model of the frame structure, began testing on concrete mixture recipes, provided some Wi-Fi board software programing, and began foundational work on the motion system the X and Y-axis.

Description of Design

The design process began with reviewing what the previous team developed as well as verifying what was given to us. From there, the team was able to purchase additional equipment and begin to do feasibility testing as well as prototyping. The team made extensive use of 3D printed parts to create custom components and created a hopper out of repurposed materials from the RIT Machine Shop.

Inherited Items

The previous team had designed and manufactured a semi-functional extruder prototype that the team was able to use as a basis for our design. The previous team had gotten the extruder to work with mortar, but the reliability and mortar recipe material properties were unknown. The overall design and the PVC shell were kept, however, everything else in the extruder was modified or outright replaced.

Another item the previous team designed and manufactured was the X and Y-axis. They were able to effectively test the motion capabilities of these axes with a marker attached to the extruder housing and the axes supported by wooden blocks. They used 16mm diameter ball screw rods for the motion that were powered by NEMA 17 motors. To house the motors, 3D printed models were made. These designs enveloped the 80/20, Inc. [1] and broke easily. It was decided to redesign these parts and print new ones. The motors and ball screw rods were deemed adequate at the time. The previous team designed a rudimentary frame and Z-axis. They used two 20 mm diameter ball screw rods driven by 5.18:1 geared NEMA 17 motors and four steel rods to prevent the axis from torquing. The parts designed to connect the Z and Y-axis as well as the Z-axis to the frame were disputed by the current team and were redesigned along with the overall CAD document as there were many small errors scattered throughout.

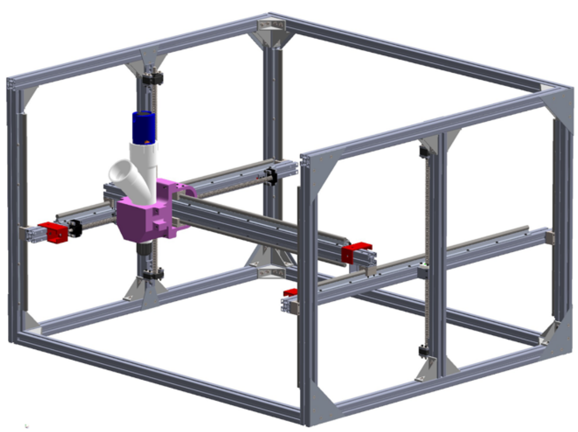


Figure 3: Previous Team's CAD Model

The control board for this project was inherited from the previous team—the Duet 2 Wi-Fi. This board is an advanced 32-bit controller typically used for 3D printers and CNC devices. Users can communicate with it through Wi-Fi as opposed to a wired connection and the board has plenty of built-in support for various 3D printing peripherals, such as the PanelDue (a full-color graphic touchscreen). It is an extremely versatile board with a large community and documentation repository behind it, which makes it an ideal choice for this project.

In House Design

As stated in the previous section, multiple parts needed to be rethought and redesigned while others needed to be designed entirely. Nearly every subsection had some design changes however the most noticeable are the extruder, frame, and hopper.

Extruder

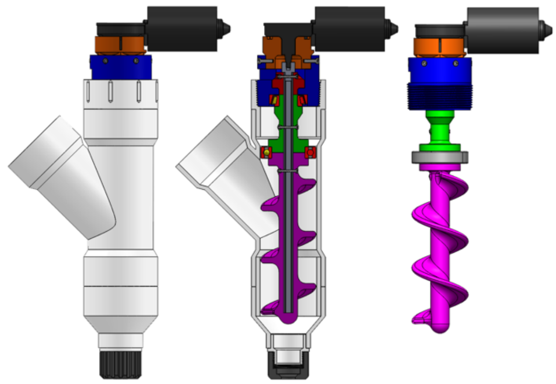


Figure 5: Extruder System CAD with Sliced and Internal Views

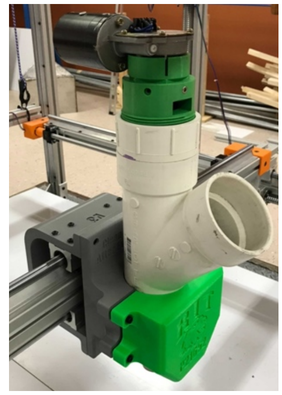


Figure 4: Assembled Extruder

The extruder design utilized multiple custom-designed and manufactured parts to improve its functionality. There are five 3D printed parts used in the current extruder design. With the exception of the auger, all are designed to be easily 3D printed without support material. Two of these 3D printed parts serve to securely mount the windshield wiper motor to the PVC shell, another two serves to align the central shaft/auger with the bearings, and the final part is the auger itself. These were all printed in-house by a team member with a personal 3D printer. This allowed for a quick turnaround on prototypes and iterations.

The extruder design also called for one CNC aluminum part—the motor coupling. It was originally 3D printed but was prone to breaking. The team reacted quickly and machined a replacement part from 6061 aluminum. This machined part went through three iterations to the final design. The original part was a copy of the original 3D printed part but because of the stark differences between these two manufacturing processes, the part wasn't well suited for machining. The second iteration of the part had concentricity issues and the third iteration of the part has worked perfectly after alleviating the problems with the previous iterations. The final part is simple, efficient, and relatively easy to machine.

Frame

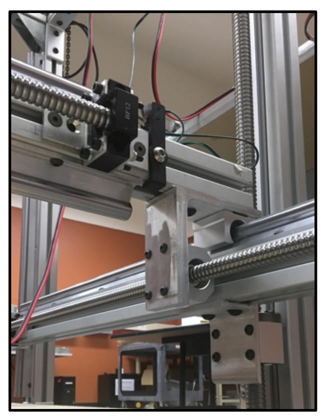


Figure 6: Close Up of Frame Intersection

The frame had many alterations to mounting hardware and printed parts. In total there are 16 types of completely custom parts being used on the printer. For the custom printed parts, their designs were rethought to allow easier attachment and removal. The motor housings were redesigned so that they did not fully encompass the aluminum extrusion and had screw holes for attachment. This redesign allowed the housings to easily be adjusted while prototyping and secured in place while testing. The motor coupler for the X and Y-axis was redesigned from a press fit on the motor shaft to a set screw as well as being elongated and narrowed to add clearance and reduce print volume. Another part that was created this year was the end stop sensors mounts. These parts have a simple design with mounting holes for the switch and 80/20 [1] and a small lip at the end to upright it when installed.

More design work and manufacturing was done for the frames' machined parts. For the z-axis, the supports for the ball-screw rods were rethought completely. Instead of using similar support structures as the X and Y-axis, two 6061 aluminum blocks were milled, drilled, and tapped to mount to the bottom of a z-axis pillar and the bottom housing of the rod. This allows the support to have a surface to push off of instead of solely relying on friction forces to support the load. The upper support for the rod was manufactured in a similar design to the X and Y supports, however, it was larger and thicker. The X to Y-axis mount was also redesigned. The original design was difficult to remove and over time bent out of tolerance to line up the mounting holes. A new design made out of aluminum L-shaped stock was made to the shape of the existing design and manufacturing drawings instead of the CAD file.

Hopper

Limitations on budget, a required internal volume of approximately one cubic foot, and the need for a sloping bottom that terminated in a 3-inch tube. It was determined that a custom hopper would need to be manufactured.

Figure 7: Hopper

Once this was decided material selection and manufacturing methods were considered. It was known that the hopper would need to be able to safely support at least 100 lbs. of mixed mortar (derived from an 80 lb. bag of martyr mixed at a 20% hydration level), be watertight, and be able to be lifted using the winch that was provided in the Active Learning Lab. These parameters and the availability of scrap sheet metal steel meeting the hopper's dimensional requirements the hopper was constructed using bending, rolling, cutting, and welding sheet metal.

The shape of the hopper utilized a truncated pyramid mated to a triangular prism to achieve an approximate internal volume of 1.2 ft and sloping bottom of the hopper. The pyramid portion was manufactured by bending a piece of sheet metal to form two sides and a triangular piece was then welded. This was then welded to the triangular prism that was constructed using three 18" by 11" sheets of stainless steel. The cylindrical outlet was constructed by rolling and stainless steel and then cutting it to fit snugly to the pyramid and was then welded. The total weight of the hopper when filled is expected to be 150lbs, to support this weight three ⅜ inch eye bolts with a working strength were installed to the hopper. To then be able to hang this hopper a harness was made using 550 cord such that each eye bolt had 3 lengths of chord supporting it giving the harness the approximate working strength of more than 1500 lbs.

Electrical

The electrical diagram is shown to the left with all the connections to the Duet laid out. The stepper motors and limit switches are wired with 26AWG stepper cable and 4-pin Dupont connectors. The DC motor in the extruder is controlled using a PWM output by the Duet. The Solid-State Relay, or SSR, was incorporated into the system to provide electrical isolation between the Duet's PWM and the DC motor, as the DC motor has a peak current of 14A which would likely damage the board if it was directly connected. This system is largely "plug and play", as almost all components have built-in functionality with the Duet. The versatility of the Duet went a long way in helping us choose compatible components. Typically, each axis has one stepper motor, but due to the size of our printer, both the Y-axis and Z-axis have two motors. The Duet is capable of supporting multiple stepper motors for each axis—there is an expansion board as well if more drives are ever needed.

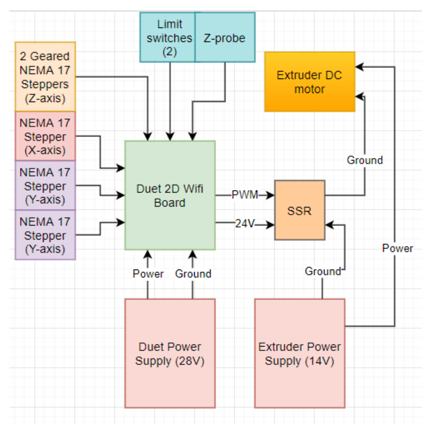


Figure 8: Electrical Flow Map

Component Selection

One of the first things the team purchased was slotted aluminum rails for the frame. The previous team created the X and Y-axis out of 45-series 80/20 [1] and to keep the printer consistent, the team decided to continue in that direction. After some purchasing hurdles, the team ended up buying aluminum extrusion from a Parco [2] distributor instead of 80/20 Inc. [1]. Parco [2] provided similar products as 80/20 [1], albeit some of their cross-sections and designs differed. The team was able to alter the aluminum extrusion slightly to fit the need of the project and continue working. To meet one of the requirements of the project the printer had to be maneuverable enough to be able to be moved if required but also stable enough to have consistent prints. The team decided on using leveling casters for their high weight capacity and leveling capabilities. These four casters were purchased from Amazon for under $50 instead of from 80/20 Inc. [1] for $60 per caster, which would be 16% of our budget for four.

The previous team's design of the extruder had a NEMA 17 stepper motor to drive the auger; however, this did not provide enough torque. For a stepper motor to produce enough torque, it would be either a very expensive stepper motor or have a high reduction gearbox which would reduce RPM capability significantly. After consulting

Professor Olaf Diegel, who teaches Mechanical Engineering at the University of Auckland in New Zealand, the team decided to purchase a windshield wiper motor from MonsterGuts.com [3]. The team consulted Professor Diegel because he is one of the few people who has built a medium-scale concrete 3D printer in the past. Windshield wiper motors have worm gears that are robust and provide high gear ratios, torque, and reasonable speeds. The team decided MonsterGuts [3] would be the best source for these motors because they always carry the same motor and they had technical specifications on the motor, and their prices were competitive.

Table 1: Motor Comparison

Specification:	NEMA 17 (5.18:1 Geared):	Wiper Motor:
Rated Torque	6.64 (in-lb)	53 (in-lb)
Stall Torque	9.735 (in-lb)	177 (in-lb)
High Speed	38 (RPM)	50 (RPM)
Low Speed	5 (RPM)	35 (RPM)
Weight	0.84 (lbs)	2.7 (lbs)
Voltage/Current	12 VDC @ 0.8 Amps	12 VDC @ 5 Amps

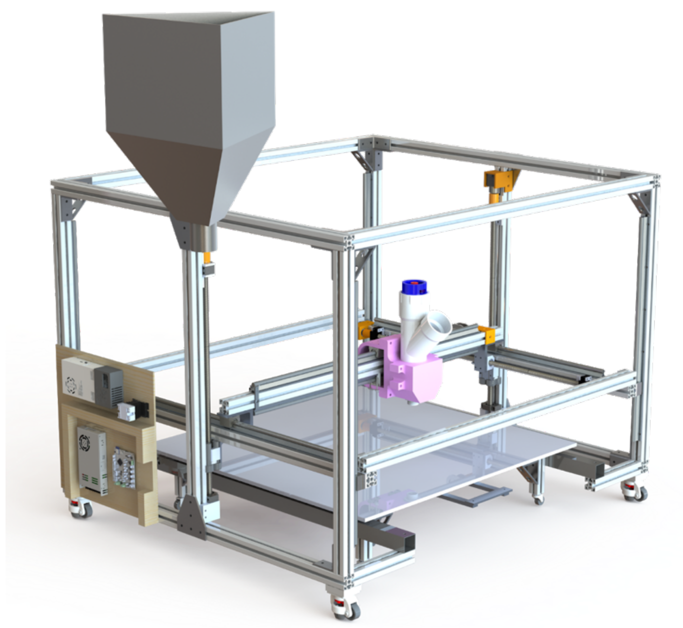
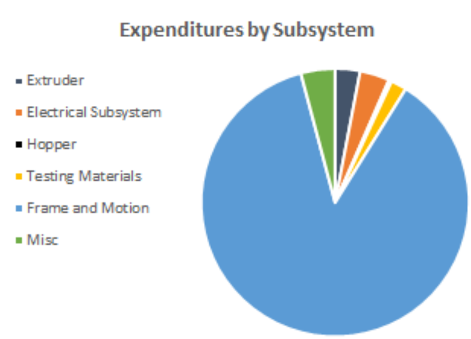


Figure 9: Full Printer CAD Model

Budget

The total budget for this project was $1,500 and was provided by Jim Swift, CEO of Cortera. The pie graph shows the budgetary breakdown, the biggest expense being the aluminum rails for the frame of the printer.



Graph 1: Budget Breakdown

Supporting Feasibility Evidence

Subsystems Testing

As the team progressed, intermittent feasibility testing was performed to ensure the team was on the correct track. Key subsystems tests are discussed below.

Extruder

The team did multiple extrusion tests with the prototype where the mortar mix was fed into the extruder and lines were extruded. The extruder functioned only intermittently during these tests, so the team tried different auger geometries, stepper motor sizes, and nozzles until it was discovered that the issue was not enough torque being provided by the motor. A quick feasibility test showed that it would take about 5 ft-lb of torque to extruder mortar through our system. Using supplier-provided torque curves the team determined that even a heavily geared NEMA 17 or 23 cannot provide this amount of torque. Geared steppers could provide 5 ft-lb of torque, but they could only do so at incredibly low speeds that would limit our extrusion rate. The team discussed our findings with Professor Ferat Sahin who advised that stepper motors aren't designed for this application. So, the team began searching for a new motor that could meet our requirements.

Once the team had selected the windshield wiper motor and the design of the rest of the extruder was optimized the team began more feasibility testing to validate our new design. The team went through six rounds of feasibility tests wherein the team discovered parts of the design that needed to be updated. Things like machining a new shaft coupler because the 3D printed version would fail under the high torque operation came to light. Features like interchangeable nozzles were highlighted as needing more development by a follow-up team. One by one these design flaws became apparent, and the team quickly iterated the design to fix them or judiciously decided to remove the feature. Finally, the extruder reached a state where it functioned flawlessly without nozzles. It could extrude mortar in a wide range of hydration ratios and could do so at a rate that exceeded our engineering requirement. The electrical aspect of the design allowed for the safe operation of the high-powered wiper motor while also giving PWM speed control and keeping the high current circuit independent from our logic circuit.

Structure

When assembling the frame and motion axis multiple roadblocks were encountered. When the team first acquired the aluminum extrusion the team noticed that some of our hardware would not fit into the channel due to variation of Parco [2] vs 80/20 [1]. To remedy this, the team worked in the machine shop to mill the channel so that the hardware could slide in. Another roadblock the team encountered was the part the team designed for the project was unnecessarily complex. The team reevaluated our parts and simplified them so that they could be made on the 2-axis Prototrak CNC machines in the mechanical engineering machine shop. After these parts were made the team was able to finish building the frame and mounting the Y and Z-axis. The next roadblock was mounting the X-axis. While mounting and dismounting the X-axis the team noticed it was exceedingly difficult to attach the connector to the X-axis and the Y-axis ball-screw. This was caused by a stack-up of tolerance errors from the previous team's parts. The mounting to X-axis difficulty was remedied by adding additional holes to the mounting piece so an allen key could be inserted with a greater range of motion. The team also realized that upon some failed movement tests where the X-axis started to yaw caused the mounting piece to warp out of tolerance. To fix this problem the team created a new part out of thicker stock and made measurements based on where the parts are physically located, rather than where they are in CAD. These changes were implemented, and the team was able to successfully get motion in X, Y, and Z directions with minor hiccups.

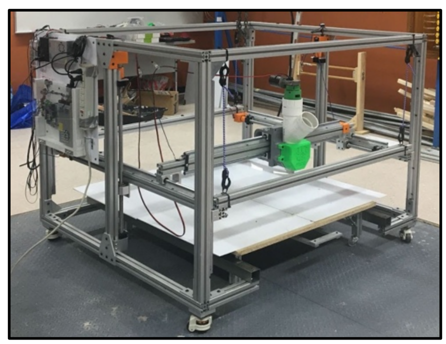


Figure 10: Full Printer Assembled

Hopper

When this project was first initiated the concern of the workable time of mortar in comparison to the time it would take to complete a print was brought up. To mitigate this time was spent investigating a volumetric mixing system that would mix mortar mix and water on demand as needed by the printer. However, after initial feasibility testing, it was impossible to get consistent mixing and it was concluded that it would be impossible to properly develop a system in the time allotted for this project and the experience gained during this test showed that the mortar mix would remain workable for about 45 min, more than enough time for a print to complete. As a result of these findings, a premixed concrete approach was decided.

The following feasibility question arose due to the shift in mortar mixing approach from volumetric mixing the question of how it would be possible to store about 100lbs of material in a matter that the extruder could access. To

solve this problem a preliminary peristaltic pump was designed in parallel with the feasibility of a gravity feed of mortar being tested. The test of the gravity feed showed very promising results with the mortar being able to flow from a bucket into a tube that was connected to the bottom. This finding was also supported by research findings that indicated that comparable mortar 3D printers also utilized gravity to feed into their extruders. These findings led to the abandonment of the design of a peristaltic pump in addition to the concerns of safety that arise from having a large spinning mass and worries about the difficulties that would be incurred with effectively pumping a slurry material such as mortar.

Once a premixed approach for mixing mortar and a gravity approach for feeding mortar the problem of how one gets 100 lbs of mortar from a mixing bucket into a hopper that sits approximately 5 feet in the air had to be solved. To solve this problem a preliminary design for a 2x4 structure was proposed that utilized a mechanical hand winch to lower the hopper to a comfortable height for filling and then again lift it to an effective height to feed the printer. Once this idea was presented to the project guide an RIT-owned electric winch that is hard mounted to the structure of the Active Learning Lab was able to be procured for the use of this project removing the need for the 2x4 structure.

Software

The Duet 2 Wi-Fi board has built-in support for the NEMA stepper motors; however, the capability of the steppers needed to be tested. The X-Y steppers were briefly connected to the Duet and ran for verification, as well as the Z-axis. However, the Z-axis motors on the printer need to be capable of lifting about 100 pounds—the weight of the X-Y axes. To briefly test this, weights were attached to the Z-axis and the stepper was tested. All tests were a success and the team concluded that the motion axes stepper motors would work for our purposes.

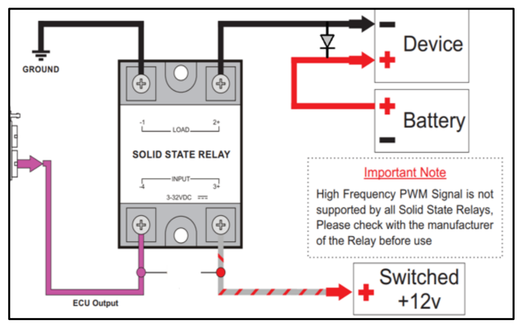


Figure 11: Software Flow Model

The PWM control of the DC motor used in the extruder was verified using a simple LED circuit. However, when wired to the SSR, it was found that the SSR is not capable of switching at frequencies higher than 10Hz. A linear increase in frequency results in an increasing linear error between the requested duty cycle and the actual duty cycle. This forces us to operate at 10Hz which is somewhat choppy for the motor. A higher frequency would allow for smoother transitions between speeds, so a potential future upgrade would be swapping out the current SSR for a better model. The wiring diagram is shown in the figure above, where the “device” is the DC motor and the bottom two pins go to the Duet heater terminals.

Cura was envisioned to be the slicing software used for this printer, but due to time constraints, the Cura profile generated was not able to be tested. However, Cura was chosen as the slicing software early on in the project’s timeline but after building it, the team believes that the best future course of action would be to create a custom slicing interface for the printer.

Full Testing

For full printer testing, the team attached the hopper to the extruder and began testing. During the test, the mix was required to be agitated in the hopper to facilitate flow through the tube. The tube also required constant attention so that it would not slump below the extruder mount, which would cause a loss of flow. For these two reasons as well as a lack of time, the team decided that for all other testing the extruder will be hand-fed. From these tests, the team produced multiple consistent samples of stacked circles and a part of a rudimentary arborloo. These samples allowed the team to evaluate the printer’s effectiveness, as described in the section below.

Results, conclusion, and recommendations

The team was able to finalize a good deal of the printer. The X, Y, and Z-axes, the purchase and assembly of the frame, and the development of an updated extruder system were all completed during this project. Additionally, duet capabilities and motor requirements were researched and applied to the printer. The 3D printer can print semi-complex objects using a hand-scooped feed. Through testing the 3D concrete printer, the team was able to succeed

in most of the specifications. Below in Table 2, a breakdown list of the Engineering Requirements (ER) that were addressed.

Table 2: Engineering Requirements Breakdown

Green: Meets Specification, Yellow: Unable to Test, Red: Does not meet specification

ER #	Category	Requirement Description
ER1	Extruder/ Motion	Print resolution in the X and Y-axis
ER2	Extruder/Motion	Print resolution in the Z-axis
ER3	Extruder	The nozzle is quickly replaceable
ER5	Extruder	Minimum concrete mass flow rate
ER6	Extruder	Maximum concrete mass flow rate
ER7	Software	Open source, easily customizable, and accessible UI that utilizes common slicing software
ER8	Concrete Mixture	Minimum compressive strength of printed parts after 7 days
ER9	Concrete Mixture	Minimum tensile strength of printed parts after 7 days
ER10	Frame	Minimum printable envelope (object) diameter
ER11	Frame	Minimum printable envelope (object) height
ER12	Concrete Mixture	Prints concrete or other cheap material
ER13	Extruder	The geometric shape of the print nozzle is maintained in the print bead
ER14	Concrete Mixture	Printed object's set (cured enough to move/handle but not at full strength) time
ER15	Frame	Size of the printer when it is in use
ER16	Frame	Printer storage size
ER17	Extruder	Extruder flow is not impeded during printing
ER18	Frame/Reservoir	Maximum reservoir fill port height
ER19	Frame/Reservoir	Minimum reservoir fill port height
ER20	Extruder	Maximum tools needed to remove and disassemble the extruder
ER21	Extruder/ Reservoir	Maximum printer cleaning time
ER22	Reservoir	Reservoir cement capacity
ER23	Reservoir/Frame	The reservoir needs to be accessible during print to add in more material
ER24	Software	The flow rate of cement can be adjusted by the user through printing control software
ER25	Extruder/Frame	The printer does not eject material outside of the printer
ER26	Extruder/Concrete Mixture	Maximum air bubble radius contained in an extruded concrete segment
ER27	Extruder	Minimum bead width
ER28	Extruder	Maximum bead width
ER29	Extruder/Concrete Mixture	Maximum bubble bead composition
ER30	Extruder/Concrete Mixture	Maximum bead width deviation
ER31	Frame	Time for Disassembly

The current state has several opportunities to enhance the printer. The team completed a very preliminary version of the hopper/reservoir, but it poses many safety risks. A future group can work towards making an automatic mixing and dispensing system for continuous flow and safer features. Another potential project could be upgrading the extruder system with finer tuned parts. Likewise, updating/partial redesigning of Z-axis drive screws could be another task for a group. Lastly, major work can be dedicated to creating custom slicing software for use with this printer. Cura is not capable of determining how much concrete is needed for a print or how long that print will take, as the material is unlike anything Cura normally handles. A custom slicing software would be able to tell the user all that and more, slicing the model such that the bottom layers are setting when the new layers are being printed to prevent the bottom layer from expanding under the weight. That would be ideal, but it does require a good amount of software knowledge and time.

If the team had the opportunity to repeat this project, knowing what we know now, we would plan a few plans differently. First, the team should have chosen a gravity feed reservoir sub-system from the start. We had narrowed down the design to three ideas. The gravity feed was a cheap and easy idea, but a peristaltic pump was more exciting. Halfway through the project we retired the pump idea and switched to the gravity feed idea. This caused some delays in the project. Second, the team should have stuck with the 80/20, Inc. [1] brand for our extruded aluminum beams instead of Parco, Inc. [2]. We had chosen Parco [2] since it was advertised as a one-to-one replacement, would be slightly cheaper, and arrive sooner. This was not the case. Upon the arrival of the beams, we noticed a very small bump that needed to be milled down for the frame to be assembled. These are the main changes we would make if given the opportunity.

References

[1] Parco T-Slot Aluminum Extrusions. ALUMINUM T-SLOT FRAMING. (n.d.). https://parco-inc.com/.
[2] 80/20 T-slot Aluminum Building System. 80/20 Inc. (n.d.). https://8020.net/.
[3] Premium 2-Speed 12VDC Wiper Motor. wiper motor.
(n.d.). https://www.monsterguts.com/store/product.php?productid=17685&cat=3&page=1.

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