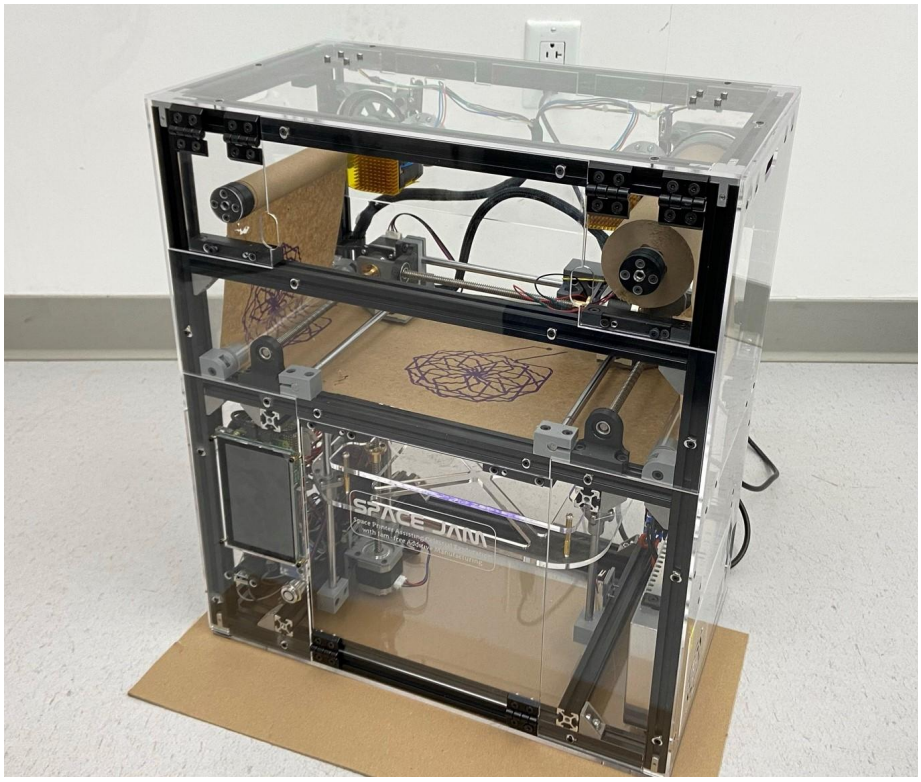
SPACE JAM:
Space Printer Assisting Celestial Exploration with Jam-free Additive Manufacturing

Isabelle Anderson, Lauren Hassi, Jeremy Kanovsky, Eric Wu

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Client: Professor Doug Matson (Tufts University), NASA

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Problem Summary

Executive Summary

The overall goal of this project was to design a self-contained, miniaturized ink-jet 3D printer that operates in zero-gravity. The final device is expected to be part of NASA's zero-gravity orbital flight as a demonstration of additive manufacturing during space exploration. For the purpose of the senior design course, a high-fidelity prototype, which validates the essential functionalities of each component, was developed to form a solid foundation for the final device that will be put together in the future.

In its final form, this printer will produce 3D geometries out of metal by applying layers of metal powder to a substrate and then bonding the layers together with a laser. NASA engineers will supply both the printhead and the laser, so our team's goal was to design the rest: the printhead/laser gantry system, substrate roller and tensioning system, electronics, and framework. We originally did not plan to build the printbed due to time constraints, but we later decided to include it in order to present a complete system.

Due to the unique constraints of launch and zero-gravity environments, our design process was subject to several key user needs and requirements. The device has a strict size constraint based on the size of the payload it will occupy, but the maximum print volume should be as large as possible. The device must print reliably and with high resolution. It should also be easy to use the printer, replace components, and secure parts during the high stresses of launch. With these requirements in mind, we began the concept generation process. We decided to consolidate the printhead and laser onto one gantry in order to maximize space for the printbed. We also chose to design a lead screw-driven gantry rather than a belt-driven one because it would better withstand the stresses of launch. The roller assembly and electronics systems were also designed for reliability and usability in launch and zero-gravity environments.

With our major design decisions made, we entered the prototyping phase. The first prototype was a simple proof of concept to test our stepper motor mounting and actuation. For the second prototype, we built the full X/Y- gantry and roller system. These are the two most critical

modules of the device, so we focused on validating these systems along with the corresponding electronics and aluminum framework. Our third and final prototype represents the complete system. We iterated upon our previous gantry and roller prototypes, and we added a Z-stage printbed. We also finalized the electronics needed to drive these systems, enclosed the hardware in acrylic, and added a user interface. The result was a device that is not only complete and functional but safe, easy to use, and professional.

Once our final build was completed, we performed a series of tests. To ensure that the device is not dependent on gravity, we operated it in all six possible orientations. We found that it functions equally well in all orientations, a good indicator that it will work in zero gravity. We tested the X/Y- gantry by mounting a marker in place of the printhead and assessing the accuracy of its tracings on the substrate. To test the rollers, we verified that they could return the substrate to a certain position after a series of random movements. In addition, we tested one-dimensional motion in the Z-stage. Having finished this thorough testing plan, we are confident that our device delivers repeatable accuracy in all subsystems, independent of gravity. Although improvements could be made to the materials and fabrication processes used, the device successfully meets all requirements for a prototype 3D printer bound for zero-gravity flight.

Background and Long-Term Vision

The technology we used is a derivation from Laminated Object Manufacturing (LOM), which is an additive manufacturing technique for printing 3D objects from custom digital files [1]. Generally, LOM devices generate 3D geometries via sequential stacking of sheet materials from a moving roller. Each layer is bonded on top of each other through lamination at specific dimensions, and is then cut away from the remaining materials using a carbon dioxide laser.

The main difference between current LOM machines and the device we are building is that instead of starting with a roll of metals to be laminated, the exact amount of materials in each layer will be applied to a roll of substrate. A custom-made ink-jet spray head on a gantry system will apply metal powder to the substrate, which will then transfer the powder patterns on top of the print bed. A fiber optic laser system will then bind the powder to the print bed while burning out the overlapped substrate materials. The device will repeat the process layer by layer to

produce 3D geometries. The remaining substrates will be collected at the other end of the machine and can be reused or disposed of. The modified technology would result in a system similar to the LOM machines but with reduced weight and size, both of which are critical to introduce new technologies to space explorations.

Currently, there exists a Fused Deposition Modeling (FDM) printer on the International Space Station (ISS). This printer is by a company called Made In Space. Unfortunately, this printer also is limited in terms of its capability. FDM printing suffers in terms of part quality and overall build volume, as well as the maximum print speed in each axis. The resolution and quality of FDM printed parts is significantly worse than machines that use laser technology to fuse material onto a part. LOM methods, applied to 3D printing in zero-gravity environments, would yield stronger, more reliable parts with better print resolution in a shorter period of time.

Problem Statement

Our goal in designing this device is to test the feasibility of new technologies compared to existing methods for printing in zero-gravity environments. 3D printing provides massive benefits for space missions that must be concerned with the overall weight of items launched by virtue of being able to quickly produce any number of parts or tools. Using LOM methods, we aim to create a device capable of printing using a novel material deposition technique, and explore the potential for novel manufacturing methods in zero-gravity environments.

Design Recommendations

Problem Definition & Description of Needs

Most of the user needs for this device are based on the client meetings and presentations given to us by the client and primary stakeholder, Doug Matson. Additional needs came from the other stakeholders, such as NASA and the astronauts who would be using the device. The majority of the functionality needs are based on the device's goal of creating 3D metal objects in space, while more technical needs are from the primary stakeholder's requests. Through our own experience in the field and research we added more functional requirements to create the prioritized table of needs seen in Appendix 1, Table 1.

The client and main stakeholder, Doug Matson, emphasised the importance of creating a functioning design while staying within set limitations. Overall Matson focused on restricting size, as weight of the prototype is less of a concern. Matson also spoke on the importance of accomplishing a functioning system that can stand up to several technical requirements which are based on the industry standards.

Working towards meeting industry standards includes needs such as resolution and print speed, as well as materials that meet aerospace specifications. This is more essential for the final design and not the prototype, but it is a goal to aim for. Our gantry and roller subsystems were all considered when creating the functionality needs. Some economic needs also come from expected prices for LOM printers. We elaborated on the need to create a reliable device by adding the needs of repeatability, reliability, and avoiding paper or substrate jams.

Our secondary stakeholders, NASA and the astronauts, were also considered and many user design needs were added. The ease to replace ink and paper, the power consumption, and accepting standard files and ease of printing overall were all considered. Making a printer that functions is essential, but it is also important that the interface is intuitive and the printer is practical and easy to use in space. This was kept in mind when grouping needs from previous tables to create the prioritized table found in Appendix 1, Table 1.

Description of Requirements

Our device has several functional and engineering requirements that dictate certain portions of our design. A full list of engineering requirements can be found in Appendix 1, Table 2. By virtue of the launch parameters for sending objects to space, and the payload size our printer will occupy, our printer must not exceed a maximum physical dimension. Similarly, the weight of the device is constrained as a function of payload size.

Other functional requirements are more directly related to the quality of the parts our printer will produce. Hobbyist and industrial 3D printers set a standard that we intended to match to prove the viability of our solution. This includes the print resolution in the X-, Y-, and Z-axes, as well as the print speed in the X-, Y-, and Z-axes. Because our X- and Y-axes are dependent on both an inkjet stage and a laser stage, we must match these two parameters. Our printer must also contain a minimum printable volume, ideally with none of the axis dimensions significantly greater than the other two.

Our printer must operate in accordance with a number of electrical constraints. The printer must be operable using the same voltage as electrical outlets used in space or on “zero-gravity” airplanes. We must also ensure the overall power requirement of the printer is not in excess of the power available from such outlets.

Finally, our printer must operate in a consistent and safe way for the operator. The framework of the device must be strong enough to both survive launch, as well as any potential vibrations or impacts it may encounter while in space. It must not pose a danger to the operator of the printer, partly in terms of pinching or crushing, but also by not exposing the user to high voltage wires. The consumables of the printer must be easily replaceable, and any jams must be diagnosable and fixable by the operator. The prototyping and actual cost of the printer should not exceed pre-specified limitations, and the cost of the consumables must not exceed the specified quantity.

Description of Weighted Matrix

As shown in Appendix 1, Table 3, we found the most important requirements to be materials used, the device's framework, and resolution of the printhead, laser, and Z-axis. It is not surprising that the materials are so important. Materials impact the cost, weight, and durability of the device. In order for our device to survive launch and be useful in space, the materials must be lightweight yet strong.

Ranked second is the framework used to enclose and protect the components. When designing a device like this, it is easy to focus on the complex components and leave the housing as an afterthought. However, this result indicates that the framework should be a priority. If the components are not completely secured, the device will not survive launch.

Ranked next is the resolution, which applies to the printhead, laser, and Z-stage. They are listed as separate requirements because each mechanism is slightly different, but they are equally important for the device's overall resolution. Resolution is one of the key qualities that separates a good 3D printer from a bad 3D printer. It is a metric that can be used to evaluate the success of our device. We may not have the ability to meet industry standards, but any improvements made to our print resolution add value for the client.

Concept Generation and Concept Evaluation

Our starting point for concept generation was provided to us by our client. As shown in Appendix 4, Fig. 1, the client's design included three stages within the printer. The first is a printhead that transfers the print layer onto the substrate, the next is a laser that cuts away excess substrate, and the third is a laser that consolidates the print layer onto the existing layers on the z-stage. Our initial goal was to simplify this design. Our client suggested that we use only one laser to accomplish both functions, so we began ideating different ways to position the printhead and laser stages within the overall assembly. The results of this ideation are summarized in Appendix 4, Table 4.

For concept generation of the end stops and our roller assembly, see Appendix 4, Table 5. Here we are showing some of the ideas that we considered before making our final decisions. For end

stops, we chose to use physical limit switches due to price, size, and availability compared to the alternate ideas. For our roller assembly, we chose to use a torsional spring mechanism for the same reason. While there exist extremely high precision roller tensioning mechanisms available for purchase, they are far more expensive than the budget we had for this prototype and difficult to find in a size that would fit into our printer.

Final Decision Rationale

During and after our concept generation phase, we considered a number of potential failure modes for our printer. Eventually, after weighing the relative pros and cons of each design decision, we settled on what would become our final prototype. We chose to use lead screws to drive the main axes of the printer as they are less susceptible to breaking compared to belt driven motion. We also chose to reduce the number of overall gantries, a choice which let us consolidate the motion required for the printhead and for the laser into a single X/Y planar motion system.

We also chose to mount the roller assembly on one side of the printer, with the roll of substrate dividing the rest of the usable volume of the printer. This allowed us to mount the X/Y- gantry for the laser and printhead on one side, with the Z-stage moving parallel to the Y-axis on the other. In doing so, we were able to free up space at the bottom of the printer for the electronics to sit. It also gave us usable space between the roller assembly where a more powerful laser diode (or other required electronics) may sit.

Once we had settled on these decisions, we analysed the most likely causes of failure and how impactful they would be to the functionality of our printer. Appendix 7 has the table we generated illustrating the failure modes. We considered these carefully while making our final design decisions. In order to prevent or repair any damages, we designed a printer housing that opens easily and closes securely. The outer plates attach with magnets and can be locked with thumb screws. This design allows users to secure all components during launch, reducing risk of damage. Users can then simply remove the thumb screws for easy access to the printer’s interior when repairs or replacements are needed.

At this stage, we also consulted on our design with our client. We asked for feedback and input regarding the design decisions we had made, so that before we begin fabrication they might voice any issues or potential problems with our plans. Fortunately, there were no major flaws found in the design at this time. We were able to begin building a series of proofs-of-concept and prototypes for each of the axes of motion of the printer.

Prototyped Solution

Prototype Stage #1: Overall placement of components and movement of X/Y- gantry

The first prototype was a simple way to see if it was possible to control two stepper motors in tandem that would in the future hold the third stepper motor. This is shown in Appendix 8, Figure 6. It was also the first iteration of the rollers and where in the assembly they would go. The electronics are shown in Appendix 8, Figure 7 along with the two stepper motors and the corresponding lead screws.

Prototype Stage #2: Roller assembly and finalized X/Y- gantry

The second prototype's CAD model is shown in Appendix 8, Figure 8. This prototype showed the first iterations of the full roller assembly, which combines two moving roller mechanisms and two idle rollers. These rollers are driven by stepper motors, and the roller mechanism that starts with the substrate is kept in tension by a torsional spring. This was also the first complete prototype of the X/Y gantry. It included the three stepper motors, the corresponding linear rails, and two L shaped brackets to attach the Y- stage to the Z- stage and the printhead holder. More electronics were added to correspond to the three additional stepper motors.

Prototype Stage #3 (Final Version): Added Z-stage, finalized electronics, wire management, and enclosure.

The final version of the printer was built based on all of our previous design and prototyping iterations. In addition to all of the previous components, we decided to make a rudimentary Z-stage to have a complete representation of the printer's hardware system for the final deliverable. The final prototype encompassed lots of changes from the many iterations that were made to optimize the design. This is shown in the CAD model found in Appendix 8, Figure 10.

Appendix 8, Figure 11 shows some of the more specific changes that were made, including wire management and a clear acrylic enclosure.

Experimental Validation of Designed Solution

As explained above, the ideal metric for the success of our printer is safe, repeatable, and consistent actuation across all the drive axes, as well as functionality independent of orientation relative to gravity. To test this, we experimented by orienting our printer on each of its six faces while experimenting with its operation. We found there was no noticeable difference between orientations and decided it could perform equally well in each state.

We also developed tests for each of the driven axes. On our printhead assembly, we included a mount for a Sharpie marker. Using this, in conjunction with our mock substrate, we have a rudimentary X/Y plotter with (pseudo-)infinite length. We created a series of test programs that would allow us to actuate the X/Y- gantry and roller system to draw patterns on the substrate. We performed a number of these tests, comparing the results each time for dimensional accuracy compared to the input parameters and commanded motion. We also experimented by drawing over the same section of the substrate multiple times sequentially to validate that it could return to the same position each time. This test also allowed us to validate the motion portion of the firmware, showing that we could correctly home all the axes against their end stops and have smooth motion across all drive axes. It also had the effect of highlighting any mechanical slop in the system or pieces that might interfere with each other during motion. These we quickly rectified before continuing with our testing.

The Z-stage, being a single independent axis, was more easily tested. We initially calibrated the Z-stage actuator using our end stop limit switch, and then performed a series of random, one-dimensional movements, which included the entire range of motion for the bed. We then commanded the Z-stage to reset itself to the original limit switch calibration state, and we manually verified that it returned to the same position it started in. This was easily done; if the bed did not interact with the limit switch, the LED on the limit switch would not turn on. If it overshot the calibration state, it would break part of our device. Due to neither of these events

occurring, we are confident it has repeatable motion. This same test we ran manually for both the X- and Y-axis after validating its success on the Z- stage.

Our roller assembly was slightly less easily tested. We began by homing the rollers by hand, which required us to manually calibrate the system until the torsional spring tensioning system was engaged on the unroller side. We then drew a mark on the paper to indicate our position, and proceeded with a number of random motions forward and backward, driving each motor at the same time. At the end of these moves, we commanded the roller system to return to its original position and compared the mark we made on the paper with where it was before we began testing. Here too we found repeatable accuracy across the two stepper motors that comprise the roller system.

We performed these tests with the printer in a number of orientations to ensure that the successful motion of the printer was not an artifact of the direction of gravity. While this isn't a perfect simulation for how the printer will function in zero-g, we are confident the motion of the printer is not dependent on gravity.

Conclusions and Future Work

Strengths and Limitations of Final Design Solution

There were a number of things our printer did quite successfully. By our final design, we had full range of actuation across X-, Y-, Z-axes, and our roller assembly. This includes driving six stepper motors in parallel and being able to calibrate and home all the axes absolutely. Our printer met the weight requirement and size requirements set forth by our client. We also successfully met the power requirements and can operate from a 24V DC power supply. Additionally, our printer does not rely on gravity to function and can operate equally well in all orientations, indicating that it would do well in a zero-g environment.

However, there are also a number of limitations to our design. One of the most major is the difficulty to repair. If a part breaks, it is possible that large portions of the printer must be disassembled in order to fix it. This is definitely sub-optimal for a printer operating in an

environment that has limited resources to fix things that may go wrong. Secondly, our printer relies on a large number of different pieces to function, too many to send replacement parts for. This means that when something breaks, it may be difficult to find a replacement without making one custom. Again, this is hard to do in the environments where this printer would be deployed. Finally, our printer was fabricated using mostly aluminum, acrylic, and 3D printed plastic parts. These together make it extremely unsuitable for deployment into space and would need to be changed for more solid components before launch.

Suggested Revisions for Future Iterations

There are a number of improvements that could be made to our device for future iterations. We found these through the fabrication process, assembly process, and while testing the capabilities and operation of our printer.

The most important consideration for future iterations would be the material choice and fabrication process of the printer. Due to time, budget, and resource constraints, we chose to primarily fabricate our printer out of aluminum extrusion, acrylic plates, and 3D printed parts (using PLA plastic). Given infinite resources, we would have chosen our construction materials much more carefully. For example, most of the aluminum extrusion could be replaced with stronger or lighter materials, cut more precisely. We, unfortunately, cut the aluminum by hand using a hacksaw (due to limited access to additional power tools), and there are pieces of the frame of the printer that do not line up as well as we would like. This introduces problems, not only in the strength of the frame, but also in the overall fit of all the other pieces being mounted against the frame. We could also recommend the acrylic plates be replaced with polycarbonate, or carbon fiber plates for the purposes of strength and weight. We chose clear acrylic because it was something we could laser cut that would still allow us to show the inside of our printer for demonstration purposes. However, it is heavier and more prone to cracking and breaking than would be ideal for this device. Where we chose to use 3D printed pieces to save on time and money, and for ease of fabrication, we would recommend a sturdier material. Perhaps, for example, these pieces might be CNC milled out of aluminum or 3D printed out of a sturdier material such as carbon fiber.

We would also recommend more consistency and quality in terms of the bolts and other attachment hardware used in assembly of the printer. We used a number of screw sizes, and many that were inconsistent with one another. This was primarily due to a scarcity of available materials and to save on cost. There are places we used standard metric nuts where nylon locking nuts would provide much better insulation against vibration and would be less likely to cause problems while testing in space, or during the launch process.

Finally, we would recommend that more money be placed into the construction of the roller assembly. We chose to construct our own tensioning system using a torsional spring, as this was the only solution we could find that would fit into our limited budget. In the future, it would be greatly beneficial to use a constant force spring or other mechanism that would ensure more stable tensioning of the substrate between the two driven rollers. We tensioned the rollers by hand for the purposes of testing and validation, but it would also be beneficial to include a torsion measuring system so the rollers may automatically tension themselves, and maintain that tension during operation.

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Appendix 1: Needs and Requirements Tables

Table 1: Prioritized Table of Needs

Needs			
Type	**Need**	**Description**	**Weight**
Economic	Prototype Cost	The cost of the prototype of the device needs to be within the limit specified by course instructor	5
Economic	Actual Cost	Cost of the final device should be similar to industry-standard printers on earth	2
Economic	Maintenance Cost	The device should be able to be maintained within reasonable cost	2
Economic	Material / Reload Cost	The materials shouldn't cost more than similar printers	2
Functionality	Contains print head, laser, roller, and Z- stage assemblies	The device should contain all components within the structure of the device	5
Functionality	Use modified LOM technology	The research and technology put into Laminated Object Manufacturing (LOM) will be used to aid the creation of the device	5
Functionality	Fits in the payload	The device should contain all components within the mini payload allotted space, 18.5" x 11.25" x 21.5"	5
Functionality	Survive launch conditions of space mission	The device needs to withstand the acceleration and tumultuous launch conditions	5
Functionality	3D print shapes in metal	The device needs to be able to create 3D objects made from metal	5
Functionality	Reliable for use time after time	The device should be able to be used repeatedly without breaking or jamming	4

Functionality	Repeatability	The device should be able to perform multiple print jobs before it needs maintenance	4
Functionality	No paper/substrate jams	The device should minimize the chance of jamming issues of the substrate	3
Functionality	Weight Constraint	The device should meet the weight constraint of the specific launch mission	2
Functionality	Functions in zero gravity	The device should be functional during orbital flight with zero gravity	5
Functionality	Attempt to meet current industry standards	The device should aim to meet the current industry standard of LOM metal printers, or equivalent metal additive manufacturing devices	3
User Design	Self-sufficient	The device should be fully functional without a need for separate components	5
User Design	Accepts custom 3D files	The device needs to be able to print based on standard file types for additive manufacturing.	4
User Design	Ease to replace inkjet/substrate	The users need to be able to replace the consumable components easily	3
User Design	Aesthetics	Users are more likely to have a positive experience if the device looks appealing and the interface is simple and comprehensible	1
Efficiency	Power Consumption	The device needs to be power efficient as it will be drawing power from the ISS	2

Table 2: Table of Requirements

Requirements		
Requirement	**Description**	**Target Value**
Dimensions	Total size of device	18.5” x 11.25” x 21.5”
Weight	Total weight of device	120 lbs
Setup Time	Time to upload and begin print	5 minutes
X/Y Printhead Speed	Maximum velocity of the printhead printing in the X/Y-axes	200 mm/sec
X/Y Laser Speed	Maximum velocity of the laser printing in the X/Y- axes	200 mm/sec
Z Axis Speed	Maximum velocity of the Z-stage gantry	100 mm/sec
Printhead X/Y- Axis Resolution	The maximum achievable resolution of the printhead jetting in the X and Y dimensions onto the substrate.	0.10 mm (100 microns)
Laser X/Y- Axis Resolution	The maximum achievable resolution of the laser gantry in the X and Y dimensions.	0.10 mm (100 microns)
Z-Axis Resolution	The maximum achievable resolution of the z-stage of the printer (i.e., the “vertical” part of the piece)	0.10 mm (100 microns)
Operating Voltage	Operating voltage of the device	124 volts DC
Power Consumption	Maximum power required by the printer for any operation	300 Watts
Print Volume	Max. capacity for completed print	190 mm x 190 mm x 190 mm
Materials Used	Materials used in the final device	Meets aerospace specifications
Setup Procedure Complexity	Number of operations needed to start print job	< 5

Structural Stability	Maximum stress the device needs to survive without breaking	6g
Framework	Contains framework to enclose and protect all components	No loose components
Number of Exposed Wires	Wires exposed to user or surroundings	None
Amount of Harmful Materials Released	Chemicals released to surroundings	None
Prototype Cost	Cost of parts, material, and components for prototype	$600
Actual Cost	Cost of final product	$150,000
Cost to Replace Components	Cost to replace components when broken	$150

Table 3: Quality Function Deployment Diagram

Stakeholder Needs	Weight	Dimensions	Weight	Z Axis Speed	XY Printhead Speed	XY Laser Speed	Framework	Structural Stability	Print Volume	Operating Voltage	Printhead Axis Resolution	Laser XY Axis Resolution	Z Axis Resolution	Power Consumption	Materials Used	Setup Time	Setup Procedure Complexity	Cost to Replace Components	Prototype Cost	Actual Cost	Harmful Materials Released	Number of Exposed Wires
Prototype Cost	5	3	3	2	2	2	5	3	3	5	6	6	6	8	4	0	2	0	10	10	1	0
Actual Cost	2	3	3	2	2	2	4	3	3	5	8	8	8	8	8	0	2	0	10	10	1	0
Maintenance Cost	2	1	1	0	0	0	4	1	1	0	4	4	4	0	7	0	0	3	10	10	1	0
Material / Reload Cost	2	1	1	0	0	0	4	1	1	0	2	2	2	0	7	0	0	10	9	9	1	0
Contains print head, laser, roller, and Z stage	5	6	6	2	2	2	8	3	4	5	5	5	5	0	4	0	2	0	0	0	1	5
Use modified LOM technology	5	3	3	6	6	6	1	1	4	5	2	2	2	0	4	0	2	0	0	0	1	2
Fits in the payload	5	10	7	0	0	0	5	7	7	5	2	2	2	0	2	0	0	0	0	0	0	4
Survive launch conditions of space mission	5	1	7	0	0	0	6	9	1	2	2	2	2	0	7	10	0	0	0	0	1	4
3D print shapes in metal	5	3	3	2	2	2	1	1	1	0	0	0	0	0	2	0	2	0	0	0	1	0
Reliable for use time after time	4	0	0	2	2	2	5	7	0	2	2	2	2	0	5	0	0	0	0	0	1	4
Repeatability	4	0	0	1	0	0	5	6	0	0	4	4	4	0	5	0	0	0	0	0	1	3
No paper/substrate jams	3	1	0	0	4	4	0	1	0	0	0	0	0	0	2	8	0	8	6	6	0	2
Weight Constraint	2	7	10	6	6	6	5	7	4	5	6	6	6	0	6	0	1	0	0	0	0	0
Functions in zero gravity	5	1	1	5	5	5	2	1	0	0	4	4	4	0	2	0	0	0	0	0	0	1
Attempt to meet current industry standards	3	3	2	0	0	0	0	1	4	6	10	10	10	0	1	0	1	0	0	0	0	2
Self-sufficient	5	3	1	2	2	2	0	0	0	2	3	3	3	8	0	10	2	0	0	0	0	2
Accepts custom 3D files	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	1	0	0	0	0	0
Ease to replace inkjet/substrate	3	2	0	0	0	0	2	0	0	0	0	0	0	0	1	10	0	0	0	0	0	2
Aesthetics	1	0	2	0	0	0	5	0	0	0	0	0	0	0	2	0	0	0	0	0	0	10
Efficient Power Consumption	2	2	2	8	8	8	0	0	0	10	5	5	5	10	1	0	2	0	6	6	0	0
Weighted Sum of Scores:		196	197	139	147	147	225	207	130	186	224	224	224	116	237	194	67	50	138	138	39	146

Appendix 2: Bill of Materials

Components	Item	Link	Link for CAD	Qty	Cost per	Total no shipping	Notes
ORDER ROUND 1							
Print head	8mmx250mm shaft	https://www.amazon.com/	will make	1	$10.99	$10.99	Pack of 2
	Slide blocks with ball bearing	https://www.amazon.com/	https://grabcad.com/lib	1	$9.29	$9.29	Pack of 4
	T8 Screw Nut	https://www.amazon.com/	https://grabcad.com/lib	1	$9.99	$9.99	Pack of 4
	NEMA 17 with T8 screw 210mm	https://www.amazon.com/	https://grabcad.com/lib	2	$25.99	$51.98	
	M4 T-nuts for 2020 Profile	https://www.amazon.com/	https://grabcad.com/lib	1	$9.78	$9.78	Pack of 100
	Paper Roll 9" wide	https://www.amazon.com/	will make	2	$3.66	$7.32	
	NEMA 17 8020 adapter	https://www.pololu.com/pr	https://www.pololu.com	1	$3.95	$3.95	
Electronics	DRV8825 Stepper Driver	https://www.amazon.com/	https://grabcad.com/lib	1	$11.99	$11.99	
ORDER ROUND 2							
	2020 corner attachments	https://www.amazon.com/		2	$12.99	$25.98	
	2020 right angle attachments	https://www.amazon.com/		1	$14.99	$14.99	
	100:1 NEMA 17	https://www.amazon.com/		2	$41.75	$83.50	19:1 NEMA 17
	GT2 Pulley 40T 8mm bore	https://www.amazon.com/		1	$7.99	$7.99	
	6811 Bearing	https://www.amazon.com/		1	$19.99	$19.99	
	NEMA 17 with T8 screw 210mm	https://www.amazon.com/	https://grabcad.com/lib	1	$25.99	$25.99	
	8mmx250mm shaft	https://www.amazon.com/	will make	1	$10.99	$10.99	Pack of 2
	2020 Extrusion 550mmx4	https://www.amazon.com/ZYLtech-Black-Aluminu		1	$92.99	$92.99	
	NEMA 17 8020 adapter	https://www.pololu.com/pr	https://www.pololu.com	2	$3.95	$7.90	
ORDER ROUND 3							
	Acrylic Tube for Idlers	https://www.mcmaster.cor		1	$7.60	$7.60	
	Torsional Spring 2	https://www.mcmaster.cor		1	$7.06	$7.06	
ORDER ROUND 4							
	Laser Module	https://www.amazon.com/HiLetgo-Adjustable-Pos		1	$8.99	$8.99	
	24V Power Supply	https://www.amazon.com/AVAWO-Switching-Tran		1	$18.88	$18.88	
	Inlet Power Switch	https://www.amazon.com/FILSHU-Current-Socke		1	$8.99	$8.99	
	Solderable Breadboard	https://www.amazon.com/dp/B082KY5Y5Z/ref=ss		1	$11.99	$11.99	
	PWR Screw Terminals	https://www.amazon.com/Hilitchi-Position-Termina		1	$11.83	$11.83	
	20awg wires	https://www.amazon.com/		1	$6.99	$6.99	
	Breadboard Screw Terminals	https://www.amazon.com/		1	$6.99	$6.99	
ORDER ROUND 5							
	Assorted Flat-head Screw	https://www.amazon.com/Glarks-510Pcs-Metric-5		1	$14.99	$14.99	
	Cable Split Sleeve	https://www.amazon.com/		1	$8.99	$8.99	For generic wire management
	Reusable Cable Ties	https://www.amazon.com/		1	$4.69	$4.69	For wire management
	14AWG Wire	https://www.amazon.com/		1	$8.88	$8.88	Power Transmission - Safety First! (rated 20A, we need 15)
	Limit Switches	https://www.amazon.com/		1	$9.99	$9.99	For homing the X, Y, and potentially the Z axis.
	Long Flanged Linear Bearing	https://www.amazon.com/		1	$11.09	$11.09	For Z stage
	Linear Rail	https://www.amazon.com/		1	$8.99	$8.99	For Z stage
	T8 Screw Nut	https://www.amazon.com/		1	$25.99	$25.99	For Z stage
	2020 Frame Hinge	https://www.amazon.com/		2	$13.29	$26.58	For making doors to key component to make the device more user-friendly
	M4x12mm Thumb Screw	https://www.amazon.com/		1	$7.99	$7.99	For mechanism to lock the doors during takeoff & return
	Pi Touchscreen	https://www.amazon.com/Raspberry-Pi-7-Touchs		1	$60.24		
	Assorted Flat Head Screw	https://www.amazon.com/Hilitchi-460-Piece-Metri		1	$15.99		
	5V Regulator	https://www.amazon.com/Converter-Regulator-Ac		1	$12.49		
	Constant Force Spring	https://www.mcmaster.cor					
	Torsional Spring	https://www.mcmaster.cor					
	12 AWG Wire	https://www.amazon.com/BNTECHGO-Silicone-F		1	$9.48		

Appendix 3: Assembly Procedure

1. 20/20 Framework
    a. The framework is based around the size of the mini payload and built securely in 20/20 aluminum extrusions. It is held together with corner brackets and drop in nuts. All the specifics for the assembly can be obtained in the final CAD model.
2. X/Y- Gantry
    a. The X/Y- gantry is built using three lead screws that give two directions of freedom. The Y direction uses two lead screws which are accompanied with linear rods and custom platforms to connect them to the X- stage. The X- stage is composed of one lead screw (with a linear rod) that attaches to the two plates on the Y-stage. On the X-stage is the printhead holder, which is the part that holds the printhead (in this case the marker) and the laser. It is all connected to the 20/20 framework with either custom brackets or brackets designed to hold the stepper motors. This design also includes two limit switches, one each in the X and Y directions, to help home the device.
3. Roller Assembly
    a. The roller assembly consists of two rollers controlled by stepper motors and two rollers that simply guide the substrate. One of the rollers begins with the substrate on it and the user puts it around the other two idlers and connects it to the second motorized roller. There are time of flight sensors that are used to estimate the amount of substrate that has been used and are connected above the motorized rollers.
4. Z- Stage Assembly
    a. The Z- stage consists of two platforms, one lead screw, and three linear rods. The lead screw is on one side of the platform with two of the linear rods, and the third linear rod is on the opposite side. There are two limit switches, one on either side of the bed to use for leveling the bed and homing the Z- stage. Four additional pieces of 20/20 were added to hold the components of the Z- stage. The rods and lead screw are held onto the lower bed with linear bearings and a T nut. The raised platform is the actual print bed and is raised with standoffs in order to be able to reach through the 20/20 framework to the substrate above.

5. Power Supply
    a. A 120V AC to 24V DC power supply is mounted in the case opposite the electronics panel. This allows it to be wired before adding the acrylic panels, and ensures all cables leading to the other electronic components can reach it. The side of the power supply should still be accessible so new wires can be added or removed as necessary. It should also be mounted near an inlet port with the on/off switch of the device, and with wall power.
6. Major Electronics, Sensors, Microcontrollers
    a. The major electronics of this printer include the stepper motors, stepper motor drivers, embedded microcontroller (in this case a Teensy 4.0), controller device (in this case a Raspberry Pi 3B+), and a touch screen display. They are mounted opposite the power supply, next to the Z-stage. The stepper motors are wired to the stepper motor drivers, which receive an input of 24V DC from the power supply, and signal and direction pins from the microcontroller. The microcontroller must have its USB port accessible so it can be fed instructions via serial from the controller device (Pi). The touch screen is mounted directly on the Raspberry Pi, in the plane of an acrylic side panel.
7. Wire Management
    a. The wires were led around the framework in order to keep them out of the many moving components. They are contained with wire covers and held to the sides of the framework with 3D printed parts and velcro straps.
8. Acrylic Panels
    a. Acrylic panels were added to the assembly last. They enclose the entire device, and some are connected directly to the 20/20 with drop in nuts and some are magnetic. There is a door to retrieve the 3D printed parts and two smaller doors in order to replace the substrate, all attached with hinges and magnets. There are also two completely removable panels connected with magnets on the sides that allow easier placement of the substrate in the assembly. All the doors and panels connected with magnets have heat set inserts that allow the door/panel to be screwed down to the assembly during takeoff.

Appendix 4: Technical Drawings

Figure 1: Diagram provided by client

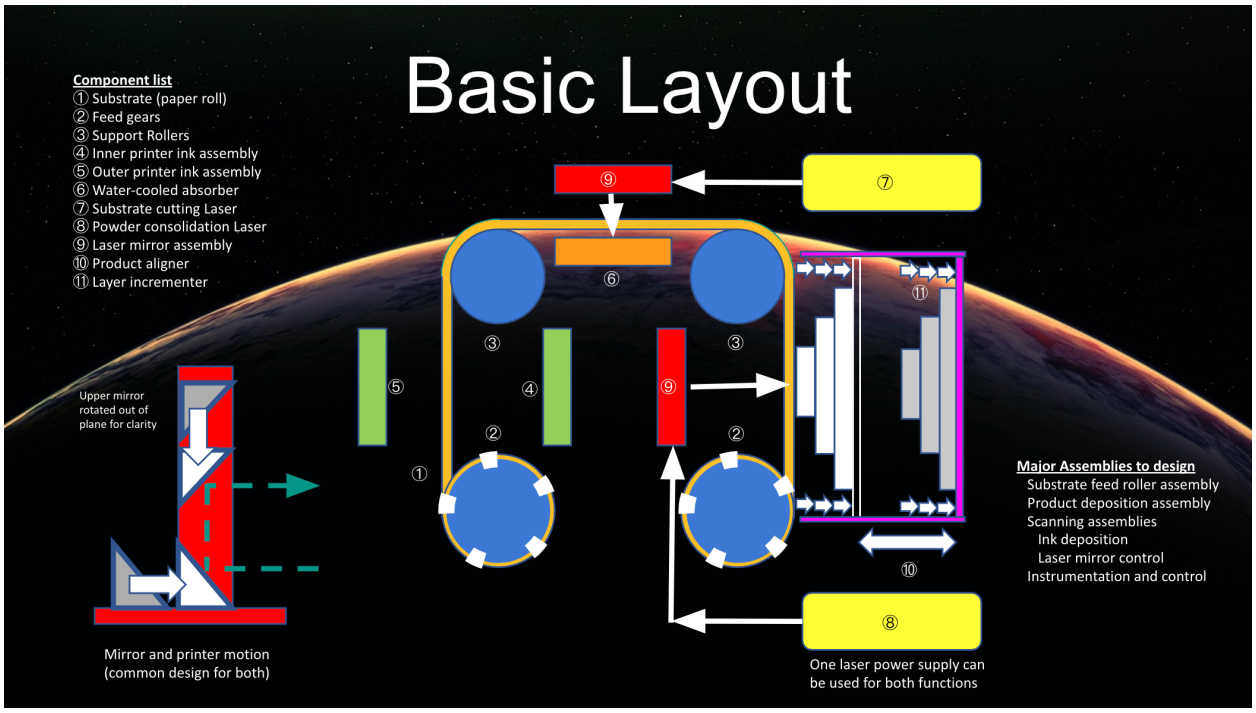


Table 4: Overall assembly concept generation

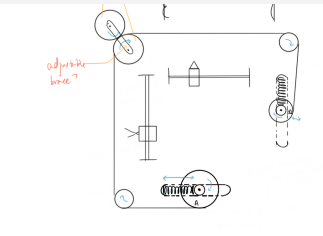
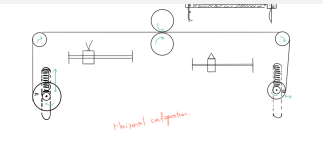
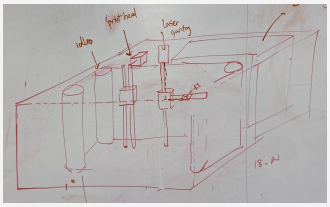
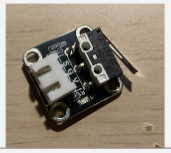
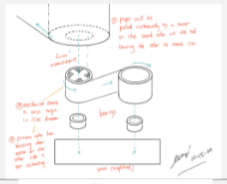
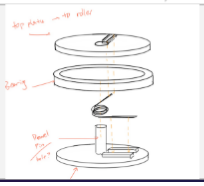
Concept	Description	Sketch	Evaluation
Square assembly	Printhead stage perpendicular to laser stage		Compact - fits in the payload, allows for a large print volume Not reliable - prints may peel off the substrate at corner
Straight line assembly	Printhead stage in line with laser stage		Reliable - no sharp corners for prints to peel Not compact - leaves less print volume
Combined assembly	Printhead and laser combined into one gantry		Compact - maximizes print volume, minimizes gantry size/weight Reliable - no sharp corners

Table 5: Concept Generation for selected sub-components

Concept	Description	Sketch	Evaluation
Physical Limit switches	Push button with extended lever arm to detect impacts		Compact enough to fit inside the payload, and easy to obtain and program
Digital Limit switches	Measures current draw from the motors to detect when the gantry reaches a physical stop		Not feasible due to cost of devices and complexity in measuring current. Also potentially damages the gantry.
Optical limit switch	Light emitter and opposite light sensor detecting breaks in the beam		Less available than mechanical limit switches, and potentially more difficult to program / measure reliably (depend slightly on ambient light)

Concept	Description	Sketch	Evaluation
Active Braking	Use electric/pneumatic brake or clutch to actively control the unwinding stage (similar to industry application such as printing press)		Not feasible - system tends to be large, expensive, and more suitable for high-speed application
Constant-Force Spring 	Wrap a constant-force linear spring with the unwinding roller to achieve constant counter-torque.		Not feasible- limited extended length Functionality not guaranteed - couldn't find existing application that is similar
Torsional Spring Mechanism	Put a torsional spring in line with the unwinding roller's rotational axis and engage the spring to tension the system		Customizable - various torsional spring available for purchase Low Cost - can actually afford to build it

Appendix 5: Electrical Schematic and Wiring Diagram

Figure 2: System overview electrical diagram

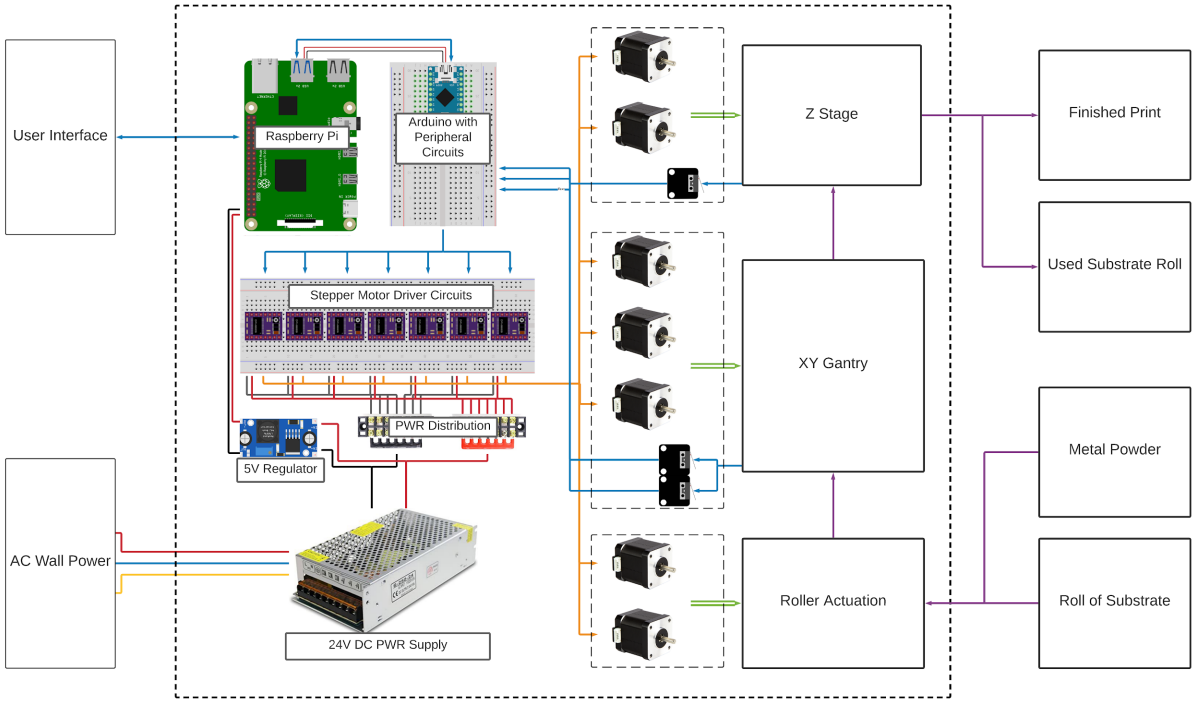
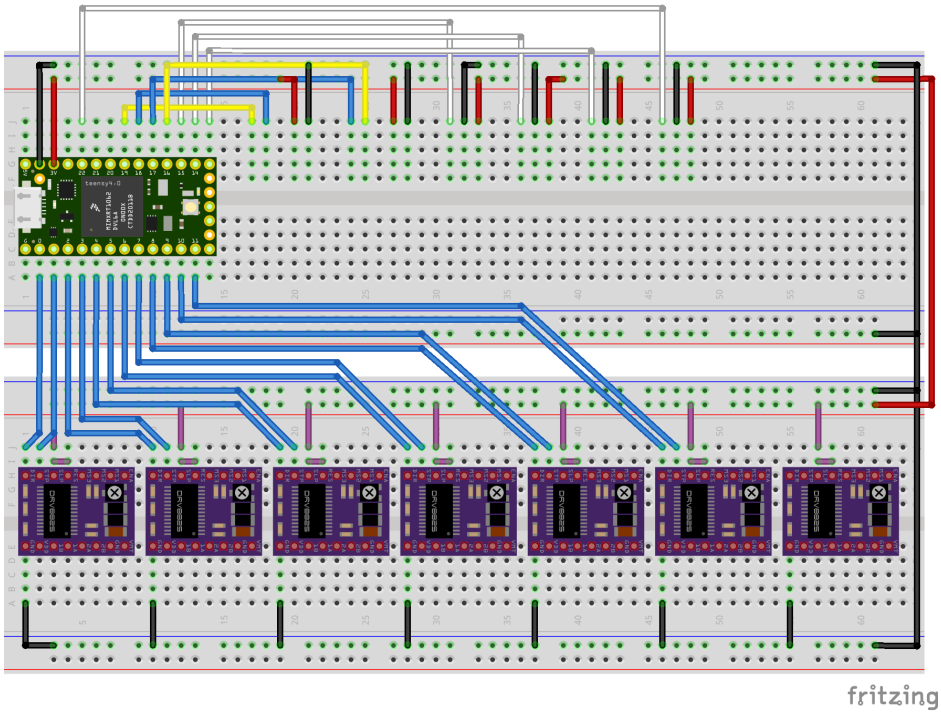
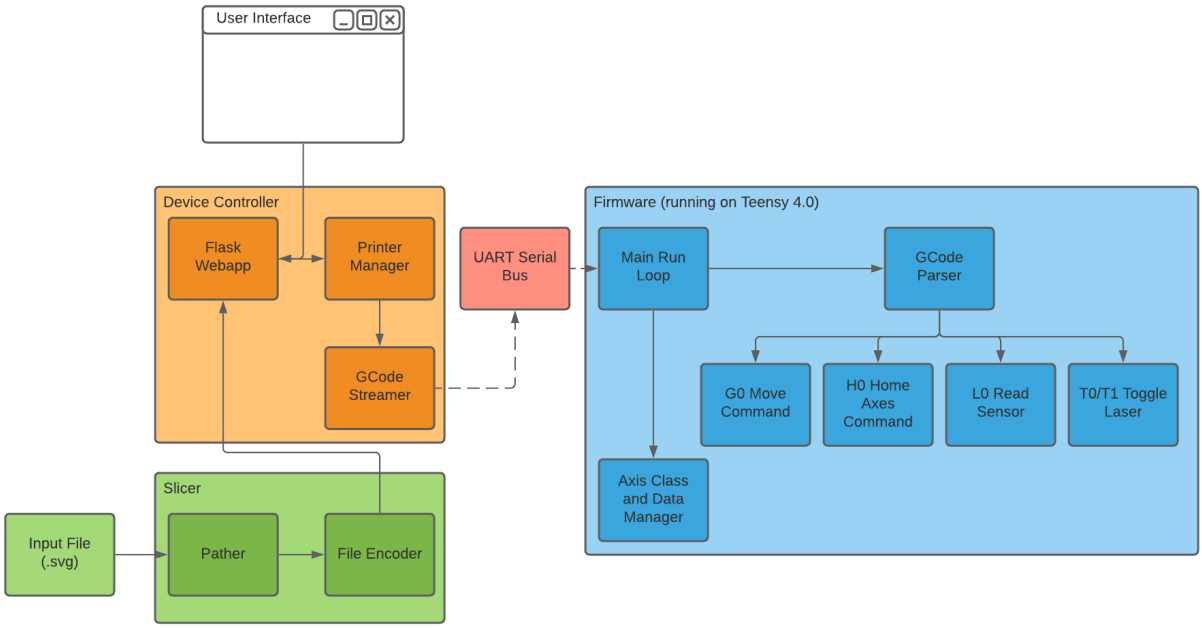


Figure 3: Implemented wiring diagram



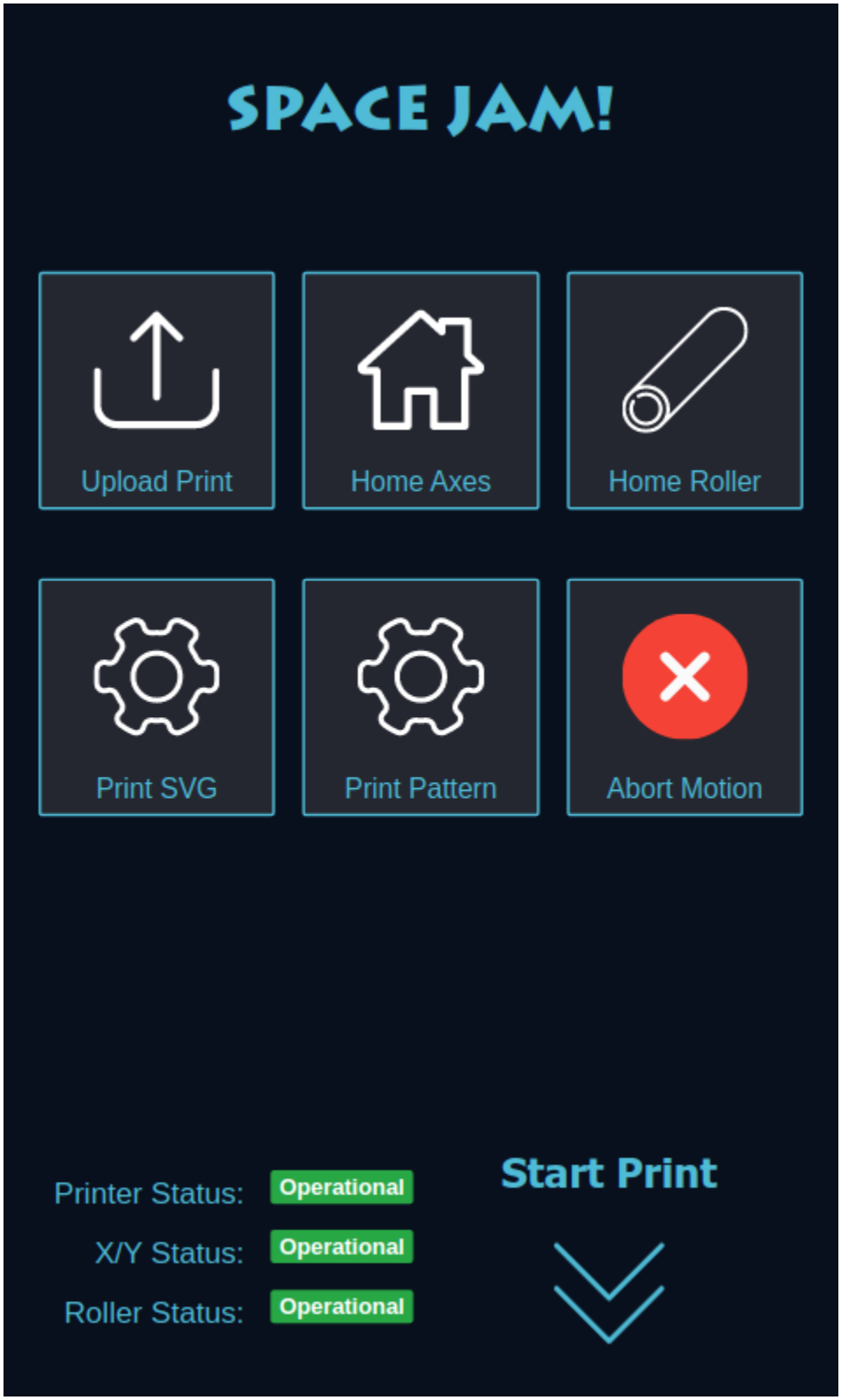
Appendix 6: Software Architecture

Figure 4: High-level software architecture for device controller and firmware



For code implementation, see https://github.com/0xJeremy/senior-design.

Figure 5: User Interface



Appendix 7: Failure Mode Analysis

Component	Potential Failure Mode	Potential Failure Effect	Sev	Potential Causes	Occ	Det	RPN	Mitigation Strategy
X/Y Gantry	Motors in Y direction do not move in sync	One side lags behind the other, leading to error in the print.	6	Motors do not receive the same signal	2	4	48	We can wire the direction and step leads from our processor to the stepper drivers identically. In this manner we will be unable to drive the motors out of sync as they will receive identical signals.
X/Y Gantry	The brackets created to hold the X-axis are not strong enough	The brackets break and the X- axis falls	7	Structural weakness in the brackets	2	4	56	We will increase the thickness of the part to increase the structural integrity of our gantry.
X/Y Gantry	X-axis is too heavy / unstable	The X axis falls or does not move up and down	7	Heavy parts used in the gantry	2	4	56	Use 3D printed parts and brackets to hold the stepper motor made from plastic instead of metal ones.
X/Y Gantry	Belts on motors snap during flight	The motors will not be able to drive the gantry or roller tensioning system	8	Extreme vibrations during launch	3	5	120	We will use stepper motors with lead screws instead of belts to remove risk wherever possible. For our roller assembly we may still use belts, however there are mitigation strategies for them below.
Roller System	Belts snapping during flight	The motors will not be able to drive the roller tensioning system	6	Extreme vibrations during launch	3	5	90	We intend to remove the belts before launch, and include a quick assembly mechanism for placing them back onto the printer.
Roller System	Belts becoming un-tensioned during flight	The rollers will not be able to move the substrate	6	Extreme vibrations during launch	4	5	120	The belts will be removed before launch, and include a tensioning mechanism for quick re-assembly.

		through the printer						
Roller System	Substrate breaking during printing	Disruption of the print	3	Weak substrate material	2	6	36	The substrate will be replaceable, so this should be easy to remove the roll of substrate and replace it.
Roller System	Tensioning mechanism fails	The substrate will become jammed inside the printer	5	Torsional spring fail to activate properly	2	6	60	We intend to design a robust mechanism to tension the rollers, and its failure would indicate a larger problem for the overall assembly. This mechanism can also be repaired by fastening the roller motors to a fixed point on the printer.

Appendix 8: Prototyping Process Documentation

Figure 6: Prototype Stage 1 CAD Design

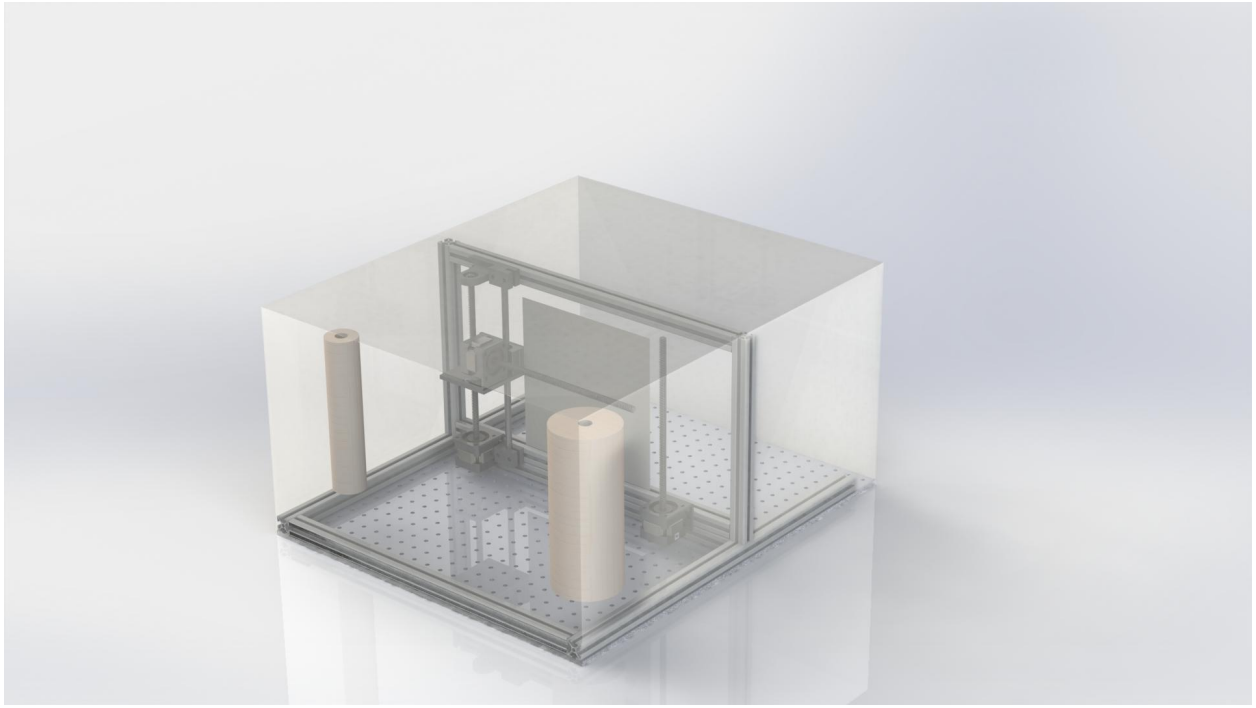
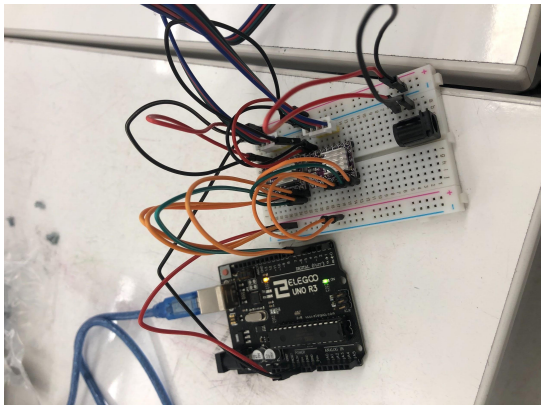
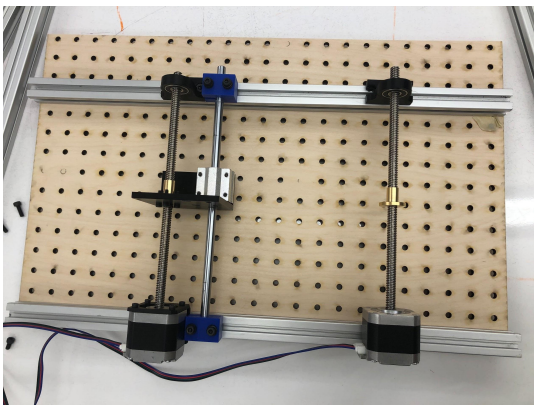


Figure 7: Prototype Stage 1 Physical Prototype

a) Two identical lead screws to test Y-axis movement, b) Electronics to control the stepper motors.



(a)



(b)

Figure 8: Prototype Stage 2 CAD Design

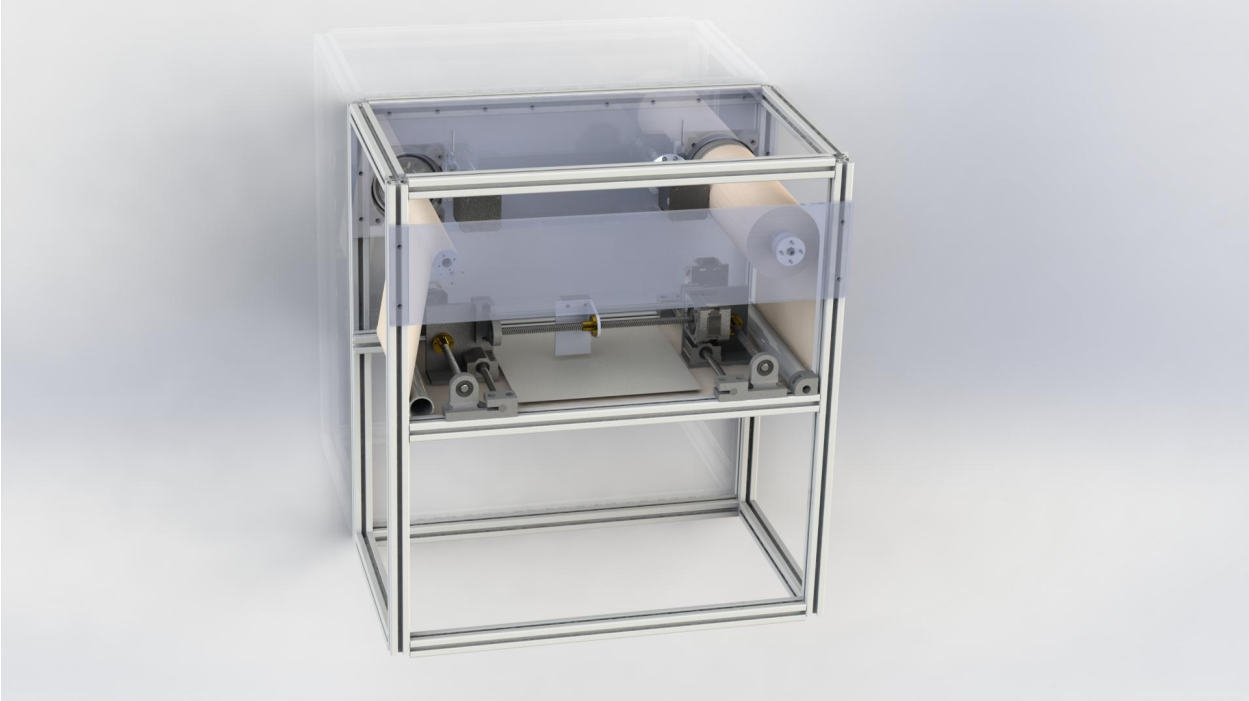
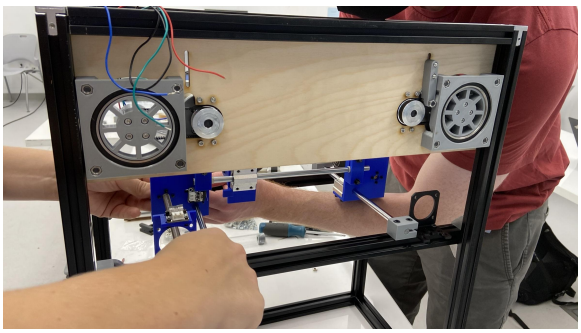
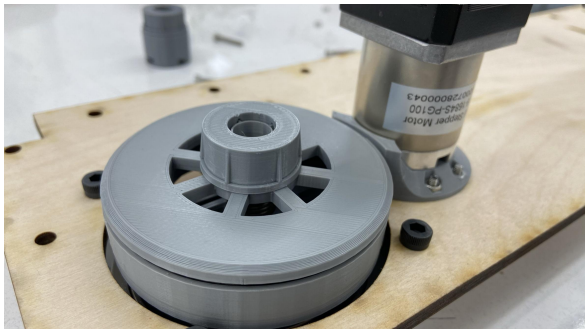


Figure 9: Prototype Stage 2 Physical Prototype

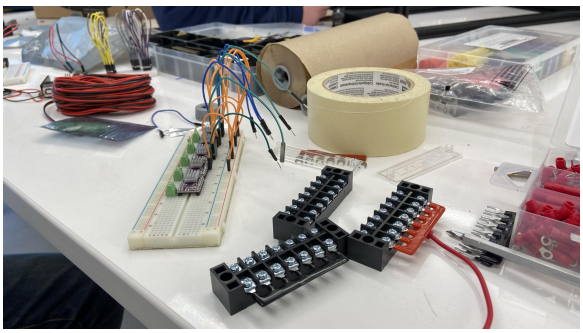
a) Assembly of X/Y- gantry and roller mechanism, b) Torsional spring mechanism for roller tensioning, c) Electronics to control the stepper motors, and d) Finished stage 2 prototype.



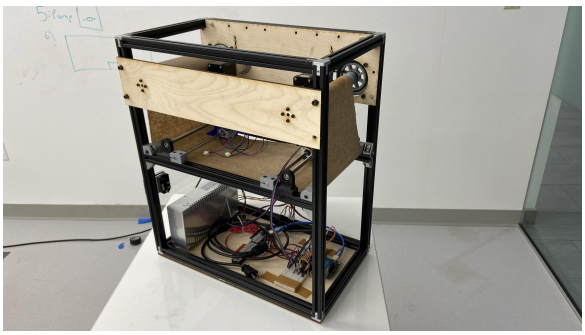
(a)



(b)



(c)



(d)

Figure 10: Final Version CAD Design

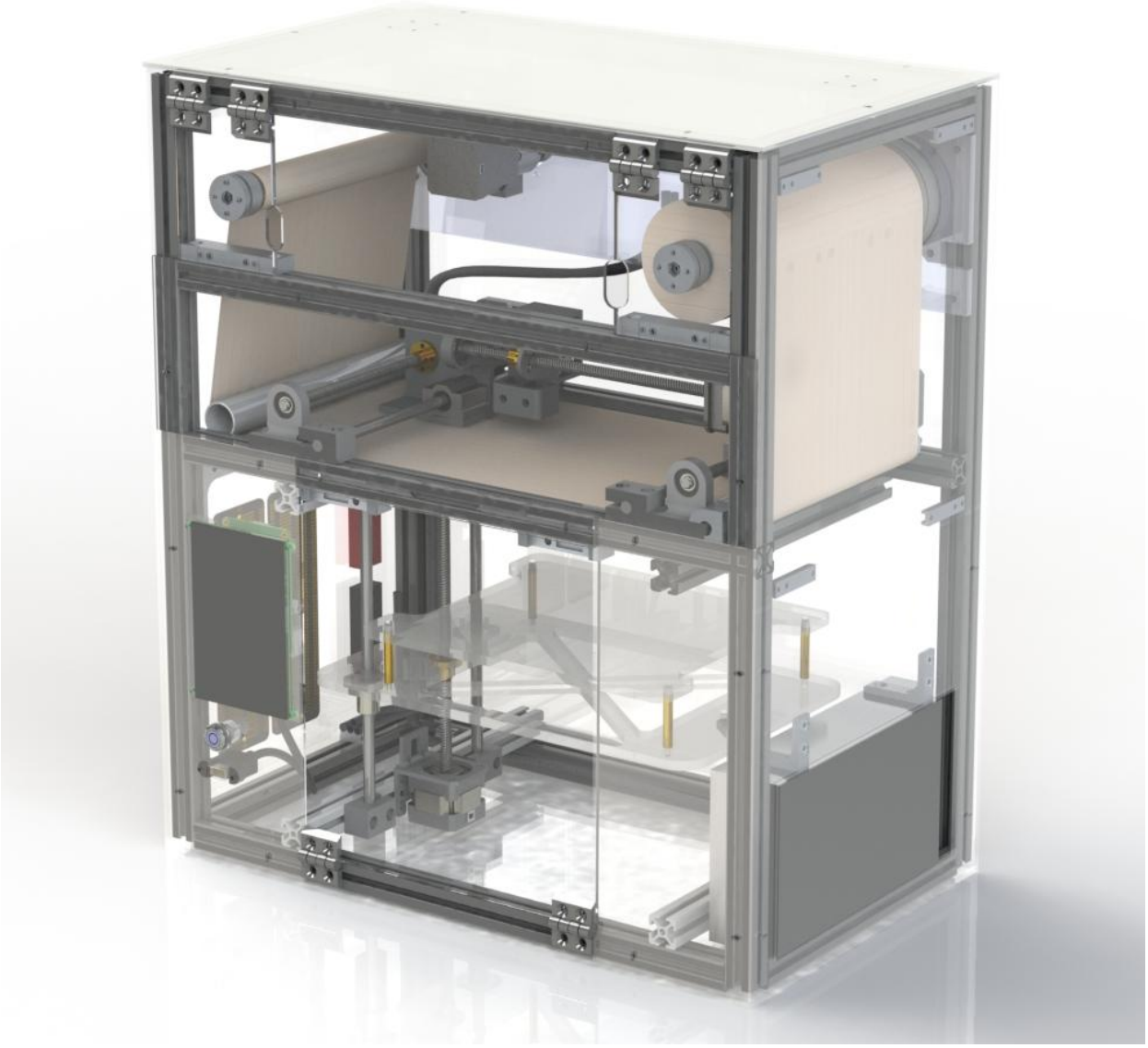
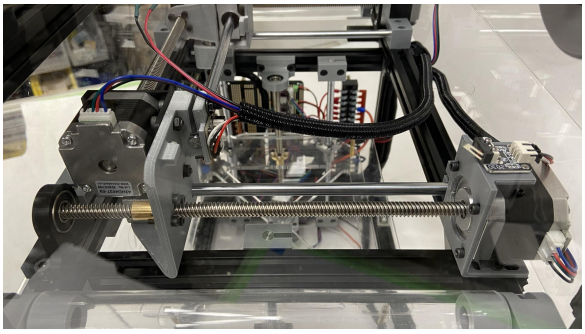
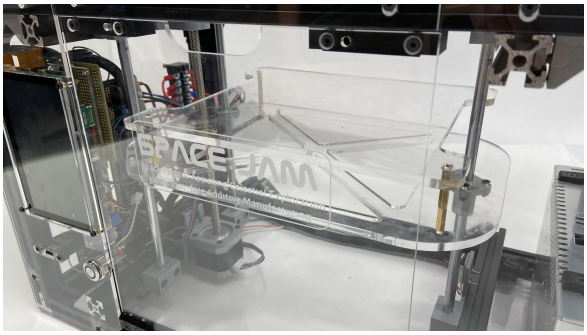


Figure 11: Final Version Build

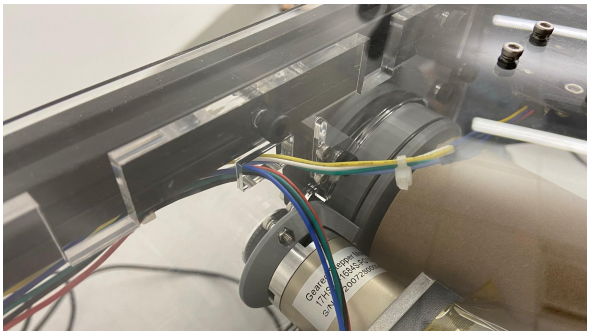
a) X/Y-gantry, b) Z-stage with front door and user interface, c) Roller tensioning and actuation system, and d) Finished final build.



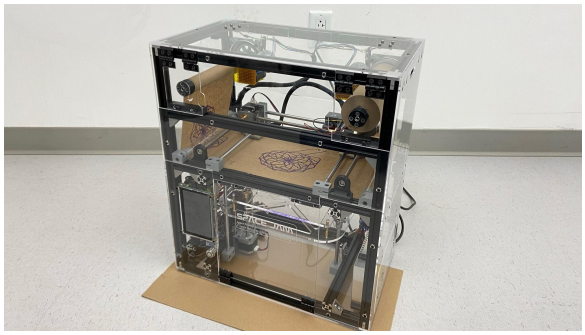
(a)



(b)



(c)



(d)