Team 104: Mobile 3D Printer

Final Report

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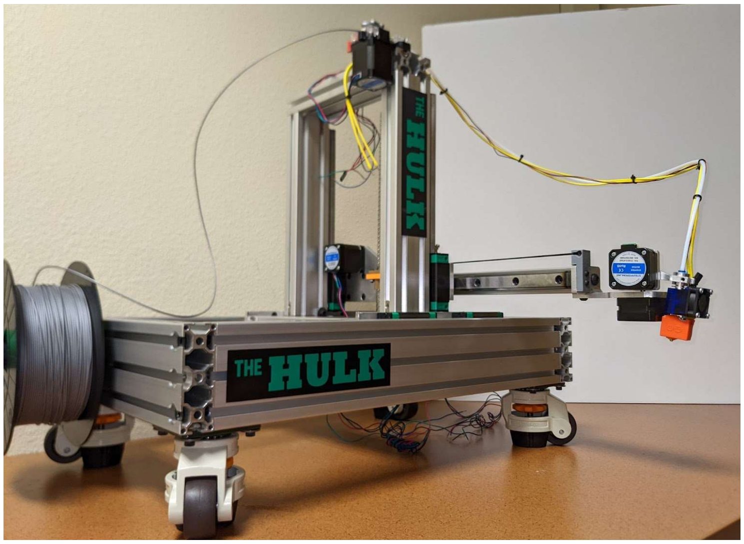

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DISCLAIMER

ABSTRACT

The Mobile 3D printer concept was imagined from the ability to use additive manufacturing in a more readily available way than current implementations. The idea was to create a robotic system that was able to assess the surface it was printing on, optimize the printing strategy, and also work in multiple job locations to create a multistage-single print that was larger than the device itself. In an ideal working case at the end of the product development process, the device (for example) would be able to drive up and position itself next to a damaged commercial airplane, or damaged defense vehicle, then assess damage and plan a repair strategy without the normally required support structures used during repairs. If the device was able to achieve this lofty goal, it would be able to streamline repairs and create countless new uses in the additive manufacturing industry. After our initial consultation with our stakeholders, they expressed the need for a software integration testbed, as there is nothing on the market that currently exists to build, test, and debug software on. After initial prototyping, we created a 5-Axis robotic system that has the ability to be rolled and positioned in the ways aforementioned by the stakeholder's requests. The device is to serve as a scaled-down software testbed and was completed successfully in the time frame allotted to our group. Using an FDM style printer to test software for the end goal of a Metal 3D printer will be cost effective, insightful, and a good intro stepping-stone for our stakeholders to explore the concept. At the end of the process, we have delivered a mechanical prototype that is ready for automation and initial integration done by the joint EECS capstone team that has been working side-by-side with us.

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1 BACKGROUND

1.1 Introduction

The Mobile 3D Printer project focuses on utilizing five axes of motion to perform precision printing on non-planar surfaces. Compared to a contemporary printer that only prints on a fixed bed with limited maneuverability, the 5 axis movements allow for a wider range of use cases. Since the print size is not limited by a pre-assigned bed, the final product can be virtually any size given the availability of raw materials. Using a mobile base allows the printer to move around the work piece and make additions in hard to get places.

The mobile 3D printer aims to solve the issue of having to send pre fabricated parts via freight to a destination. In the case of military applications, instead of shipping volatile cargo, the raw materials as well as the printer can be sent instead. This significantly reduces the risk of transportation as well as ensuring that in the case that the equipment gets lost in transit it poses no threat. The sponsor for this project, Oregon Manufacturing Innovation Center (OMIC), works with industries such as military and aerospace, and they require on-site repairs as well as on the fly modification solutions which this printer can provide.

1.2 Project Scope

Dr. Matt Campbell and OMIC R&D have requested the development of a mechanically sound mobile 3D printer. The design basis is expected that the mechatronic system is able to move in five planes, otherwise known as a five DOF (Degrees of Freedom) machine. The goal of Capstone Team #104 is to begin the design process and prove the feasibility that a system meant for additive manufacturing can be implemented in a small, rigid, and cost-effective manner before future design, iterations, and development occurs. After meeting with our stakeholders, OMIC R&D and Dr. Matt Campbell, the base idea was clarified that the fully realized project goal is to be able to use the platform as a mobile repair machine for the aerospace, automotive, and defense industries. Some of the future goals are the ability to drive over uneven terrain, realize and plan a repair process based on computer vision, and allow for direct metal deposition welding for larger and more intense repairs. The expected deliverables for this project, as it is in the beginning stages, ask for the small-scale development of a test-bed iteration that explores joint configurations and how the mechatronic system can perform when working to print around complex surfaces. The first iteration is expected to prove the concept through the use of FDM (fused deposition modeling) printing techniques.

2 DESIGN PROCESS

2.1 Customer Requirements and Engineering Specifications

The design process began with the development of the customer requirements. The main requirements set for the ME team are as follows: First, the printer structure needed to be capable of 5-axis motion, such that it could print on a cylindrical surface by keeping the nozzle normal to it at any given surface point. Second, the printer structure needed to be approximately the size of the Prusa i3 printer, and capable of an equivalent print envelope when stationary. Finally, the printer structure had to be capable of executing fusion deposition modeling (FDM) printing methods. Each of these requirements was tied to an agreed specification. To satisfy the first requirement, the printer needed 5 motion joints, with a minimum of 2 being rotational. For the second requirement, the printer could take up no more than 18 cubic inches of space. And finally, the printer had to be able to print anywhere within a volume of 10 cubic inches, although precision and head angle may vary throughout the volume. A full list of the customer requirements and corresponding engineering specifications can be found in Appendix A.

A key thing to note is that because the EE/CS capstone team has been assigned to the programming and control infrastructure of the printer, the ME team was not responsible for any robotic movement. It was accepted that the robot may only move via manual manipulation at the end of the ME's second capstone term, as the other team will have a third term to complete their responsibilities.

2.2 Research

Once the customer requirements and engineering specifications for the ME team were identified, research into existing technology began. The aim of this project is to create a novel machine that resolves several common limitations of 3D printers. However, there are many kinds of different 3D printers already in existence that were designed to resolve one or two of these limitations at a time. For example, cement printers (Figure 1) used to construct small buildings and support structures are capable of being mobilized to different job sites [3]. While their mobility is an asset, the tradeoff in decreased rigidity and accuracy, combined with three-axis motion limitations, makes their existing robotic structure insufficient for our target market.

Figure 1: A structural cement 3D-printer [3] (left) and the BAAM 3D-printer by Cincinnati [4] (right).

Gantry style printers, such as The BAAM (Big Area Additive Manufacturing) machine (Figure 1) by Cincinnati [4], have been scaled large enough to produce enormous parts at tight tolerances. However, this style of machine also has its limitations. They require dedicated floor space for specialized printing beds, and even should the need for the bed be overcome, the gantry structure would be difficult to mobilize. Additionally, most gantries utilize motion of the print bed to control movement along the

Y-axis, meaning the gantries themselves are truly only capable of two-axis motion. In another case, extrusion heads have been fitted to six-axis robot arms designed for automated assembly operations to produce a five-axis printer [5]. However, their mobility is as limited as an average 3D printer.

2.3 Concept Generation

After concluding research, each team member was asked to come up with preliminary concept sketches for the printer to be built. The concepts illustrated by the sketches were not required to completely satisfy the design requirements, or even be feasibly buildable at this stage of brainstorming. The resulting sketches were discussed as a group, and a Morph Matrix (Appendix B) was generated based on common subsystem solutions presented within the concept sketches. The sketches were then evaluated by the whole group using a Pugh chart (Appendix C). The result was that a few sketches were selected as favorites, several others were selected for revision, and those that remained were discarded. The Morph Matrix was also reviewed, and some subsystem solutions were eliminated for infeasibility while others were generated via team brainstorming. A few of the key initial concept sketches are shown below (Figure 2).

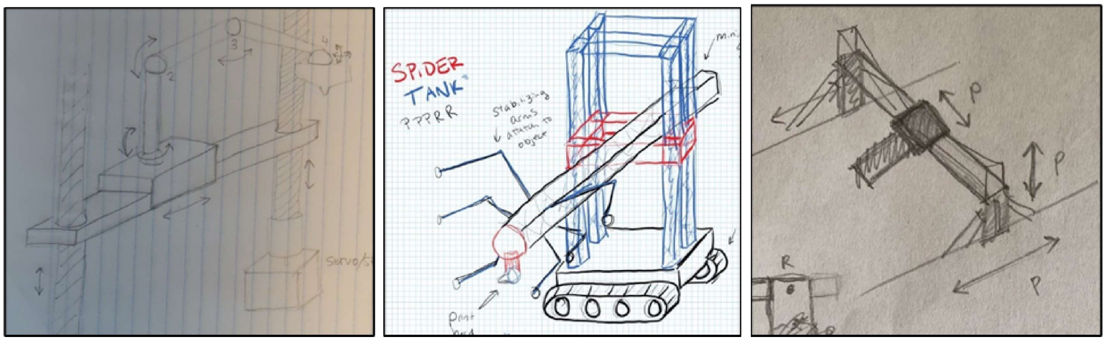


Figure 2: Key concept sketches including "The Horse" (left), "Spider Tank" (middle), and "The Crane" (right).

In this system, movement and joints had to be prismatic (linear extensions or retractions) or rotational (angular driven links). To achieve the full five degree-of-freedom (DOF) movement capabilities, the machine would require at least two rotational joints. Most 3D printers are currently based on a design where the workpiece (printed part) is contained within the printer's gantry or joint configuration. For example, the Prusa i3 MK3s+ uses a PPWP system where the two prismatic joints working the Z and X-axis (PP) are combined to act on the workpiece (W) which is relying on the movement of the Y prismatic joint (P) to create the third degree of motion needed for printing [10]. Contrary to this, it was determined that the mobile 3D printer would need to be constructed to isolate all movement and operations to the gantry of the printer as the workpiece will be stationary. Below, Figure 1 gives a visual example of a basic multi-axis mechatronic system, with a joint layout description in the same fashion as our team is using for our design. An example joint layout will look like this: PRPPRW where the order characterizes the joint layout chronologically working from a ground effector until the machine can interact with the workpiece. Using matlab with example joints and base orientations, it was determined that the hundreds of possible configurations could be reduced down to 26 possible configurations for the first round of concept generation.

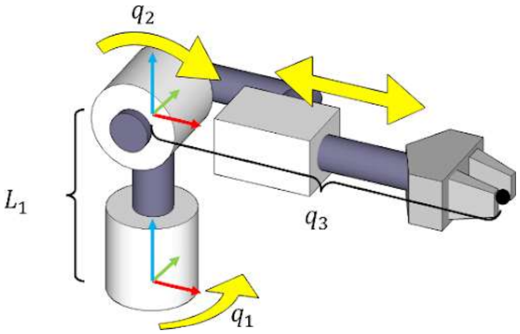


Figure 3: Example of a RRPW System (Rotational-Rotational-Prismatic) [11]

2.4 Concept Selection

Following the revision of the Morph Matrix, a second round of individual concept generation and revision was completed. For this, each team member took their favorite concepts and modified or combined them into something new. The resulting concepts, along with the favorites from the first round, were discussed by the group. It became evident that the group was in strong support of a “PPPRR” style structure, meaning that the robot should have 3 prismatic joints with 2 rotational joints at the printing end. One reasoning for this was that maximizing the number of prismatic joints at 3 would enhance rigidity and precision without significant detriment to mobility. With this decided, several concepts were eliminated. The team wanted one or two concepts to propose to the customer for feedback. It was decided that “The Hulk” and “The Bruce” designs (Figure 3) would be presented, the ladder simply being a lighter and simpler version of the former.

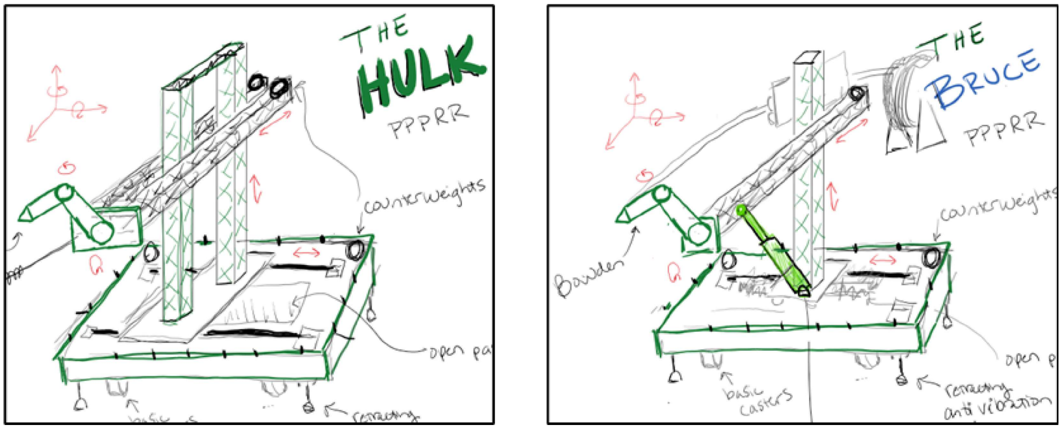


Figure 3: “The Hulk” (left) and “The Bruce” (right) concepts.

3 DESIGN PROPOSAL – First Term

After discussion with the project sponsor, it was decided to pursue future design and CAD work that follows the "The Hulk" concept with the "PPPRRW" joint configuration style [12]. The decision was made through the collective agreement that this joint configuration would be sufficiently stable, easy to iterate upon, capable of five-axis movement, and scalable. The following section will further describe this concept, and how it was developed into a buildable design.

3.1 Design Overview

A large portion of design discussions was placing heavy weight towards making the design easy to iterate or scale for future teams of engineers to work on. Moving on, the axis designations of the design are as follows and can be viewed below in Figure 4: The base of the printer houses the X-axis prismatic joint, next there is the Z-axis prismatic joint, then there is the Y-axis prismatic. At the end of the Y-axis, there are two, 90 degree out-of-phase rotational joints to allow for spherical manipulation of the end effector which holds the FDM hotend (the polymer heating and precision extrusion assembly).

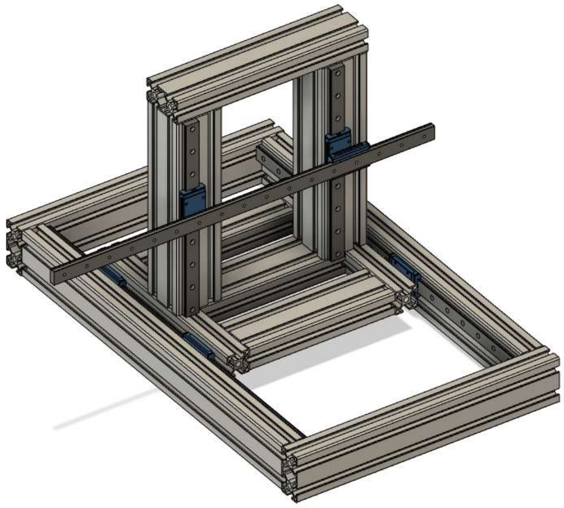


Figure 4: Prototype CAD Gantry Rendering

“The Hulk” design was originally developed while holding precision and rigidity as top priority. Its first iteration, “Spider Tank”, had several issues with over-constraints. Following the self-learning assignment and Morph Matrix evaluation, it was revised to incorporate a larger print envelope while eliminating the over-constraints. In addition to its focus on stability, this design was a good fit for employing state-of-the-art 5-axis motion, without overloading the EE/CS team with inverse kinematics. Additional structural features and a “Core-YZ” or "Inside-H" belt pulley system were added during group discussion of the concept before it was presented to the customer. While it was more similar to existing technology than the customer would have liked, they felt the reasoning for the simplicity was well defended, and the ode to precision and rigidity in the design was thoroughly appreciated.

To fulfill the FDM printing requirements, a light-weight bowden style extruder to drive filament into the hotend was chosen. The aim was to have a very slim style hotend to allow for efficient heating and deposition of the polymer slurry while allowing for workpiece and previously printed part avoidance. If there is a high degree of mobility on the end effector, there is a better interaction between the machine and the workpiece for printed part quality. Having a high-mobility end effector would also allow for more complex surfaces to be printed on. The hotend and extruder must be linked by the bowden tube to allow for constriction of the filament, which also dictates the need for the system's gantry to be tangle free and simple, hence the usage of the Inside-H style drive mechanism [13].

3.2 Proof of Concept Prototype

Once the design concept was fully formed, a proof-of-concept prototype was built to put the "PPPRR" joint configuration to the test (Figure 5). Craft foam board was selected as the main medium for this prototype because of its ease of use. The lead-screw driven X-axis was simulated by attaching hooks to the gantry platform that could ride along wooden dowel rods. The inside-H belt system to drive the Y and Z axes was represented by sliding joints formed with the foam board. The rotational axes at the end of the Y axis were simulated using smaller wooden dowels to attach separate sheets of foam board, and a red sharpie was used to represent the printing hotend. While the foam board prototype was far from a realistic representation of a 3D printer, it was an essential step in developing the team's understanding of the design process.

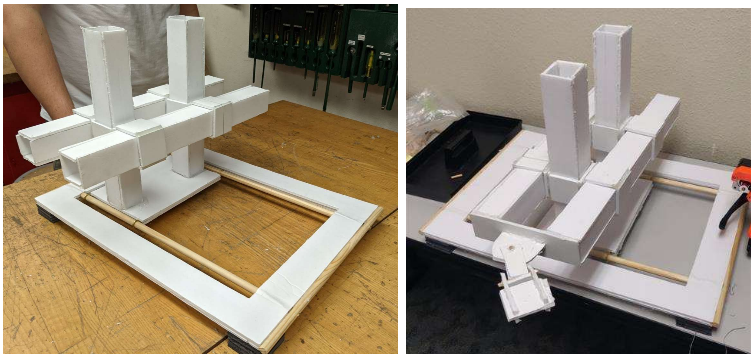


Figure 5: Foam-based proof-of-concept prototype

3.3 Final Proposal

There were not many pitfalls discovered while building the foam prototype, but transitioning the design to CAD presented many challenges. Materials were chosen based on common, readily available known engineering materials that are well known for prototyping. This included linear rails and t-slot extrusions, to achieve the basic frame that has the capability of being rigid and resisting deflection under all operating conditions. The inside-H belt pulley system was abandoned due to the complexities it would create both in building the design and in the implementation of the inverse-kinematics-based supporting software. It was resolved instead that the X and Z axis would be driven via lead screws, and the Y axis would be belt driven, all utilizing stepper motors. Current printers have the ability to use custom made and designed stepper motor drivers and mainboards, but these functions are the responsibility of the EECS capstone team working side-by-side on this project.

Using the idea to design the mechanical system from the end effector backwards, allowed for weight calculations to be factored into the axes coming beforehand to ensure they were structurally stable. Having knowledge of the system's weight also allowed for the use of basic FEA software to measure expected deflection and allow for changes to be made before purchasing materials that were potentially incompatible for use on the fully realized prototype.

The final product of the team's first term of work is shown below in Figure 6. The CAD model was a full representation of the design, complete with simulated motion along the axes. An accompanying Bill of

Materials (Appendix D) included links to the purchased components. In addition to the buyout components, the model featured many custom components that would need to be machined or printed. The model and materials were presented to the customer at the conclusion of the term, and received approval for the next step of the process: building.

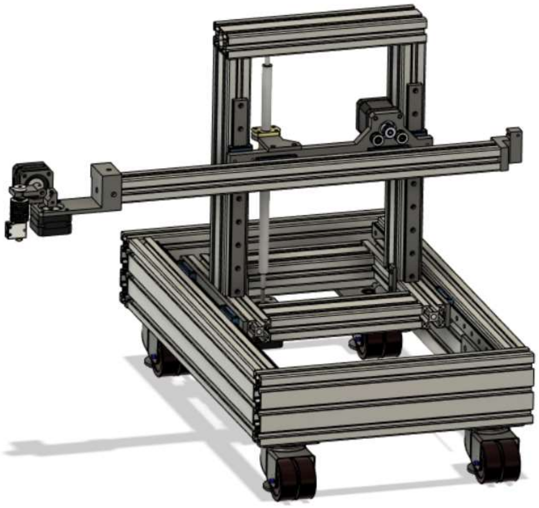


Figure 6: Final Design CAD Model at conclusion of the first capstone term.

4 Design Solution

In the previous section, time was spent outlining the final design of the printer. In this section, the focus will be on how that design was implemented and what the printer can do. The design solution stayed true to the final design outlined in other documents and modeled in the Fusion 360 CAD assembly.

4.1 Description of Solution

Discussion of the solution should begin with the three linear axes. The X-axis rides on linear rails that are mounted to the 3090 Aluminum extrusion of the base. This can be seen highlighted in Figure 7 below. This axis is powered by a Nema 17 stepper motor that is connected via an aluminum coupler to a 35 mm pitch lead screw. The other end of this system is connected to a 3D mounted bracket to reduce deflection and houses the lead screw nut.

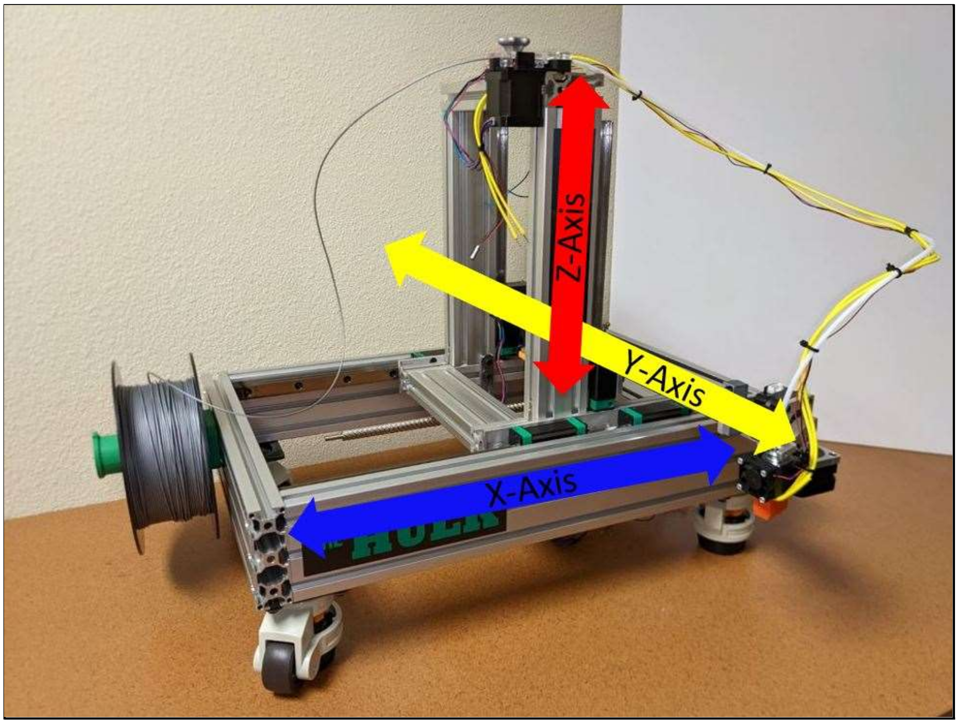


Figure 7: The Hulk with axes highlighted.

The second linear axis was the Z-axis, which also rides on a linear rail system very similar to the X-axis. The YZ tower that houses these rails also consists of a robust 3090 Aluminum extrusion frame. This axis is powered by another Nema 17 motor mounted on the bottom of the tower and powers a second ball screw. The Z-axis is also powered by another Nema 17 motor, mounted transversely to the end effector arm. This motor runs a rubber belt that is secured to the end effector on either end by printed clamping pieces. The linear joints all contribute significantly to meeting customer requirements and engineering specifications. Namely, achieving five-axis motion and meeting several different engineering specs related to print volume and movement precision.

Focusing on the specifics of the finished end effector assembly, Figure 8 shows that it is driven by two Nema 17 SLIM motors. These motors have significantly reduced size over their larger cousins and have a lower torque rating at just 0.13 Nm. These motors work great on the robot however, ensuring that it meets the requirements to print on irregular surfaces and have reduced costs (by using the smaller motors). Furthermore, the end effector components have been milled from aluminum to ensure there is little to no deflection and to properly dissipate excess heat from the printer hotend. Using these aluminum parts also helped us meet the engineering specifications of reduced weight and a simple open design. It is important to note that the milled aluminum parts in conjunction with the Nema 17 SLIM motors were able to exceed the engineering specifications of 90 degrees up and 160 degrees side to side. The final end effector, after testing, achieved 120 degrees up and 240 degrees from side to side.

Figure 8: End effector setup.

Now it is important to go into detail about the hotend assembly itself. The implemented version consists of an E3D Volcano Hotend connected to a bowden drive assembly. The SeeMeCNC EZR Struder is located on the top of the YZ tower and powered by a Nema 17 stepper motor. This system draws filament from the filament role rack located on the side of the frame. All of this is highlighted in Figure 9.

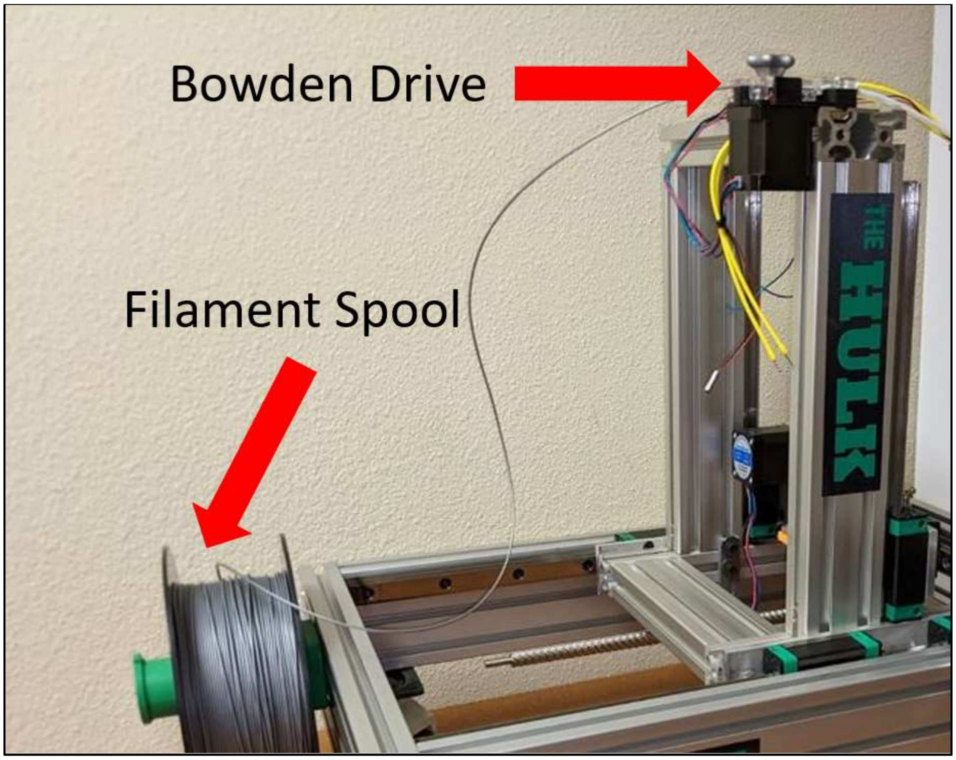


Figure 9: Bowden Drive System.

The end effector components and arrangement were extremely important in reaching customer requirements of easy serviceability, capable of FDM style printing and comparable industry standard print precision. Using the bowden drive system helps us meet the engineering requirements of weight reduction and decreased deflection ratio as the gantry nears the origin. The E3D Volcano Hotend also helps meet requirements by having a nozzle opening of 0.4 mm and achieving the desired nozzle temperature levels.

The last aspect of the final solution that needs to be addressed is the base and caster mobility system. The base is extremely rigid, being made from 3090 Aluminum extrusion that has been drilled and tapped to accept M8 countersunk bolts. The base was able to achieve almost zero deflection due to this design. The frame sits on four Skelang casters that are equipped with retractable rubber brakes that allow for easy movement of the printer and quick transition to a rigid locked position. This rolling caster system is key in achieving the customer requirements of increased mobility over other 3D printers and large discontinuous print volume.

4.2 Project Results

Testing began with measuring deflection of different components of the robot. This was especially important for the Y-axis arm because it housed the end effector. Thanks to the sturdy design there was only 1 mm of deflection of the Y-axis from the beginning of its travel to its furthest extension. More importantly for engineering specifications, the ratio decreases as the arm returns to its home position with a deflection of only 0.4 mm at half of the full travel. The other axes were tested for deflection and it was found that there was 0 mm of deflection. This is because these axes were overbuilt as mentioned above.

The next set of testing included operating the different axes. Since the EECS team is not totally complete with their components it was impossible to test all functions of the robot. The equipment that was tested included the X and Y axes movement. The Y-axis movement was smooth and controlled. Thanks in large part to the belt drive system, with its two idler gears that help control the movement. The X-axis was also tested for functionality. This axis is much harder to move because it has to move the combined weight of the entire gantry. Initial testing led to stalling of the motor and very choppy movement. Adjustments were made by the EECS team to the amount of current being pulled by the motor. This led to increased movement and smoothness of the axis. However, the motor continued to stall at the end of the gantry's travel. It took a while to troubleshoot, but ultimately it was determined that the X-axis screw connector was deflecting too much, reaching a max displacement of 1.42 mm from center. This was due in large part to it's PLA construction, making it weaker than the milled aluminum components and added unnecessary strain to the motor.

It is important to mention how our sponsors responded to the project. Starting with Dr. Campbell and his team of graduate students. During the course of the project, they really emphasized rigidity and precision in our design. Their goal is to have a robot that can be relied upon to have tight tolerances while printing. With that being said, they were very happy with the design and with the deflection tolerances that we achieved. They also appreciated the sturdy design of the base and the ability to make future modifications to the modular aluminum extrusion frame. If they had one major concern or issue, it was that the final product is quite heavy. This leads to complications regarding the torque required to move the system. With weight issues aside, the team felt quite good about the robots ability to meet requirements. Dr. Campbell feels the team produced a robot that is capable of all the tasks it needs to do and is ready for the EECS team to make it print.

It is also important to briefly speak about OMIC's response to the project. Since they are the group who is funding Dr. Campbell's team it is important that they are happy. Their representative, Jordan Meader, attended weekly update meetings to ensure we were meeting objectives and to help guide the project. He has been happy with the project, offering helpful feedback whenever necessary. OMIC as a whole feels that the project is on track and that the robot's design is intriguing and worth continuing the project further. Speaking of the future, the project will continue to be funded into next year with plans to have another capstone team continue work on the mechanical systems.

5 LOOKING FORWARD

5.1 IMPROVEMENTS

5.1.1 Installing planetary gearbox

For better actuation of the printer motion, consider installing planetary gearboxes on the X and Y axes of the printer. Planetary gearboxes would help in supplying extra torque to drive each axis with Nema 17 motors. The motor bracket for the X-axis (Figure 10) should be redesigned by adding more length so it could fit both the motor and the gearbox. This step needed editing of the CAD file of the bracket. Installing the gearbox in the Z-axis is more crucial as the Y-axis weight overloads the motor. This could prevent the Y-axis from moving in vertical motion to do the printing. For the Z-axis, there is a steel bracket holding the motor where it has enough spacing to fit in the gearbox. There is no need for redesigning the bracket.

Figure 10: X-Axis 3D Printed Motor Bracket.

5.1.2 Electrical Components Installation

Final design of the printer from the mechanical side has not allocated spaces for electrical components to be installed. Yet, this process could be easily done as the side of the base provides plenty. The electrical components should be placed as near to the motors as possible to allow for simple wiring management. The placement should avoid being in the way of any axis, especially the X-axis as this is located in the base.

5.1.3 Weight Reduction

Weight reduction focuses on the Y-axis that sits on the Z-axis. Z-axis constitute the linear rails, the bracket for Nema 17 motor and spacer, the end effector, and aluminum extrusion. To lose some weight, one could simply swap the linear rails with a lighter brand. Currently, there are plenty of options in the market. However, the cost for these linear rails has been a Team 104 constraining factor. This is the first iteration of the project, hence the team Bill of Material consists of all parts needed to build the printer from scratch. For the next iteration, team members could build off of the initial printer and their BOM should consist of less items hence more allocation for other material such as linear rails and sliders, and lead screw. If the next team were not planning to substitute the linear rails, they could reduce the weight of the linear rail. To do so, they have to machine the rail without changing its shape so that it retains rigidity and mobility of the sliders. It could also be that there is a spring attached to the Y-axis and the top of the Z-axis to provide stiffness which could assist the movement in the vertical direction. Nonetheless, the former solution would take time and risk of tools defect when machining the steel linear rail.

5.2 FUTURE TEAM DEVELOPMENT

5.2.1 Upscale

The printer can be upscale to suit its needs in the industry of which it is applicable. For upscaling, parts that need to be increased in dimension would be all aluminum extrusions, lead screws, and linear rails. For enough torque to provide movements, motors should be switched as well. The upscaling process should not pose any problem when all of the axes are upscaled at the same time.

X-Axis

For the base, if larger dimensions of aluminum extrusions are used to increase the base dimensions, the lead screw that sits inside of the base should be switched to retain the same amount of travel. As for the motor placement, there should be enough space for larger size motors. However, the use of 3D printed components such as the bracket should be reconsidered to using stiffer material if the weight of the motor exceeds and causes deflection on the bracket. The 3D printed nut on the X-axis (Figure 11) lead screw should be swapped to a stiffer material such as aluminum or steel. This is to ensure no deflection occurs when the movement of the axis is actuated.

Figure 11: X-Axis 3D Printed Nut.

Z-Axis

For vertical motion, using a larger dimension for aluminum extrusions would increase the height of the Z-axis. In addition to that, longer linear rails are needed to provide the vertical motion. Currently, there is an extra linear rail with 800 mm length. It can be cut in half and provides approximately 400 mm travel in the vertical motion. To increase the height further, future iteration might need to consider a support system in the X-axis direction to avoid large deflection when X-axis movement is actuated. It is very important for having a support specifically when only the Z-axis dimension is upscaled with disregarded upscaling in the other axis.

Y-Axis

The most important part of the Y-axis for future integration would be focussing on the end-effector. As mentioned by the client, this printer might integrate additive manufacturing of metal which would have different “printer” heads. As for now, the setup of the end-effector should prevent deflection when it moves. The bracket that holds the two Nema 17 Slim Motors is sturdy. If different printer heads should be used, the arms and the clamp at the end might need some renovation to fit in the metal printing head. Considering that, future teams should pay attention to the deflection of the Y-axis. As of now, the linear rail and the aluminum extrusion provide good support and have no deflection as they are both rigid. In any case that the end-effector weight overloads, sturdier aluminum extrusions should be used.

5.2.2 Movement and Leveling

For the first iteration, team members had used manual leveling casters that were installed on the base. To level the printer, the nuts on the casters are turned to give maximum height so that all casters are at the same height. Future projects could focus on developing an automatic leveling system, or at the least, develop a certain measurement method of the level. In terms of movement, the client had talked about the Autonomous Ground Vehicle (AGV) [15][16] integration into the printer. This will allow for automatic movements of the printer to the print surface. This surely would involve massive collaboration with the Electrical and Computer Science Engineering team.

In addition to that, a sensing system to print could be developed in the future. While most of the programming would involve Computer Vision, the mechanical aspect of the development could involve the mechanism to hold the sensor in place. This might require renovation on the Y-axis altogether or additional arm or whatever suits the requirement of such a system.

6 CONCLUSIONS

At the beginning of the project we were tasked with creating a design solution for a client with something that hasn't been done before in the commercial sense. To complete this project we had to break apart the work and focus on our individual strengths and weaknesses to be able to develop our solution. To start, we assigned engineering specifications to customer requirements and that allowed us to make a house of quality to be able to give meaning to the qualities and components to the impending project. Next, we began our design prototyping phase which involved concept generation and selection through the use of a morphological matrix. Once we decided as a team to focus effort onto the prototype dubbed “The Hulk” we ran into small errors in calculations and misconceptions about the cost of parts, which required slight redesigning and alteration of the existing team design. During this rapid iteration phase we were able to come up with many changes to the design which helped achieve the finalized goal of having precise linear movement. The total sum of our work has culminated in a moveable software test piece that can be iterated upon easily by future capstone teams for however long is needed until the project reaches a phase where it is ready to be picked up by a professional engineering firm for in the field applications.

Our design made sure to use the most readily available and budget friendly parts while conforming to the calculations and engineering requirements set in the beginning of the project, we created a mechanical system that is safe to use, easy to understand and iterate upon, and did not create a massive carbon footprint, all manufacturing was done with the ideal of rapid prototyping and small scale manufacturing. All parts were made custom to order so that we would minimize waste and when waste was unavoidable we chose to use recyclable materials such as Aluminum and steel, and biodegradable materials such as PLA. Overall, we tried to minimize the environmental impact of our project while delivering the requested specifications and features to the stakeholders while remaining on-time and in-budget. We delivered on the initial concept and requests according to the specified metrics of this report.

7 REFERENCES

[1] Pandian, A., and Belavek, C., 2016, "A review of recent trends and challenges in 3D printing", *ASEE North Central Section Conference*, American Society for Engineering Education, University Center, MI.

[2] 2021, "How 3D Printing Works", 3D Maker Engineering.

[3] 2021, "A Turnkey Solution, Maxi Printer", En.constructions-3d.com [Online]. Available: https://en.constructions-3d.com/la-maxi-printer. [Accessed: 24- Oct- 2021].

[4] 2021, "BAAM - Big Area Additive Manufacturing", Cincinnati Incorporated [Online]. Available: https://www.e-ci.com/baam. [Accessed: 24- Oct- 2021].

[5] MitsubishiFAEU, 2017, Six-axis robot turns 3D printing into an art form. Available: https://www.youtube.com/watch?v=NxgeESWS3z0. [Accessed: 24- Oct- 2021].

[6] Slocum, A., 1992, Precision machine design, Prentice Hall, Englewood Cliffs, N.J.

[7] Martin Culpepper, and Alex Slocum. 2.75 Precision Machine Design. Fall 2001. Massachusetts Institute of Technology: MIT OpenCourseWare, https://ocw.mit.edu. License: Creative Commons BY-NC-SA.

[8] Jitendra Khatait, 2021, Design of Precision Machines. Indian Institute of Technology Delhi, https://youtu.be/XH3ir55wTcc

[9] Smith, S., and Chetwynd, D., 1992, Foundations of Ultra-Precision Mechanism Design, Gordon and Breach Science Publishers, Montreux, Switzerland ; Philadelphia, Pa., U.S.A

[10] "Original prusa i3 mk3s+," *Original Prusa i3 MK3S+ | Original Prusa 3D printers directly from Josef Prusa*. [Online]. Available: https://www.prusa3d.com/category/original-prusa-i3-mk3s/ [Accessed: 22-Nov-2021].

[11]"Robot Kinematics," *Kinematics*. [Online]. Available: http://motion.cs.illinois.edu/RoboticSystems/Kinematics.html [Accessed: 04-Dec-2021].

[12] P. Wiktor, "Coupled cartesian manipulators," *Mechanism and Machine Theory*, 11-Jul-2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0094114X20301245 [Accessed: 22-Nov-2021].

[13] Jeff Kerr, "Inside-H: Modified H-Bot Belt Drive", YouTube, 03-Jun.-2016. [Online]. Available: https://www.youtube.com/watch?v=Zsf3603Dets&ab_channel=JeffKerr [Accessed: 22-Nov.-2021].

[14] "Cartesian Motion Platform," *CoreXY*. [Online]. Available: https://corexy.com/ [Accessed: 22-Nov-2021].

[15] "Autonomous Ground Vehicles - AGVs - Robotics and Autonomous Systems Group", *Robotics and Autonomous Systems Group*. [Online]. Available:

https://research.csiro.au/robotics/our-work/research-areas/autonomous-ground-vehicles/. [Accessed: 10-Mar- 2022].

[16]C. Lam Loong Man, Y. Koonjul and L. Nagowah, "A low cost autonomous unmanned ground vehicle", *Future Computing and Informatics Journal*, vol. 3, no. 2, pp. 304-320, 2018. Available: https://www-sciencedirect-com.ezproxy.proxy.library.oregonstate.edu/science/article/pii/S2314728818300084. [Accessed 11 March 2022].

8 APPENDICES

8.1 Appendix A: Customer Requirements and Engineering Specifications Table

Customer Requirements (CRs)					
CR#	**CR description using complete sentences**	**Weight (250 total)**	**Matching Engineering Specification**	**Targets with Tolerances (+ = or more - = or less)**	**Test Procedure Number**
1	The Print head should be capable of motion in 5 axes.	39	Number of Joints	5 +	1
2	The Printer should print on irregular, 3D surfaces. (i.e. should print a box on a cylinder)	35	%Print Volume Full Tooling Range	75% +	2.1
			Full Tooling Range Volume	6 in^3 +	2.2
			Print Angle Maximum	45 deg. +	2.3
3	The Printer should be capable of printing objects larger than itself.	31	Stationary Print Volume	10 in^3 +	3.1
			Print Volume to Work Volume (Ratio)	1:1 +	3.2
4	The Printer should have increased mobility over the current standard.	30	Weight	30-50lb	4.1
			Printer Volume	10 in^3 -	4.2
			Print Volume to Work Volume (Ratio)	1:1 +	3.2
			Deflection ratio decreasing as gantry nears origin	1/10" to 1/100"	4.3
5	The Printer should be constructed at lowest costs feasible.	27	Cost of Parts	$2000 -	5.1
6	The Printer should be able to print discontinuous prints.	24	Print Volume to Work Volume (Ratio)	1:1 +	3.2
			Discontinuous print tolerance range	+/- 0.1 in	6.1
7	The Printer must be easily serviceable to allow future prototype iterations.	22	# of Components	60 -	7.1
			Simple, Open Design	Yes	7.2
			Readily Available Components	Yes	7.3
8	Printer should extrude using FDM	20	FDM Print Head	Yes	8.1
			Nozzle Heat	285 C +	8.2
9	Documentation and BOM should be detailed and complete	12	Technical Part Drawings w/ GDT complete	Yes	9.1
10	Printer should be achieve print tolerances comparable to industry standards	10	Stationary Print Tolerances	+/-.02 in	10.1
	Sum (should be 250)	250			

8.2 Appendix B: Morph Matrix

Function	Idea #									
	1	2	3	4	5	6	7	8	9	10
Import Control	Serial Cable	Wifi	Bluetooth							
Guide (Steer)	Computer	Joystick	Steering Wheel	Remote Control	Manual					
Actuate Motion (Robot)	Wheels	Tank Tracks	Helicopter Blades (Drone)	Rails	Lift and Carry	Sit-in drive (lawnmower style)	3D printing Roomba	Boston dynamics robot	Cables	
Stabilize Object	Ground Screws	Axis Locks	Stabilizing Arm	counterweight	Scissor jack	Actuating Anti-vibration feet	Removable weights	gyroscopes	Arms that attach to object	Tension Cable
Sense Object	Vision System	CMM Probe	Physical Placed Sensors	Manual (Programming for specific geometry)						
Actuate Motion (Print Head)	Prismatic Joints - screws	Rotational Joints	Helicopter Blades (Drone)	Prismatic – belts and pulleys	Prismatic – linear/pneumatic actuators	Prismatic – scissor lift	Cables / Cable joints	Delta printer style	Core-xy style	
Extrude Material	Prusa Print Head – direct drive	Weld	Prusa Print Head – Bowden	Prusa Print head – remote direct drive	SLA / UV					
Display Status	Computer	LED Panel								
Joint Configuration	PPRRRR -horse	RRRRR -snake -arm	RRPRR -flamingo	PPPRR -gantry on rails -spider tank -crossbow	RPPRR -crane -crossbow	PRPRR -scissor	PRRRR -edward scissor print	MORE THAN 5		

8.3 Appendix C: Pugh Chart

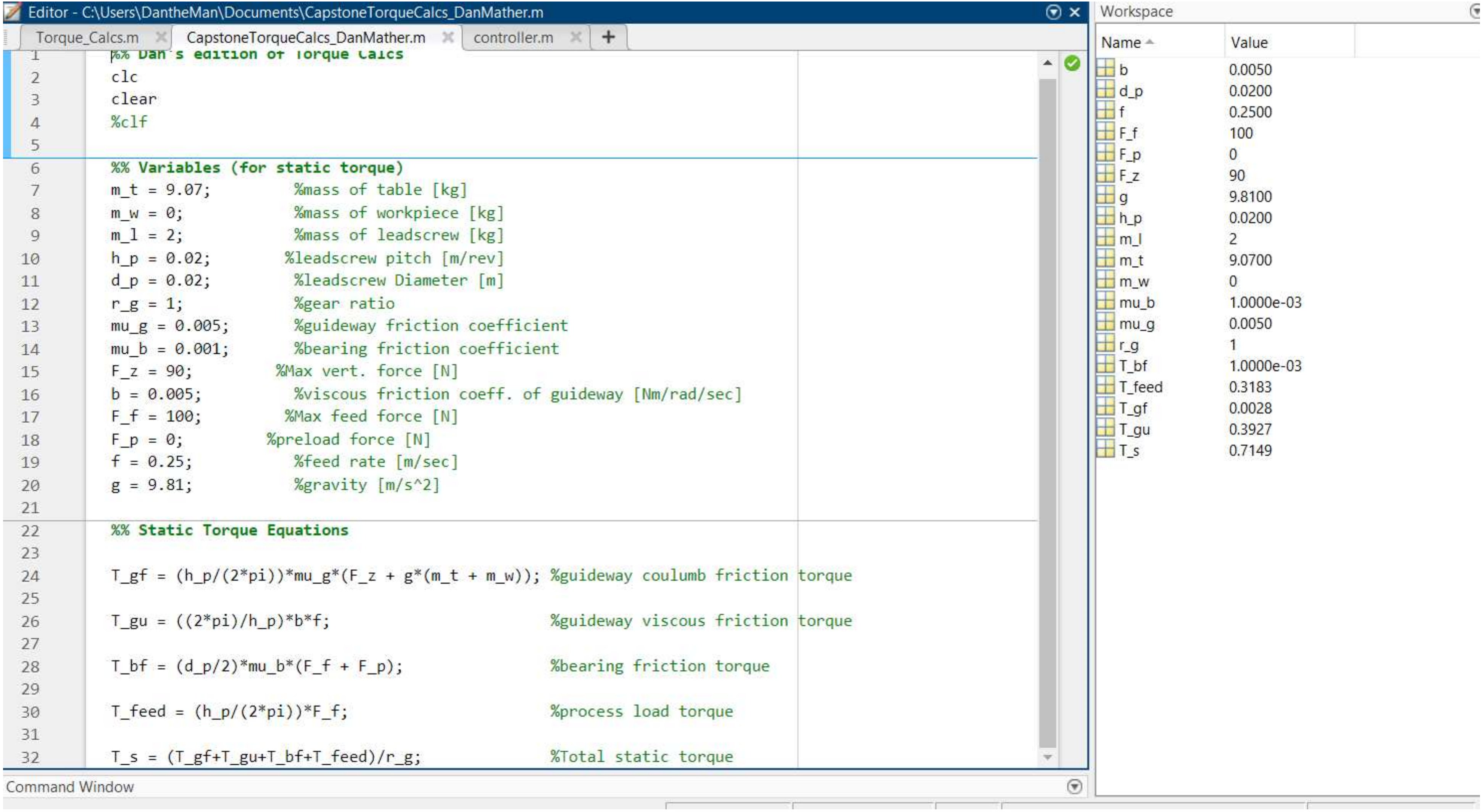
	CV 1	CV 2	CV 3	CV 4	CV 5	CV 6	CV 7	CV 8	CV 9	CV 10	CV 11	CV 12
Criteria	Horse	Flamingo	Crane	Spider Tank	Edward Sciss	Cowboy	Wasp	Snake	Crossbow	RRRRR	PRPRR	RPPRR
The Print head should be capable of motion in 5 axes.	0	-1	0	-1	1	0	1	1	1	1	1	1
The Printer should print on irregular, 3D surfaces. (i.e. should print a box on a cylinder)	0	-1	-1	1	1	1	1	1	0	1	1	0
The Printer should be capable of printing objects larger than itself.	0	1	-1	1	1	0	1	0	-1	0	1	0
The Printer should have increased mobility over the current standard.	0	1	-1	0	0	0	1	0	0	0	0	1
The Printer should be constructed at lowest costs feasible.	0	0	1	-1	-1	0	-1	-1	0	-1	-1	0
The Printer should be able to print discontinuous prints.	0	0	-1	0	0	-1	-1	1	-1	1	0	0
The Printer must be easily serviceable to allow future prototype iterations.	0	-1	0	-1	-1	1	-1	-1	0	-1	0	1
Printer should be achieve print tolerances comparable to industry standards	0	-1	1	1	0	1	-1	-1	0	-1	0	0
Difficulty of Manufacturing	0	-1	1	-1	-1	1	-1	-1	-1	-1	0	-1
∑(1)	0	2	3	3	3	4	4	3	1	3	3	3
∑(-1)	0	5	4	4	3	1	5	4	3	4	1	1
∑(0)	9	2	2	2	3	4	0	2	5	2	5	5

🟥 Abandoning Idea
🟨 Salvage Parts from Idea / Revise for Clarity
🟩 Exciting Idea, add Revisions to Mitigate Negative Attributes

8.4 Appendix D: Bill of Materials (no links)

Category	Component	Quantity	Price	Link	Description	Cost
Frame	3030 Extrusion 254mm	2	5,64	https://us.m	GFS6-3030-254	11,28
Frame	3030 Extrusion 508mm	1	8,38	https://us.m	GFS6-3030-508	8,38
Frame	3060 Extrusion 194mm	2	7,35	https://us.m	GFS6-3060-194	14,7
Frame	3060 Extrusion 254mm	1	7,35	https://us.m	GFS6-3060-254	7.35
Frame	3060 Extrusion 305mm	2	8,78	https://us.m	GFS6-3060-305	17,56
Frame	3090 Extrusion 508mm	2	16,71	https://us.m	HFS6-3090-508	33,42
Frame	3090 Extrusion 350mm	2	11,51	https://us.m	HFS6-3090-350	23,02
Frame	Skelang 4-Pcs Leveling Machine Casters with Nylon Wheel and Rubber Foot	4	44.99	https://www		179,96
FDM	E3D Volcano Hotend	1	48,3	https://e3d-		48,3
FDM	SeeMeCNC EZR Extruder	1	33	https://www		33
FDM	Bowden Tube	1	12,99	https://www		12,99
Kinematics	Lead Screw Couplers	1	7,62	https://www		7,62
Kinematics	Lead Screw and Nut X-Axis	1	114,93	https://us.m	MIsumi PN MSSRW1236-345-F20-V6-S20-Q6	114,93
Kinematics	Lead Screw and Nut Z-Axis	1	114.93	https://us.m	MIsumi PN MSSRW1236-308-F20-V6-S20-Q6	114.93
Kinematics	NEMA 17 motor	4	15,4	https://www		61,6
Kinematics	NEMA 17 motor SLIM	2	8.56	https://www		17.12
Kinematics	NEMA 17 Bracket	1	5,28	https://www		5,28
Kinematics	Linear Rail 800mm x2 4x Carraiges	2	89.56	https://www		179.12
Kinematics	Belts	1	11,88	https://www		11,88
Kinematics	Toothed Idler	1	8,98	https://www	5 pack sufficient (need 2 or 3) - GT2 Idler for stepper motor	8,98
Kinematics	Toothless Idler	1	10,98	https://www		10,98
Fasteners	Assorted 3030 Al T-nuts	2	14,99	Keadic 120	120 t-nuts (m4,m5,m6)	29,98
Fasteners	SHCS M8 x 1,25 mm Thread, 30 mm Long	1	8,98	https://www	McMaster PN 90128A276 - pack of 25	8.98
Fasteners	Steel Oversized Washer for M5 Screw Size, 5,5 mm ID, 18 mm OD	1	12,57	https://www	McMaster PN 98363A111 - pack of 100	12,57
Fasteners	SHCS Black-Oxide, M5 x 0,8 mm Thread, 14 mm Long	1	15.6	https://www	McMaster PN 91290A230 - pack of 100	15,6
Fasteners	SHCS Black-Oxide, M5 x 0,8 mm Thread, 18 mm Long	1	16,61	https://www	McMaster PN 91290A238 - pack of 100	16,61
Fasteners	FHS 90 Degree Countersink, M3 x 0.50 mm Thread, 10 mm Long	1	6,36	https://www	McMaster PN 91294A130 - pack of 100	6.36
Fasteners	FHS 90 Degree Countersink, M5 x 0.80 mm Thread, 10 mm Long	1	10,35	https://www	McMaster PN 91294A208 - pack of 100	10,35
Fasteners	Black-Oxide 18-8 Stainless Steel Washer for M5 Screw Size, 5.3 mm ID, 10 mm OD	1	5,33	https://www	McMaster PN 98269A440 - pack of 100	5,33
Fasteners	SHCS M4 x 0,7 mm Thread, 16 mm Long	1	9,97	https://www	McMaster PN 90128A215 - pack of 100	9,97
Fasteners	18-8 Stainless Steel Hex Nut M4 x 0.7 mm Thread	1	6.32	https://www	McMaster PN 91828A231 - pack of 100	6.32
Fasteners	Alloy Steel Cup-Point Set Screw M4 x 0.7 mm Thread, 6 mm Long	1	5,31	https://www	McMaster PN 91390A112 - pack of 100	5,31
Custom Parts - Y axis	Y Axis Endplate	1			3D Printed PLA	0
Custom Parts - Y axis	Y Axis Tensionser	1			3D Printed PLA	0
Custom Parts - X axis	X-Frame Bracket	2			Machined Aluminum	0
Custom Parts - Z axis	Z-Bracket Arm	1			3D Printed PLA	0
Custom Parts - X axis	XZ Bracket	1			Machined Aluminum	0
Custom Parts - X axis	Motor Bracket	1			3D Printed PLA	0
Custom Parts - X axis	Screw Connector	1			3D Printed PLA	0
Custom Parts - Y axis	Belt Holder	1			3D Printed PLA	0
Custom Parts - End Effector	End Effector to Extrusion Arm	1			Machined and Welded Aluminum	0
Custom Parts - End Effector	Stepper1 Arm	1			Machined Aluminum	0
Custom Parts - End Effector	Stepper2 Arm	1			Machined Aluminum	0
Custom Parts - Spool	Spool Holder	1			3D Printed PLA	0
Total Cost:						1049,78

8.5 Appendix E: Torque Calculation Figures



```
%% Dan's edition of Torque Calcs
clc
clear
%clf

%% Variables (for static torque)
m_t = 9.07;         %mass of table [kg]
m_w = 0;            %mass of workpiece [kg]
m_l = 2;            %mass of leadscrew [kg]
h_p = 0.02;        %leadscrew pitch [m/rev]
d_p = 0.02;         %leadscrew Diameter [m]
r_g = 1;            %gear ratio
mu_g = 0.005;       %guideway friction coefficient
mu_b = 0.001;       %bearing friction coefficient
F_z = 90;          %Max vert. force [N]
b = 0.005;          %viscous friction coeff. of guideway [Nm/rad/sec]
F_f = 100;         %Max feed force [N]
F_p = 0;          %preload force [N]
f = 0.25;           %feed rate [m/sec]
g = 9.81;           %gravity [m/s^2]

%% Static Torque Equations

T_gf = (h_p/(2*pi))*mu_g*(F_z + g*(m_t + m_w)); %guideway coulumb friction torque

T_gu = ((2*pi)/h_p)*b*f;                        %guideway viscous friction torque

T_bf = (d_p/2)*mu_b*(F_f + F_p);                %bearing friction torque

T_feed = (h_p/(2*pi))*F_f;                      %process load torque

T_s = (T_gf+T_gu+T_bf+T_feed)/r_g;              %Total static torque
```

Workspace

Name	Value
b	0.0050
d_p	0.0200
f	0.2500
F_f	100
F_p	0
F_z	90
g	9.8100
h_p	0.0200
m_l	2
m_t	9.0700
m_w	0
mu_b	1.0000e-03
mu_g	0.0050
r_g	1
T_bf	1.0000e-03
T_feed	0.3183
T_gf	0.0028
T_gu	0.3927
T_s	0.7149