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Autonomous Material Refill for Swarm 3D Printing

William C. Jones

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Autonomous Material Refill for Swarm 3D Printing

An Honors Thesis submitted in partial fulfillment of the requirements
for the Honors Program in Mechanical Engineering

by
William Jones

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Abstract

3D printing currently offers robust and cheap rapid prototyping solutions. While standard 3D printing remains at the periphery of mass production, the technology serves as a starting point for the development of swarm manufacturing. Since swarm manufacturing is predicated upon autonomy, swarm technology companies such as AMBOTS are seeking to minimize human involvement in the swarm's functions. At present, the 3D printing swarm consists of the printers, a transporter which can take them between job sites, and the floor tiles which provide power and support the build surfaces. To add to this ecosystem, this project is focused on the design and construction of a station which automatically refills filament for the swarm printers. This was done using materials and mechanisms already common to the swarm. As of the publishing date, the station exists as a functional first-iteration prototype which proves the viability of the concept and serves as a basis for future development.

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Chapter 1: Background

1.1: Swarm Manufacturing

Swarm manufacturing is an autonomous manufacturing platform for making digital designs on-demand using a coordinated swarm of mobile robots [1]. This differs from standard manufacturing methods in many ways, but the key difference is rigidity versus mobility. Consider a standard press brake. It performs a single operation, it cannot coordinate with other machines, and its tooling limits designs. Even a production line of such machines creates a one-dimensional process which is limited to making a narrow range of products. These constraints require the scheduling and operation commonly used in modern manufacturing, and they pose a risk to the survival of a factory as products change. Swarm manufacturing introduces mobility, dynamic calibration, and cooperation between autonomous entities. It mimics the natural production behavior observed in swarms of eusocial insects, such as bees and ants. These qualities make a swarm more versatile and less linear than a set of standard production machines, opening the door to generalized factories which can produce on-demand.

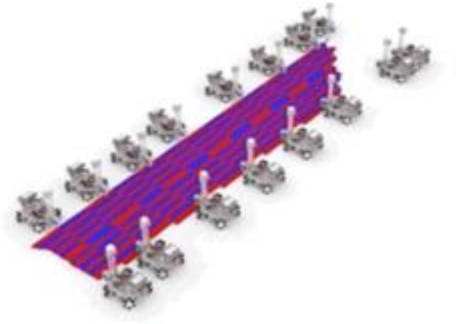


Figure 1: Swarm robots printing cooperatively [2].

1.2: 3D Printing

Additive manufacturing, commonly known as 3D printing, is the construction of a three-dimensional object from a digital model. It involves processes in which a computer-controlled printer deposits and solidifies material on a platform [3]. The technique allows for the creation of geometrically complex objects which would otherwise be nearly impossible to produce. As of 2020, fused filament fabrication is the most common form of 3D printing [4]. In this process, a continuous thermoplastic filament is heated and extruded from a toolhead onto a bed. As the molten filament is layered on top of the bed, the toolhead rises to add more layers onto the previous ones. The material cools back into a solid form, leaving a complete 3D print. The objects formed from this process are often partially hollow and composed of small trusses which retain most of the material's strength while reducing weight and print time.

1.3: Swarm 3D Printing

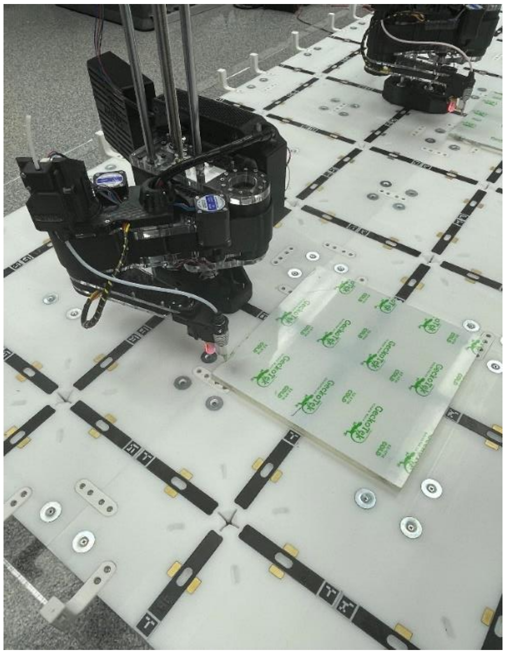


Figure 2: SCARA with z-axis structure.

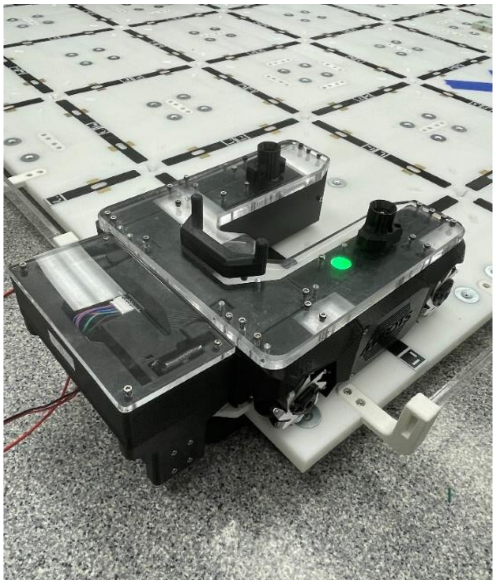


Figure 3: Transporter docked with power supply.

While swarm manufacturing is still largely conceptual, implementation is beginning with 3D printing technology. As shown in Figure 1, Swarm 3D printing systems utilize mobile robots which are capable of cooperatively printing large components and, in some cases, assembling loose components together. The robots in swarm 3D printing are diverse and specialized in their roles. In its latest version, the AMBOTS swarm consists of stationary printing robots and transportation robots which carry them to the proper floor tiles for the job. Each printer robot consists of a Selective Compliance Assembly Robot Arm (SCARA) which moves a toolhead in the x-y-plane and a z-axis mechanism which moves the entire arm vertically as shown by Figure 2 [5]. Once set in place by the transporter (Figure 3), the printer receives wireless power from the electrified floor tiles and commands from the control hub to begin a print [6, 7]. The printer robots can either print individually or cooperatively using a ‘chunk-based’ slicing method. This splits the digital design into numerous ‘chunks’ assigned to each printer, which allows for printing objects such as the one shown in Figure 4.

The vision offered by swarm 3D printing and, more broadly, swarm manufacturing is an industry supported primarily by these autonomous systems with the goal of making products at lower cost and in less time. The challenge is in automating manufacturing processes in such a way that affords these benefits without sacrificing efficiency or capability. The robots must navigate encounters with both the production environment and other swarm members, which is simultaneously a software and hardware problem. AMBOTS is a company taking on these problems using the technologies developed by the AM^3 and SiDi labs [9, 10]. Currently, they have working robots which can autonomously execute individual and cooperative prints. But they still require a range of manual support, including manual material resupply.

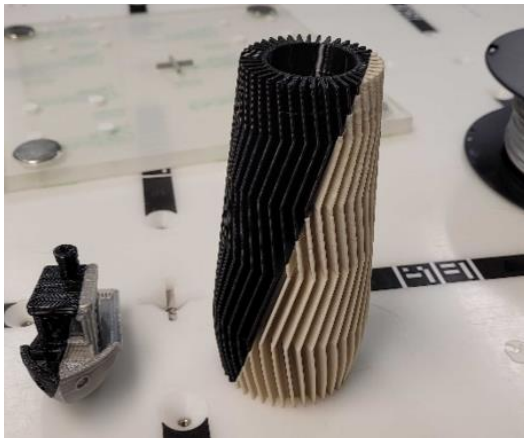


Figure 4: Examples of chunk-based printing [8].

1.4: Project Scope & Criteria

Since the vision of swarm manufacturing is to maximize automation, developments are approached with the goal of minimizing the time and effort required of human operators. The mobile robots in the swarm are already capable of autonomous cooperative printing, but they still require periodic resupply of printing materials. AMBOTS printers currently utilize spooled filament (Figure 5), meaning an operator must manually remove old spools, hang new spools, and insert filament into the robot's extruder for the entire swarm. This stands as a barrier between the current state of the project and the vision of swarm manufacturing. The objective of this research is to eliminate this barrier by designing and building an automated filament resupply station.

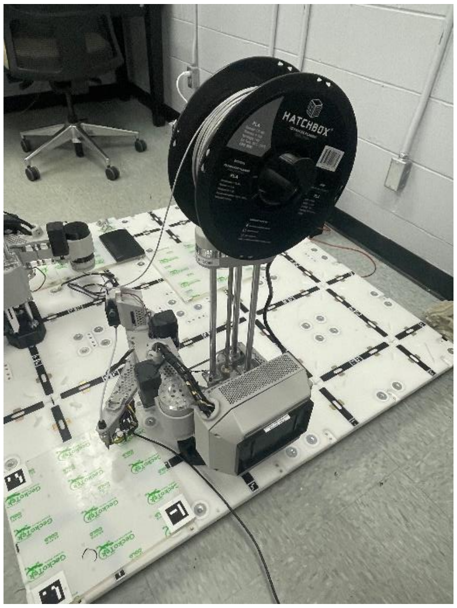


Figure 5: Current filament spool configuration.

The design solution must meet five main criteria to be a viable addition to the swarm.

- Improved cycle time. Currently, 130 seconds elapse between the extruder unloading its filament and reloading the new filament supplied by an operator. The station should be capable of reloading a robot in the same amount of time or less.
- Easy access. Robots must be able to access the station using their normal means of transportation. Additionally, they should be able to signal their need for resupply, initiate the resupply sequence, and resume their prints automatically.
- Standard filament container. The spools are ill-suited for robotic manipulation on their own. The filament end's movement is not constrained, and it can appear at any position around the spool's circumference. By placing the spools into a standard container, or cartridge,

the filament end’s position can be consistent. The cartridge can also contain other features which allow both the station’s tooling and the robot to move and retain the assembly.

- Autonomous operation. The reload station must be able to execute all movements to unload, discard, and reload automatically upon receiving commands from the control hub. By the same principle of automation, the station must also have a reserve of loaded cartridges and space for holding depleted ones. This reduces the effort demanded of human operators to maintain the station’s function.
- Simple functions. The station’s functions must be sufficiently simple to run with commands from a single Duet 2 Wi-Fi control board. This means keeping powered elements within the number of pinouts available on the Duet and on the external drivers it can support.

Chapter 2: Design

2.1: Overview

The general approach to the design is to use materials and mechanisms commonly employed by AMBOTS' and other 3D printers' designs. Just as a desktop 3D printer has motion axes, an extruder, and a toolhead, the station has defined axes and its own unique set of tools. Specifically, the station can be broken down into three high-level assemblies plus the cartridge assembly. The frame assembly provides a structure to support the others and facilitate their movements through the attachment of motors, bearings, and brackets. The carriage retains tools for changing cartridges and moves those tools between cartridge destinations. The cartridge towers are built into either side of the frame, and they move stacks of cartridges vertically to exchange with the carriage as the sequence progresses. The cartridge itself is unpowered, but it has features to be gripped by the carriage, retained by the robot, and have its filament extruded down to the robot's on-board extruder.

2.2: Frame

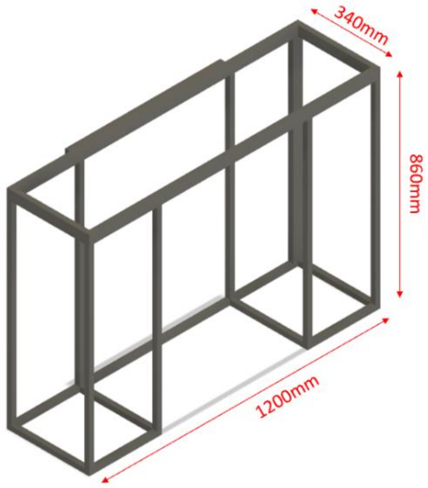


Figure 6: Overall frame dimensions.

The frame must be light enough to be moved into position by a single operator, large enough to house the robot and cartridge reserves, and sufficiently simple to modify the locations of various motors, bearings, and brackets which it supports. It must not be so large as to severely limit the swarm's workspace. These criteria are met by constructing the frame from extruded aluminum beams. These beams have an M4 t-slot extrusion profile which allows for flexibility in fastening the various other components. The frame is dimensioned to fit over the AMBOTS floor tiles with the robot docking point in the center (Figure 6). It forms a

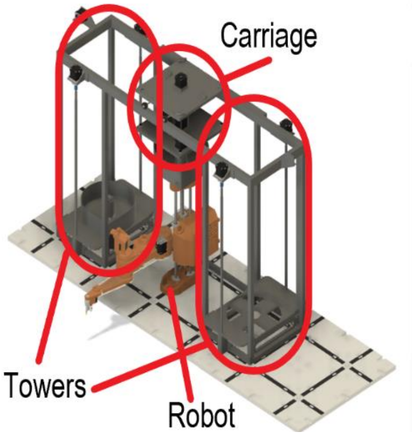


Figure 7: Basic frame structure and station components.

structure beside and above the docked robot. In addition to housing the robot, this structure supports one stack of cartridges on either side and a tool carriage which travels along the top rails between towers (Figure 7). This places the reserve of full cartridges, the parked robot, and the stack of empty cartridges in the same plane. With this arrangement, the carriage will only have to travel along the horizontal axis to perform all functions. Movement along the vertical axis will be handled by sub-components of the towers and carriage.

Table 1: Frame design parameters.

Frame	
Parameter	Value
Overall Length	1200mm
Overall Width	340mm
Overall Height	860mm
Robot Bay Width	600mm
Tower Width	260mm
Track Width	300mm
Empty Weight	16lb
Full Weight	42lb

2.3: Carriage

The carriage (Figure 8) is the vehicle which moves and manipulates filament cartridges within the station. It must be able to move horizontally across the frame while also moving its tooling vertically. Its tooling must be able to pick a cartridge up, set a cartridge down, and extrude filament out of a cartridge. To enable motion in both horizontal and vertical directions, it is split into two subassemblies to handle these two directions individually. The top carriage is responsible for horizontal movement. It is made from a ½” x 275mm x 292mm acrylic plate, which was laser cut from a larger sheet and outfitted with special frame wheels and a variety of printed plastic brackets. Rather than powering its own wheels, it is driven by a belt which is routed between a NEMA 17 stepper motor and idler pulley mounted on either end of the frame. The on-board NEMA 17 motor is used to drive a lead screw which moves the sub-carriage vertically. The four 8mm steel guide rods serve to stabilize the sub-carriage.

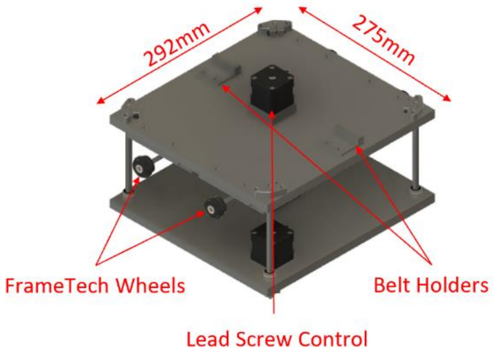


Figure 8: Carriage assembly dimensions and features.

Table 2: Carriage design parameters.

Carriage	
Parameter	Value
Overall Length	292mm
Overall Width	275mm
Max Height	310mm
Min Height	245mm
Vertical Travel	65mm
Max Speed	4000mm/min
Max Acceleration	500mm/s^2
Weight	7.6lb
Carrying Capacity	4.1lb

The sub-carriage is also constructed from a ½” x 275mm x 292mm laser cut acrylic plate. It features linear bearings to receive the guide rods, a printed plastic bracket which retains the lead screw nut and provides 65mm of vertical travel, and two NEMA 17 stepper motors (Figure 9). The central motor drives a tool called the ‘locking shaft’. This printed plastic shaft features a tapered design with two integral side arms. This is designed to insert into the filament cartridge and turn 90° clockwise from the above perspective. This drives the side arms into matching channels within the cartridge (Figure 10). In this position, the locking shaft retains the cartridge, allowing the carriage system to move it vertically and horizontally. The corner motor drives a printed plastic shaft with a tooth-design head for transmitting force to a matching shaft on the cartridge. This motion will be used to drive an extruder inside the cartridge which moves filament down a Bowden tube to the robot’s own extruder.

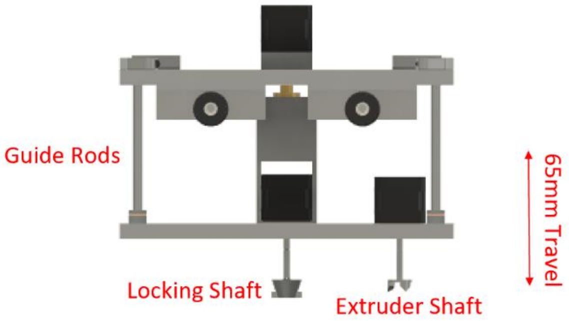


Figure 9: Carriage assembly side view.

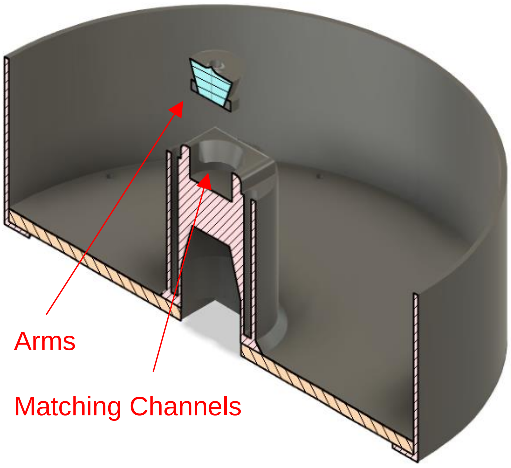


Figure 10: Locking shaft and cartridge cross-section.

2.4: Cartridge

Figure 11: Filament spool dimensions.

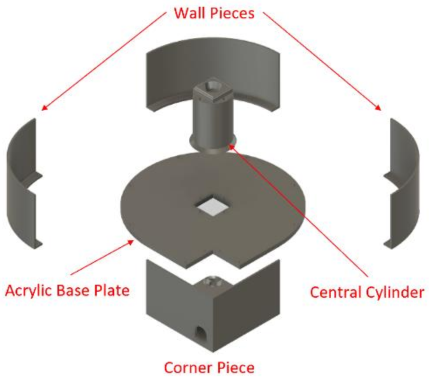


Figure 12: Cartridge exploded view.

The cartridge must support the standard AMBOTS filament spool (Figure 11). It must match the lifting and extruding tooling found on the sub-carriage as well as the robot top piece on which it rests. Cartridges must also be stackable for consistent location within the towers. The filament cartridge is a combination of ¼” laser cut acrylic plate and printed plastic walls (Figure 12). These are intended to be used and re-used with an indefinite number of spools. They are enclosed on the sides and bottom, whereas the top is open for easy spool removal and installation. The square corner contains the on-board extruder and the custom shaft mentioned previously (Figure 13). Since the extruder is ultimately driven by the sub-carriage extruder shaft, the cartridge does not require an on-board motor to function. The center of the cartridge is occupied by a printed plastic cylinder (Figure 14). The spool rides on a chamfer at the base of the cylinder which acts as a plain bearing for smooth unspooling. The top of the cylinder contains the tapered hole and channels to match the locking shaft. It

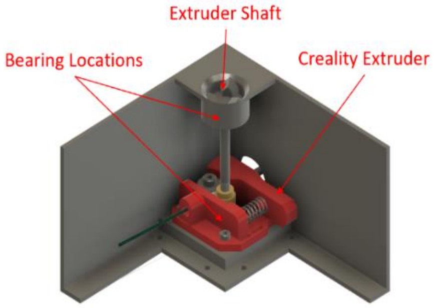


Figure 13: Cartridge corner components.

Figure 14: Central cylinder features.

also features a raised square profile which matches a cut in the acrylic base plate. This allows the cartridges to stack on top of one another, and it prevents them from rotating while mounted to the mobile robot.

Table 3: Cartridge design parameters.

Cartridge	
Parameter	Value
Outer Diameter	240mm
Overall Height	91.85mm
Empty Weight	1.3lb
Spool Weight	2.8lb
Spool O.D.	200mm
Spool I.D.	55mm
Cylinder O.D.	52mm

2.5: Towers

As previously mentioned, these cartridges will be stacked in the towers on either side of the frame (Figure 15). As the station completes many cycles, the tower containing full cartridges will dwindle and become shorter while the one for empty cartridges will grow taller, so each tower must be able to support the weight of the cartridge stack and move vertically without upsetting it. Each tower will have base plates which raise and lower with dual ball screws mounted to the frame (Figure 16). The plates are an assembly of several acrylic pieces, each of which serves a different purpose (Figure 17). The plates in the middle cradle the cartridges, while the outer plates retain the ball nuts. Both are supported by vertical wheel plates which are equipped with the same t-slot-compatible wheels found on the top carriage. This makes for a sturdy base capable of carrying seven loaded cartridges.

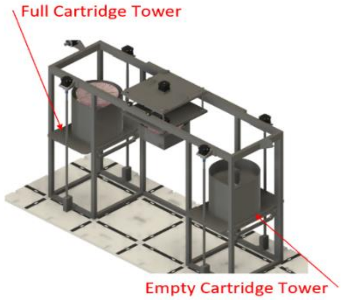


Figure 15: Tower states mid-sequence.

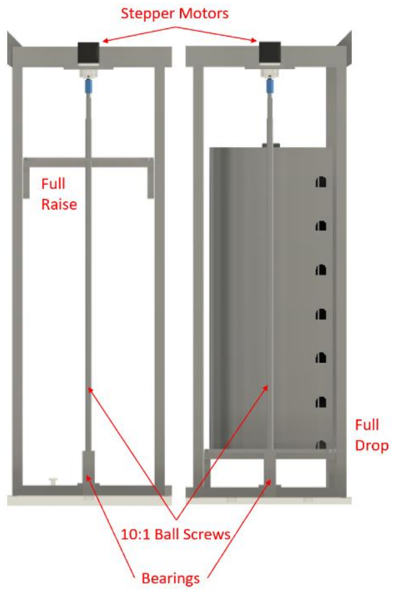


Figure 16: Tower components.

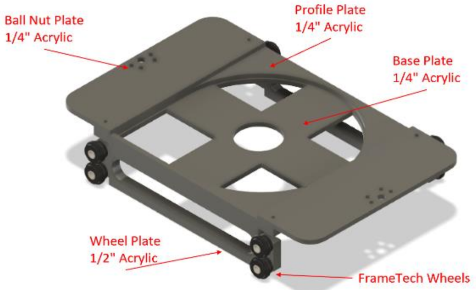


Figure 17: Tower plate construction.

Table 4: Tower design parameters.

Tower	
Parameter	Value
Max Stack Height	700mm
Ball Screw Pitch	10:1
Gear Reduction	5:1
Max Speed	180mm/min
Cartridge Capacity	7

2.6: Communication, Control, and Positioning

All these components are controlled by a single Duet 2 Wi-Fi control board (Figure 18). This motherboard has pin-outs to control six different stepper motors, and it hosts a daughterboard which outputs to two external motor drivers for the seventh and eighth motors on the filament station (Figure 19). The wiring between frame-mounted motors and the board can be routed in the extrusion slots, whereas the wires between carriage-mounted motors will run through a drag chain along the top of the frame. The Duet software allows for both manual control and the programming of larger sequences. It can receive information from the AMBOTS control hub to initiate its sequence and tell the control hub that a sequence has finished or encountered an error. This control hub also coordinates the movements of the mobile robots, so it plays a crucial role in the refill process. Upon receiving the command from the control hub, the sequence proceeds as shown in Figure 20. Based on the speeds and accelerations set for each function in the Duet software, this sequence could theoretically be completed in 73.1 seconds.

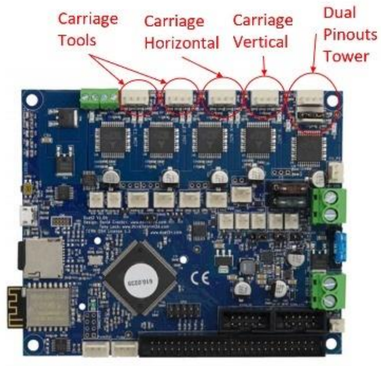


Figure 18: Duet board pinouts.

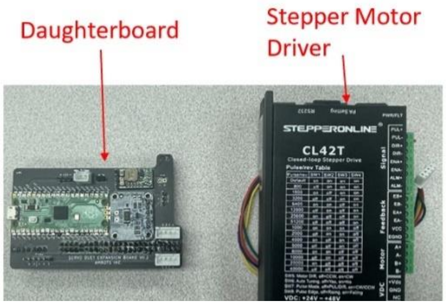
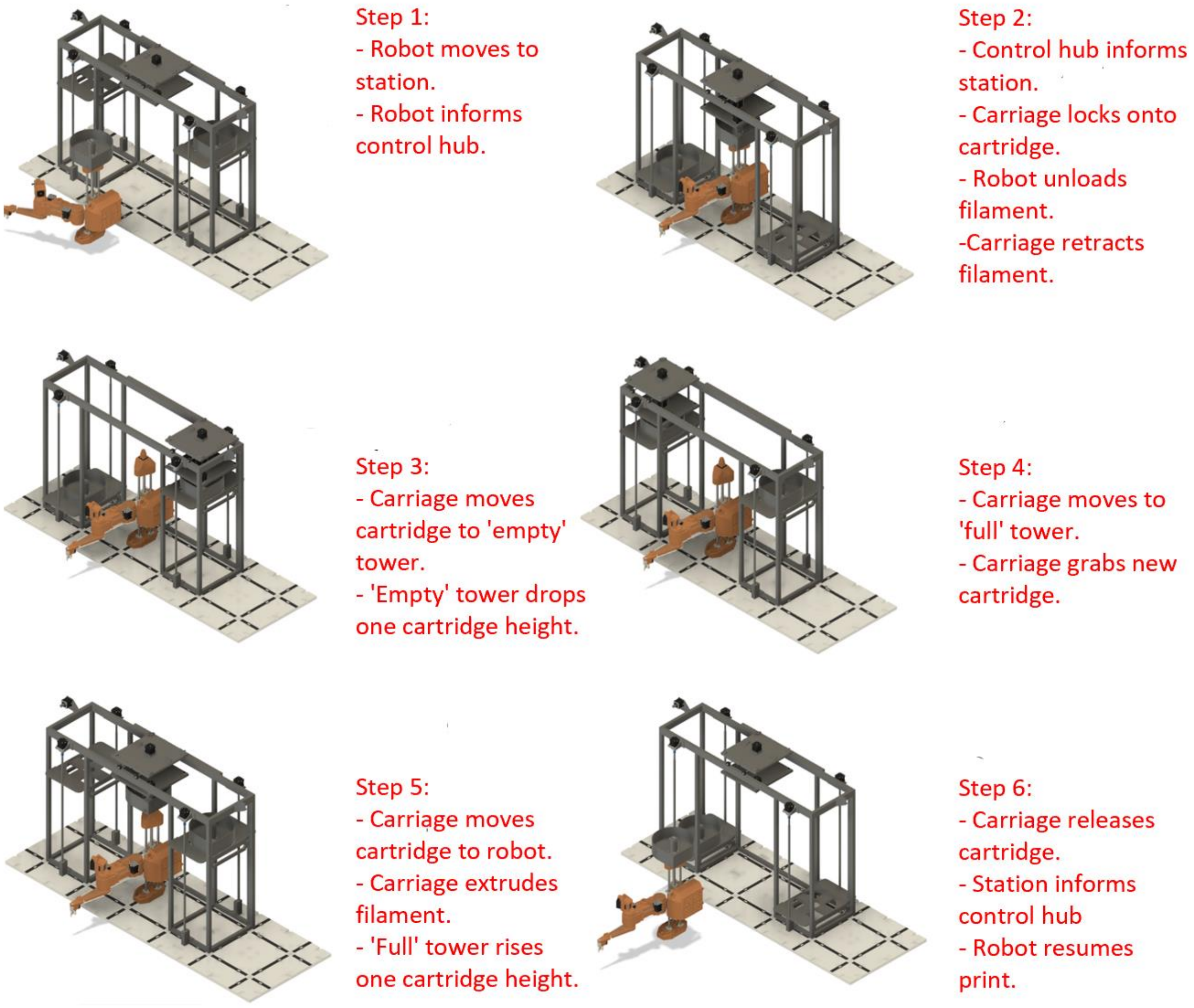


Figure 19: Duet board expansion with stepper driver.



Step 1:
- Robot moves to station.
- Robot informs control hub.

Step 2:
- Control hub informs station.
- Carriage locks onto cartridge.
- Robot unloads filament.
-Carriage retracts filament.

Step 3:
- Carriage moves cartridge to 'empty' tower.
- 'Empty' tower drops one cartridge height.

Step 4:
- Carriage moves to 'full' tower.
- Carriage grabs new cartridge.

Step 5:
- Carriage moves cartridge to robot.
- Carriage extrudes filament.
- 'Full' tower rises one cartridge height.

Step 6:
- Carriage releases cartridge.
- Station informs control hub
- Robot resumes print.

Figure 20: Sequence of functions.

It is worth noting that none of these functions are planned to require sensors. The frame is designed to fit over the floor tiles, and the robots dock at specific locations on those same tiles. As a result, the robot will theoretically be centered in the frame. This places the center of the robot in one plane with the centers of the towers and the center of the locking shaft (Figure 21). Since the taper on the locking shaft goes from 15mm to 25mm in diameter, the robot could theoretically be 5mm off-center in any direction before preventing the sub-carriage from docking with the old cartridge. Within the station, all motion will be displacement-based. For example, the Duet can be programmed such that the tower plates will move in precise increments the height of each

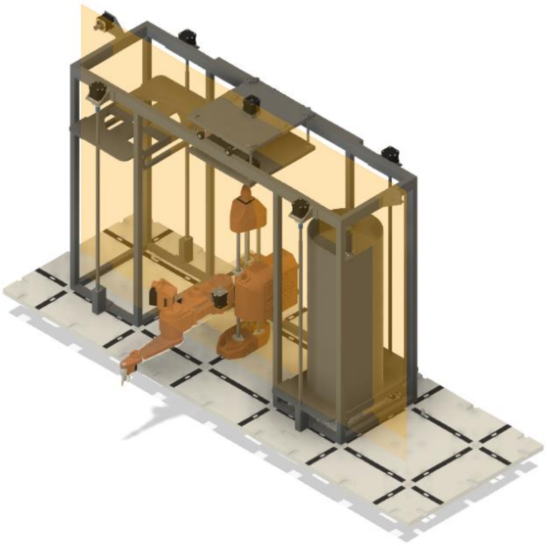


Figure 21: All cartridge mounting points in one plane.

cartridge. It can do this for a number of cycles equal to the maximum cartridge capacity before returning to the home position. The biggest risk to this method is the components being moved by outside forces. For example, if some external force were to move the carriage to the left or right, the control board would not know that the carriage's true position. Depending on the magnitude of this displacement, it could cause alignment issues or crash the station later in the sequence.

Chapter 3: Prototyping

3.1: Overview

While each function has remained the same, the mechanisms and materials used have changed with prototyping and testing. Initially, every non-purchased component was either 3D printed or made from aluminum extrusion. This became untenable due to the size and shape of the larger bodies, and the design strategy shifted to use a combination of acrylic and 3D printed parts. This increased part count and assembly time, but it hastened development since it could be more easily altered during testing. The carriage and cartridge mechanisms did not fundamentally change through the refinement process, but the tower mechanism changed entirely from a spring system to the final ball screw system. The frame has gone entirely unchanged from its initial construction.

Table 5: Overview of prototyping materials and processes.

Component	Material	Process
Frame	6063-T6 Aluminum	N/A
Carriage	PLA	3D Printing
	12x12x0.5" Acrylic Plate	Laser Cutting
Towers	PLA	3D Printing
	12x12x0.5" Acrylic Plate	Laser Cutting
Cartridge	PLA	3D Printing
	12x12x0.5" Acrylic Plate	Laser Cutting

3.2: Carriage

The initial carriage concept was a platform constructed from aluminum extrusion which would move in the horizontal direction only (Figure 22). This presented two challenges. First, it would be difficult to modify and expensive to construct multiple iterations. Second, it would rely on grabbing the cartridge and traveling between the robot and towers without any vertical movement. As a result, the split carriage concept using a non-metal frame quickly became preferred in design meetings. The vertical motion was initially going to be handled using a belt and pulley system. This changed to the lead screw since it was simpler, and the vertical motion did not demand the speed of a belt drive. The locking shaft motor was initially going to be a servo motor since the position of the shaft was all that mattered. This changed with the decision to use a Duet board, which could only control stepper motors.

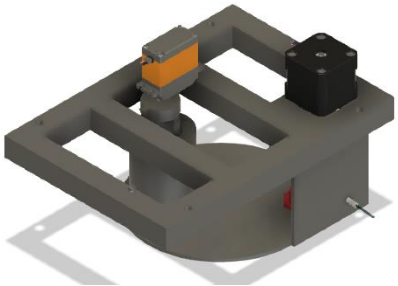


Figure 22: Initial carriage concept.

Table 6: PLA specifications [11].

Plastic Filament Parameter	Value
Material	PLA
Diameter	1.75mm
Print Temperature	180-220°C

The first prototype featured 3D-printed frames with these mechanisms and motors (Figure 23). The first carriage successfully crossed the frame horizontally, moved the sub-carriage vertically, locked and released a cartridge, and extruded filament from a cartridge. For this iteration, all functions were tested independently with an operator holding the cartridge at height. Two main problems manifested in this version. First, the horizontal belt drive was directly over the rear frame crossmember. While this did not pull the carriage off-track, it did present a challenge for

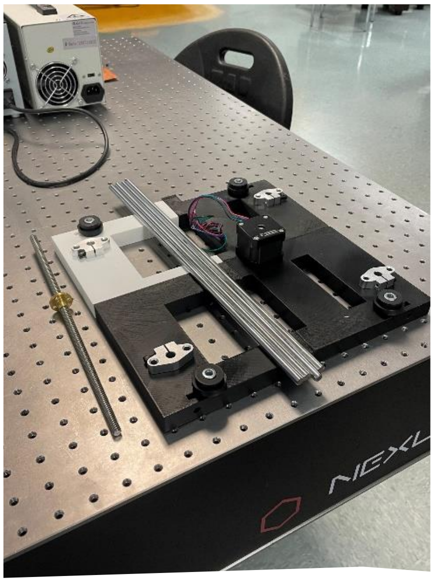


Figure 23: First top carriage prototype.

locating the drag chain and interfering with the tower motors as that design need became clear. Second, the 3D-printed construction was too big to be made in a single print. Rather, the carriage required eight total pieces to be printed and glued together. Furthermore, the edges of these prints often pulled up from the bed during printing. This is caused by uneven heat dissipation resulting from the large, flat shape of the components [12]. For these reasons, the final iteration was made from a combination of acrylic plates and 3D-printed brackets, including ones which could hold the belt near the middle of the carriage rather than hanging off the side.

3.3: Cartridge

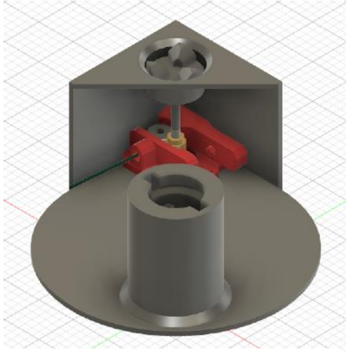


Figure 24: Initial cartridge concept.

The cartridge was initially a leaf-shaped base with only the central cylinder and extruder corner (Figure 24). The purpose of this design was to enable 3D printing of the entire cartridge as a single piece rather than as multiple glued pieces. This left most of the spool exposed, which presented challenges for stacking and concerns for objects getting caught in the cartridge. For these reasons, the first prototype was a fully walled, two-piece print (Figure 25). The extruder shaft had a single bearing at the bottom, and the central cylinder only included extrusions for the locking shaft. Extrusion and locking were successfully tested, but the robot had no way to retain the cartridge body. The body also had warpage problems for the same reasons as the carriage.

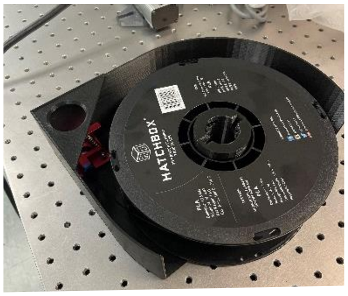


Figure 25: First cartridge prototype without secondary piece.

The final cartridge prototype took inspiration from the new carriage. The base was cut from acrylic, whereas the walls, central cylinder, and corner piece were printed and attached with screws. The cylinder was outfitted with a square extrusion at its top which was designed to fit into a square cut in the acrylic plate of the cartridge above it while stacked. This square cut also served as a retention mechanism for the robot top to prevent sliding and turning. The final corner piece featured a second bearing near the top for the extruder shaft, which made extrusion smoother and reduced the bending load on the shaft. This allowed the entirety of the shaft to be 3D-printed rather than assembled from a steel rod and a printed head.

3.4: Towers

The towers were the last mechanism to be designed and tested. The first tower mechanism was a base plate attached to the top of the frame by a set of springs (Figure 26). The idea was to select the springs based on the weight and height of the cartridges so that the addition or removal of a cartridge from the stack would move the plate up or down by one cartridge height. Finding springs which would behave in exactly this manner over the entire height of the towers was impractical, and it assumes that the cartridge C.O.G. lies directly above the geometric center of the plate, which is not the case. Resultingly, the tower mechanism was changed to the current ball screw design despite demanding four additional motors.

Table 7: Aluminum extrusion specifications [13].

Aluminum Extrusion Parameter	Value
Material	6063-T6
Finish	Clear Anodized
Weight	0.40 kg/m
Surface Area	1.60 cm^2

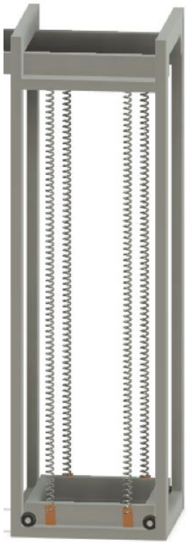


Figure 26: Spring concept.

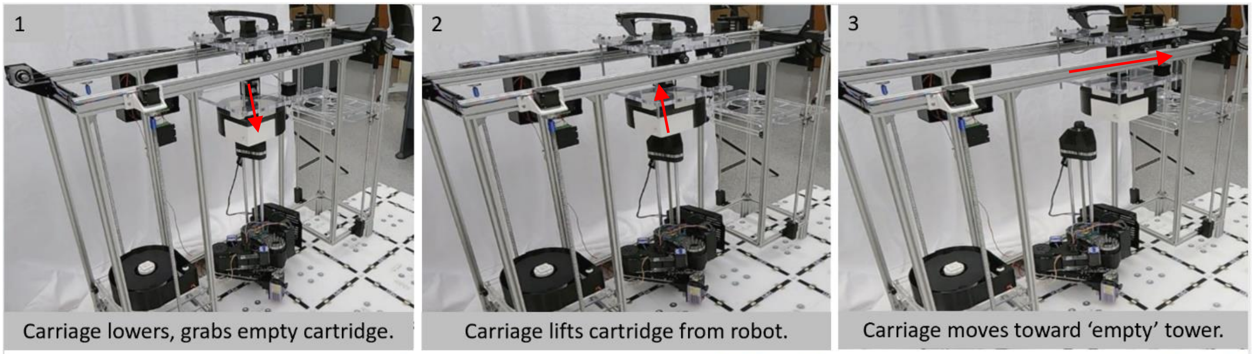
3.5: Costs

The prototypes were constructed from newly bought items and materials commonly stocked at AMBOTS. The final cost estimate for the station is shown by the bill of material in Figure 24 to be $1255.99, and each cartridge costs $34.61 to make. Cost information can be found in the bill of materials in Appendix A.

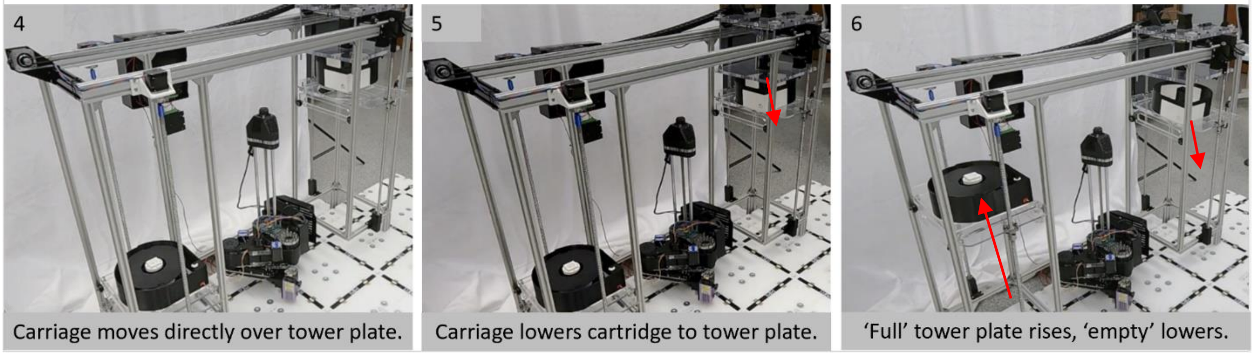
Chapter 4: Testing & Discussion

4.1: Completed Functions

Every mechanism is constructed and can be moved by manually entering g-code commands into the Duet user interface. To validate the internal station functions, the station begins with a robot parked and centered inside and an empty cartridge on top. The carriage lowers and locks into the cartridge with the locking shaft. It then lifts the cartridge from the robot. Once the sub-carriage is fully raised, the belt system activates to the carriage toward the 'empty' tower. Once positioned over the tower plate, the carriage lowers the cartridge and releases it. The 'empty' tower plate lowers while the 'full' tower plate rises, and the carriage moves across to the 'full' tower (Figure 27). (Note that the planned sequence has the 'full' tower plate rising into position after the carriage has grabbed the top cartridge. This is altered here for demonstration purposes.) Once in position, the carriage lowers, locks onto the new cartridge, and lifts it from the plate. The carriage moves directly above the robot, lowers the new cartridge into position, and



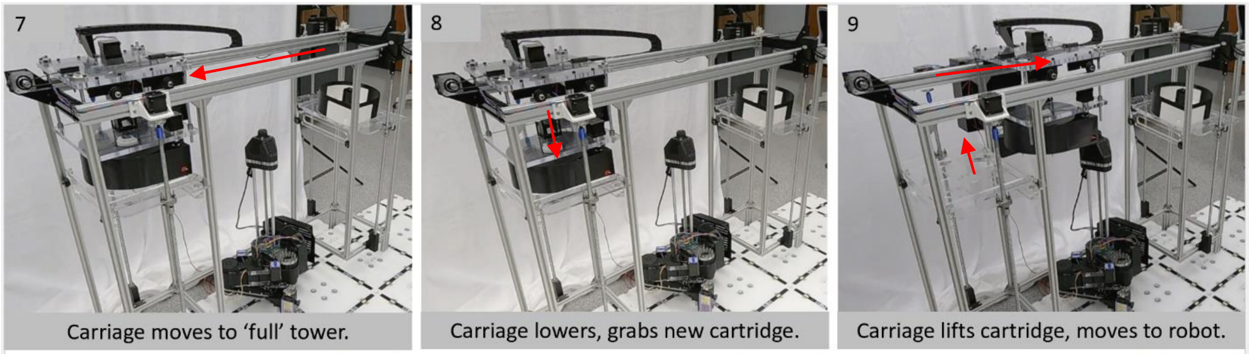
Carriage lowers, grabs empty cartridge. Carriage lifts cartridge from robot. Carriage moves toward 'empty' tower.



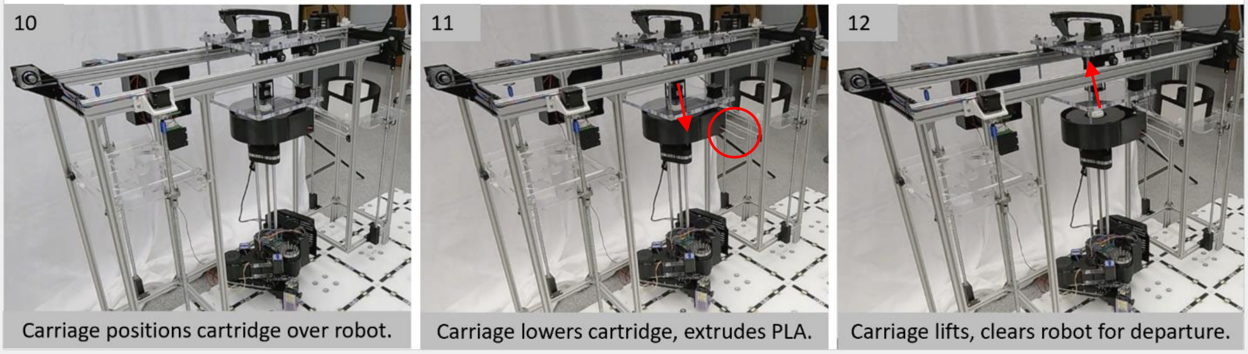
Carriage moves directly over tower plate. Carriage lowers cartridge to tower plate. 'Full' tower plate rises, 'empty' lowers.

Figure 27: Unload Sequence.

extrudes the filament. The carriage then releases the cartridge and clears the robot for exit (Figure 28).



Carriage moves to 'full' tower. Carriage lowers, grabs new cartridge. Carriage lifts cartridge, moves to robot.



Carriage positions cartridge over robot. Carriage lowers cartridge, extrudes PLA. Carriage lifts, clears robot for departure.

Figure 28: Reload Sequence.

4.2: Challenges

The frame is too short to house the current robot model with sufficient clearance for the sub-carriage. Placing the four corners of the frame onto 80mm tall pieces of extrusion brought the sub-carriage to a workable height (Figure 29), but it still required removing the top 32mm from the 65mm tall robot top (Figure 30). This indicates that the frame was 112mm too short in total, which requires an integrated solution to operate safely.

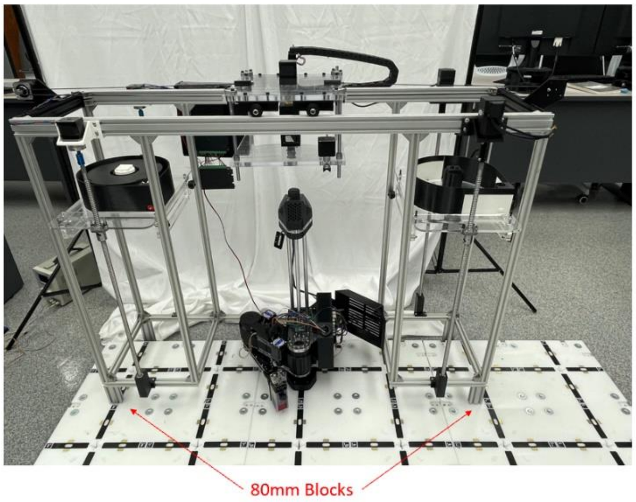


Figure 29: Blocks to raise frame.

Figure 30: Chopped robot top.

The carriage axle design and construction allow for the top carriage to slide laterally on its axles, meaning it can move out of the plane formed by the tower and robot center points (Figure 31). Since the forces from the belt are not applied along the center of the top carriage, the body can twist and catch itself on a frame member. The sub-carriage moves as intended, but the tooling on the sub-carriage requires more rigidity to function reliably. When the sub-carriage lifts a cartridge, the locking shaft is not always sufficient to hold the cartridge level. This

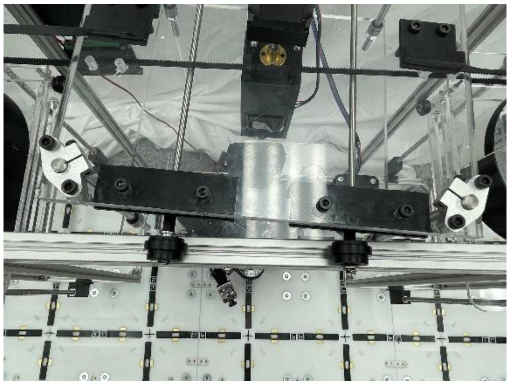


Figure 31: Carriage sliding on axles.

results in a misalignment between the extruder shafts on the carriage and cartridge which often requires manipulation by hand to fix (Figure 32).

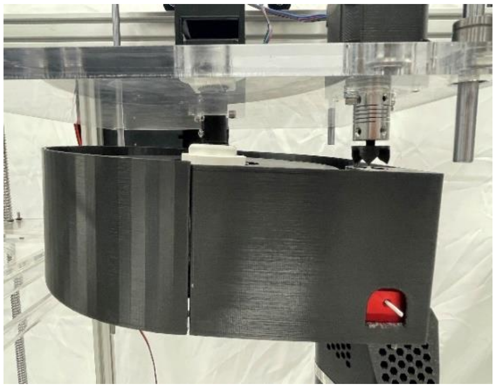


Figure 32: Extruder shaft misalignment.

The on-board cartridge extruder is a Creality 3D printer extruder, and it functions properly only when exchanged for a lighter spring (Figure 33). While the initial one-bearing design for the extruder shaft worked, the two-bearing design is much smoother and reduces bending on the shaft. That said, it is rather difficult to assemble given its many components and attached extruder. Its unloaded weight of 600g is acceptable, but this makes it difficult to scale the tower concept and requires the tower components to be heavy for strength.

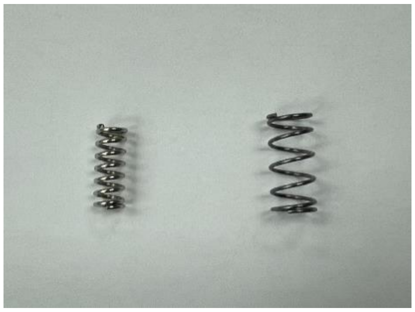


Figure 33: Proprietary spring (left) vs improved spring.

The ball screw tower mechanism is sound, and all four motors work. The issue is coordinating the motors to spin at the same rate. The motors which drive the loaded cartridge tower are connected to a twin pinout specially made for dual motor z-axis control in 3D printers. Their movements are identical as a result. The motors which drive the empty cartridge tower are connected to two external drivers through a daughterboard, which means they are not automatically coordinated. They do not spin at the same speed or for the same duration, causing the cartridge plate to tilt and bind (Figure 34).

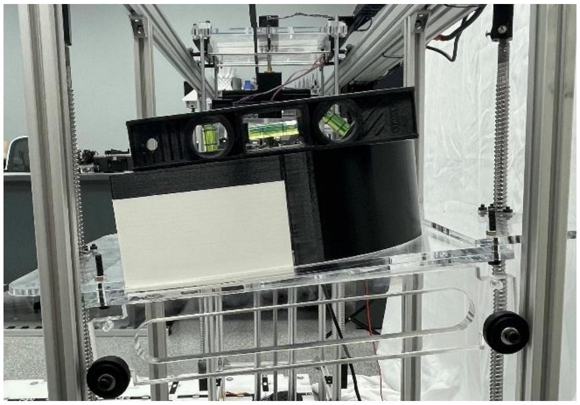


Figure 34: Tower plate binding from motor mismatch.

Based on a video recording of the station cycle, the cycle time is above target time and its theoretical potential. At present, it takes the station more than 45 minutes to complete a cycle when being controlled by both manually entering G-code and troubleshooting the previously mentioned problems. Subtracting operator interventions needed to make the next step and function reattempts, it takes approximately 8 minutes. If all the previously mentioned challenges were resolved and the sequence was pre-programmed, the station could cycle in 260 seconds or less. This is still much greater than the theoretical minimum time of 73.1 seconds. The towers can move while other operations are happening, so increasing their speed does not take away from overall cycle time. The most used function through the cycle is raising or lowering the sub-carriage, which theoretically takes 5.2 seconds in one direction. This, however, is calculated from the assumption that it only must travel 65mm in either direction. In testing, the sub-carriage was kept well above this height from the cartridge plates to avoid collisions caused by location and alignment issues. Reducing this vertical travel would do the most to minimize station cycle time.

4.3 Incomplete Components


Figure 35: Waste bin.

Before returning to the job site, the robot will need to load and extrude a small amount of filament. This necessitates a container for this waste material. The waste bin (Figure 35) is to be located immediately in front of either tower. This allows the arm to reach over, extrude filament, and discard it into the bin. The bin is printed, bit it needs bristles or small rubber fingers around its top rim to help separate the waste from the tool head.

Additionally, the filament extruded from the cartridge by the carriage needs to be guided to the robot’s extruder. This requires a cone affixed to the robot which will be positioned near the filament output on the cartridge (Figure 36). This cone is attached to a Bowden tube which runs to the robot's print head. The cone and tube have been assembled and tested under the power of the extruder while being manually held in place. The Bowden tube was cut to a length of 750mm, which is roughly equal to the maximum distance between the cartridge output and the toolhead as measured with the SCARA arm fully extended. The cone forced the filament into the tube as designed, but the friction between the filament and tube became excessive after traveling roughly 400mm. It did, however, push past the 90° downward turn without issue. This preliminary test indicates that reducing the distance between the cartridge and SCARA extruder is necessary to successfully refill the printer. One solution could be to have the arm raised to its maximum height during the reloading process, reducing the required Bowden tube length to 400mm or less. Once the filament is loaded into the arm's extruder, the arm can pull more filament out of the cartridge by moving downward.

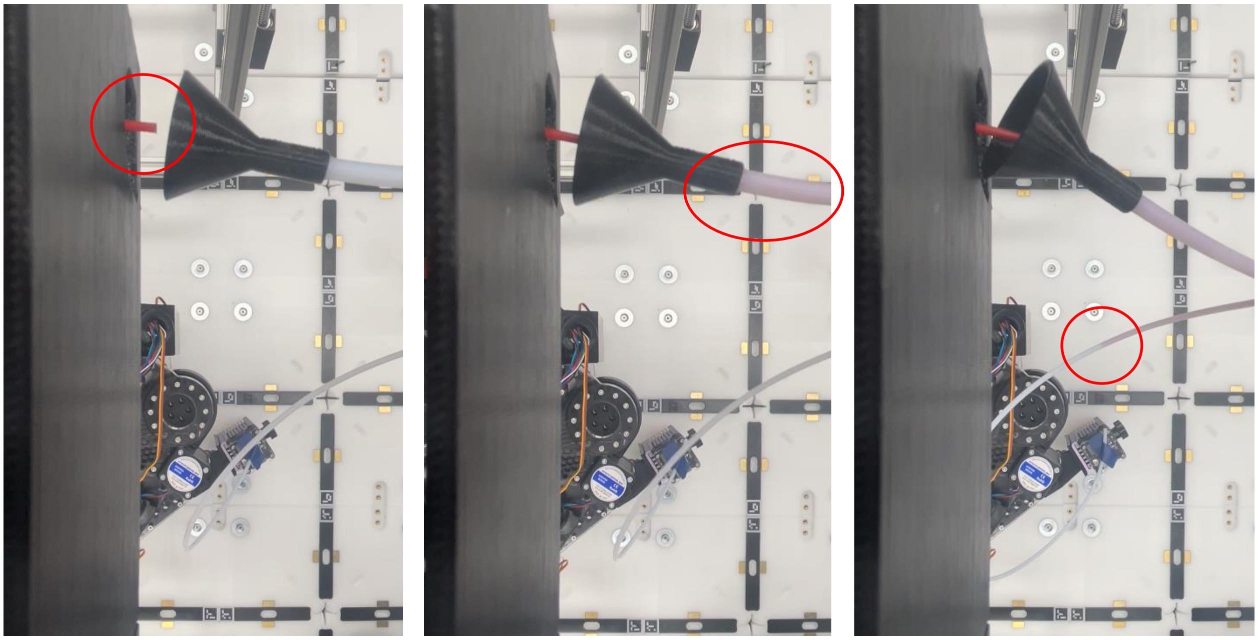


Figure 36: Filament progressing through Bowden tube.

Chapter 5: Conclusions

The vision of swarm manufacturing is to change the industry from one which is linear and rigid in its processes to one in which a digital platform of diverse mobile robots autonomously produces digital designs on-demand. If realized, this vision will result in enhanced quality and reduced cost of manufacturing and supply chain assets. This project has taken steps to close the gap between today's manufacturing environment and that of this vision:

- Developed automated filament resupply from an identified need to a specific design.
- Constructed a working prototype with cheap, common materials based on this design.
- Demonstrated the possibility of automating material supply for manufacturing swarms.
- Provided a starting point for the future development of automated material supply.

Chapter 6: Future Work

6.1: Refining the Current Iteration

The results to date indicate several areas of improvement for this prototype, and they inform a design path for the next iteration. The keys to refining the current iteration are dimensional accuracy and precision, greater rigidity, and better driver coordination. The frame needs to be 112mm taller than it currently is, and it needs to be anchored to the floor tiles rather than loosely resting on their surface. This will improve the reliable location of the robot, carriage, and cartridge during the reload sequence. This could be accomplished by printing plastic stands which fasten to the bottom of the frame (Figure 37). The rear set of stands could be designed to fasten to the extrusion underneath the floor tiles, and the front set could fit into the slots which are used to locate robots on the tile surface.

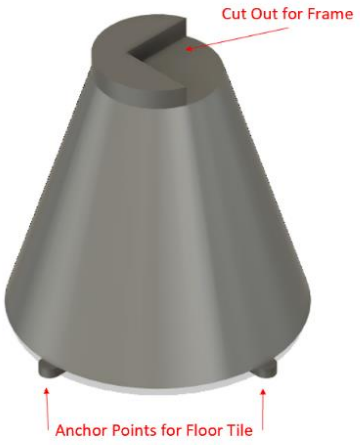


Figure 37: Frame foot concept.

The freedom of movement between the top carriage body and axles needs to be eliminated. Rather than resting on two solid axles, each axle bracket should have its own shaft. Printed shafts will be too weak to bear the weight of the carriage, but steel shafts which are pressed into the printed bracket would solve this problem (Figure 38). With the wheels sandwiched closely between bracket and the cotter pin, the body will not be able to move relative to the wheels. To further reduce the magnitude of such

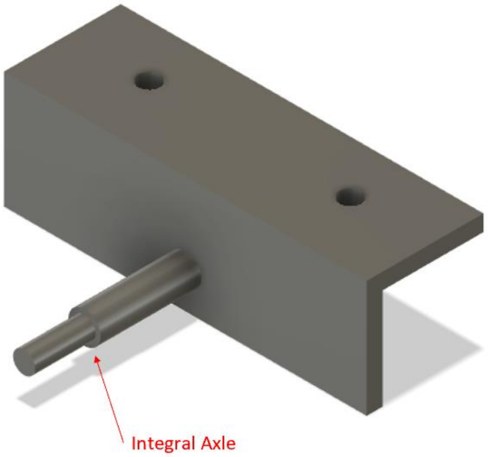


Figure 38: Integral shaft axle bracket concept.

displacement, the belt brackets and frame motor mount should be modified such that the belt moves above the top carriage rather than beneath. This is safer for the belt, and it eliminates the need to have the tension forces off-center to avoid interference with the lead screw.

The sub-carriage locking shaft and cartridge cylinder should be modified to work with four arms instead of two (Figure 39). The two-arm design creates an axis about which the cartridge can rotate. Adding another pair at 90° to the current pair will eliminate this problem.

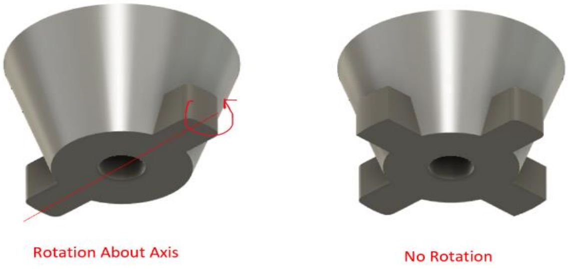


Figure 39: 4-arm locking shaft concept.

The next version of the cartridge should be made with reduced weight and complexity. Completely solid walls and base are not necessary for proper function, and cuts should be made wherever feasible (Figure 40). Furthermore, the cartridge should be designed such that the central cylinder and extruder shaft bearings are contained within the same piece (Figure 41). This increases the accuracy of the distance between the two, thereby reducing the alignment issues seen between the carriage tooling and the cartridge. The Creality extruder should either be replaced with one which has a lighter spring, or it should always be assembled with the lighter replacement spring.

Figure 40: Lightweight wall concept.

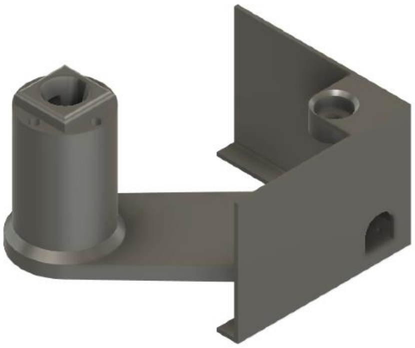


Figure 41: One-piece cylinder and corner concept.

The full cartridge tower worked flawlessly, so it needs no functional change. Making the wheel piece tinner and narrower would reduce the weight, but this is not necessary. The empty cartridge tower needs to function as well as the full cartridge tower. This would have to be the result of making the two external drivers which power it behave as the twin pinouts which drive the full tower. This fix requires further investigation to ensure that it is possible and to discover how it can be accomplished in the Duet system.

6.2: Designing the Next Iteration

Even with these solutions to refine the current iteration, it is still plagued with two fundamental design flaws: it is overly complex, and it is restricted in its capabilities. The tower motor problem is the chief symptom of the complexity, but others manifest themselves throughout the design. From the high part count of the cartridge and carriage assemblies to the three different systems which each have their own independent vertical motion, the station presents many opportunities for simplification. It is not that the complexity affords greater function or versatility. By leaving the vertical motion of cartridges partially to two towers rather than solely to the carriage, the station's cartridge capacity is limited to a single stack on either side. And the number of motors required to operate this configuration not only exceeds the Duet board's capacity, but also limits options for tooling. If even two motors were freed up, a third or fourth iteration could have either an enhanced set of primary tooling or a secondary tool set.

One way to achieve these solutions is shown in Figure 42. The carriage becomes a single platform which is mounted to a belt-driven horizontal axis. The entire structure of this axis is supported by Dual ball screws which move it vertically. This

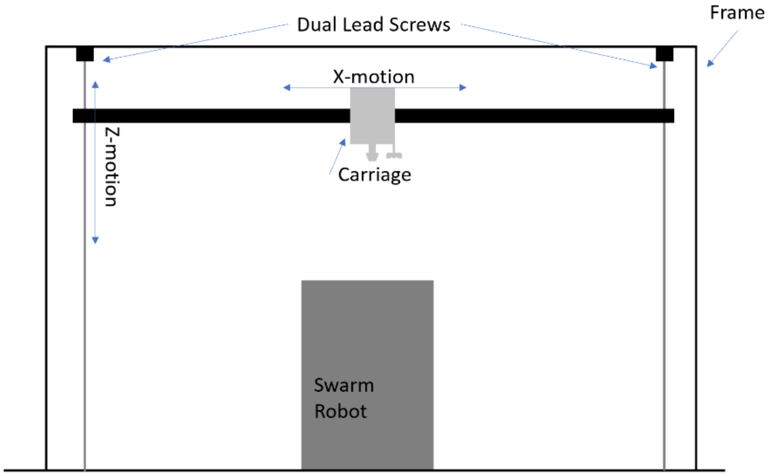


Figure 42: Next iteration concept.

design allows the carriage to be a single body rather than being split between an upper and lower half. It also enables the carriage to move vertically and horizontally within the entire space of the frame, which means the cartridges could be stacked on the floor tiles with as many stacks as the frame width allows. The frame itself could feature a triangular rear truss since nothing needs to move across the top rails. This station design would function with five motors: two for the ball screws, one for the horizontal belt, one for the locking shaft, and one for the extruder shaft. This eliminates the need for external motor drivers and leaves one open pinout on the Duet, which could be used for an additional tool or function to either aid in the filament refill process or to serve a new purpose.

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Appendix

Appendix A: Bill of Materials

Table 8: Bill of Materials

Description				QTY	Per Unit Cost	Total Costs
0	1	2	3			
Resupply Station						$1,255.99
	Frame					$ 240.40
		6mm Extrusion, 1x1, 300mm		6.0	$ 5.20	$ 31.20
		6mm Extrusion, 1x1, 1200mm		1.0	$ 14.05	$ 14.05
		6mm Extrusion, 1x1, 800mm		8.0	$ 12.08	$ 96.64
		6mm Extrusion, 1x2, 300mm		1.0	$ 7.11	$ 7.11
		6mm Extrusion, 1x2, 1200mm		3.0	$ 21.70	$ 65.10
		Corner Gussets, 20pc		2.3	$ 7.99	$ 18.38
		M4 T-Nut, 6mm Slot, 100pc		0.8	$ 9.78	$ 7.92
	Carriage					$ 183.63
		Top Carriage				$ 133.62
			Motor Pulley, 20T 5pcs	0.2	$ 5.99	$ 1.20
			Idler Pulley, 10pcs	0.1	$ 13.49	$ 1.35
			GT2 Timing Belt, 5m	0.5	$ 14.99	$ 7.50
			NEMA 17 Motor	2.0	$ 10.99	$ 21.98
			5mm x 300mm Rod, 5pcs	0.4	$ 9.99	$ 4.00
			8mm x 300mm Rod, 4pcs	1.0	$ 19.88	$ 19.88
			8mm Shaft Support, 6pcs	0.7	$ 10.99	$ 7.33

			Framing Technology RLR2906	4.0	$ 6.86	$ 27.44
			5mmx8mm Shaft Coupler, 4pcs	0.3	$ 12.99	$ 3.25
			Tr8x8 Lead Screw, 400mm	0.2	$ 15.59	$ 3.12
			M5x35mm SHCS, 20pcs	1.0	$ 9.77	$ 9.77
			M5 Hex Nut, 100pcs	0.2	$ 9.49	$ 1.90
			Top Carriage Body	1.0	$ 20.00	$ 20.00
			Axle Bracket	4.0	$ 0.32	$ 1.30
			Axle End	4.0	$ 0.05	$ 0.20
			Motor Spacer	1.0	$ 0.30	$ 0.30
			Frame Motor Mount	2.0	$ 0.55	$ 1.10
			Belt Bracket	2.0	$ 0.20	$ 0.40
			GT2 Timing Belt Spring, 10pcs	0.2	$ 3.99	$ 0.80
			M3x30mm, 50pcs	0.1	$ 10.34	$ 0.83
		Sub-Carriage				$ 50.01
			NEMA 17 Motor	2.0	$ 10.99	$ 21.98
			8mm Linear Bearing, 12pcs	0.3	$ 10.95	$ 3.65
			5mmx5mm Shaft Coupler, 5pcs	0.2	$ 9.99	$ 2.00
			M3x30mm, 50pcs	0.2	$ 10.34	$ 1.65
			Extruder Shaft	1.0	$ 0.08	$ 0.08
			Locking Shaft	1.0	$ 0.13	$ 0.13
			Locking Shaft Coupler	1.0	$ 0.15	$ 0.15
			Central Motor Bracket	1.0	$ 0.38	$ 0.38
			Sub-Carriage Body	1.0	$ 20.00	$ 20.00
	Tower					$ 523.67
		NEMA 17 Motor, 5:1 Reduction		4.0	$ 35.90	$ 143.60
		ZYLTech 12mm Anti-Backlash 1204 Screw w/Ballnut, 700mm w/o Blocks		4.0	$ 58.95	$ 235.80
		8mm Bearings, Pack of 4		1.0	$ 7.99	$ 7.99
		8mm Rigid Shaft Coupler, 2pcs		2.0	$ 7.99	$ 15.98

		Tower Motor Bracket		4.0	$ 0.63	$ 2.50
		Tower Bearing Block		4.0	$ 0.45	$ 1.80
		Ballnut Flange		4.0	$ 8.00	$ 32.00
		Wheel Piece		4.0	$ 5.00	$ 20.00
		Profile Piece		2.0	$ 16.00	$ 32.00
		Cartridge Rest		2.0	$ 16.00	$ 32.00
	Electronics					$ 308.29
		Duet 2 Wi-Fi Control Board		1.0	$ 192.10	$ 192.10
		Duet Expansion Board		1.0		$ -
		Closed Loop Stepper Drive		2.0	$ 44.33	$ 88.66
		Drag Chain, 10x20x1000 mm		2.0	$ 13.49	$ 26.98
		Duet Printed Case		1.0	$ 0.55	$ 0.55
Cartridge						$ 34.61
	Extruder			1.0	$ 9.99	$ 9.99
	Extruder Shaft Bearings, 10pcs			0.2	$ 7.99	$ 1.60
	Base Plate			1.0	$ 16.00	$ 16.00
	Wall			3.0	$ 1.20	$ 3.60
	Corner			1.0	$ 1.60	$ 1.60
	Central Cylinder			1.0	$ 1.75	$ 1.75
	Extruder Shaft			1.0	$ 0.08	$ 0.08