Multidisciplinary Senior Design
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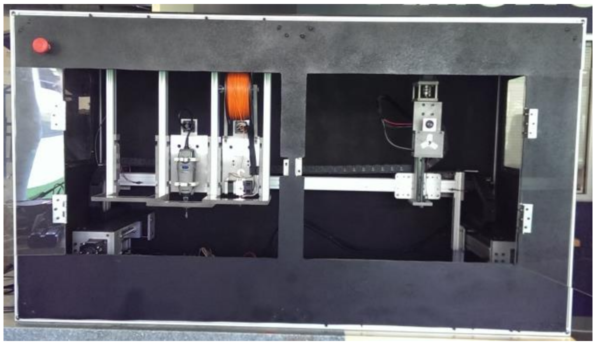
Project Number: P14551

MULTI-PROCESS 3D PRINTING



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ABSTRACT

Traditional 3D printers generally implement a single printing process, allowing for the creation of a part composed of a single material. In the past decade, substantial time and money has been dedicated to researching and developing new additive manufacturing techniques to increase the capabilities of 3D printing systems. Some of this research is dedicated to creating machines which can synthesize multi-material components through the simultaneous or sequential manipulation of multiple print mediums (i.e. mixing materials in different ratios or printing with multiple materials one after the other).

The main objective of this project was to design and build a multi-process 3D printer prototype capable of utilizing both additive and subtractive processes through the implementation of a generalized interfacing system. The critical design objectives included: a low system cost ($\leq$ \$5,000), fully autonomous system operation, an open source design, and the capacity for additional system expansion and design by future senior design teams. This project was completed over the course of two semesters of Multi-Disciplinary Senior Design by a team of five students. At the end of the second semester, the project reached a semi-successful end-state having met some but not all of the engineering specifications given.

NOMENCLATURE

EMHI – Electrical–Mechanical Head Interface, Motion System side of the Interface
FDM – Fused Deposition Modeling, a common additive manufacturing technique
HRMT – Hybrid Rapid Manufacturing Tool
MSD – Multidisciplinary Senior Design
PRP – Project Readiness Package
UMB – Universal Mounting Bracket, Process Head Side of the Interface

BACKGROUND

The field of 3D printing has experienced rapid growth in the past decade, with numerous companies and independent groups developing cheap and accessible 3D printers. The range of systems available span a wide price and functionality range, from a couple thousand dollars for basic FDM printers to machines in excess of hundreds of thousands of dollars which are able to print using powdered titanium. The most substantial growth has been in the area of low-cost printers targeted at individual hobbyists and small companies. Every couple of months, inventors and hobbyists are introducing systems that provide new capabilities in the area of 3D printing. Started in 1993, the Rapid Conference is an event dedicated to showcasing these new technologies. A multi-process 3D printer called the Multi Prototyping Lab won the Innovation Award at the 2013 Rapid Conference. This system demonstrates the ability to carry out multiple additive and subtractive processes through the implementation of a head interchange system. However, the starting cost of the Multi Prototyping Lab is in excess of \$150,000. The goal of this project is to reproduce the basic functionalities of the Multi Prototyping Lab at a substantially reduced cost, while simultaneously generating a system that is fully open source allowing for future development.

PHASE 1 – SPECIFICATION OF REQUIREMENTS

The first step of any project is to identify the primary stakeholders. The driving force of this project was the customer, Dr. Denis Cormier, the Earl W. Brinkman Professor at the Rochester Institute of Technology. Dr. Cormier is a firm believer that innovation in a 3D printing market is often driven by hobbyists who are also stakeholders. After meeting with the primary stakeholder, the team created a list of needs that was expected to be met at the conclusion of senior design. The needs that the team and customer agreed to be most important were:

- A universal interface for the implementation of other existing HRMTs
- Emergency stops and other safety sensors
- At least one additive and subtractive process
- A robust system architecture that allows for the ready expansion of the system
- Automated tool loading

Once the customer needs were compiled, a list of engineering specifications was created to capture the physical meaning of the customer needs in a more quantifiable form. Some of the key identified parameters include:

- Using open source software to control the system
- Enclosure dimensions that fit on top of a standard lab bench (defined as 60”x30”)
- A total system cost of less than $5000
- System shutdown upon user interaction during machine operation
- Capacity for system to be readily expanded by future teams
- Ability to manipulate process heads in excess of 2 kg
- Accurate and precise control of the motion system (repeatable positioning and zeroing)

The team then created a risk assessment tool to address relevant concerns regarding system design and execution. The risk assessment tool measures concerns on a weighted product of issue severity and occurrence probability. The first of two concerns with the highest risk scores was the possibility of the process head falling off of the EMHI due power loss with an “active-on” interface. The second concern was the possibility of process head misalignment in relation to the EMHI during an automated tool change. The remainder of the customer needs, engineering specifications, and risks can be found on the teams EDGE website [1]. The generated risk assessment document also includes mitigation plans for identified risks which were implemented in the system design.

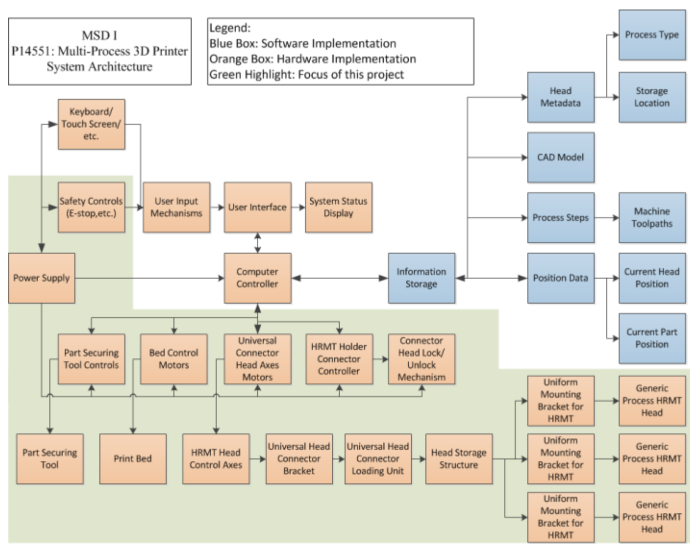


Figure 1. System Architecture diagram identifying key hardware (orange) and software (blue) elements of the system. System components identified as within the scope of this project are highlighted in green.

As part of the initial project planning, the system architecture diagram shown in Figure 1 on the right was generated to identify key system elements to be implemented by the team. The diagram is divided into hardware (orange) and software (blue) components, with system elements identified as the focus of this project highlighted in green. The purpose of this diagram is to provide structure to the design process and to broadly identify all elements of the system that need to be considered as part of this project. At the time this diagram was generated, it was agreed upon by the team that the project would generally be focused on hardware development rather than software design.

PHASE 2 – CONCEPT GENERATION AND SYSTEM DESIGN

As part of the concept generation and system design phase of the project, the team brainstormed a set of design concepts for the overall system. The focus of this phase was to generate a variety of design concepts with variations across as many system design parameters as possible. At this point in the project, the goal was to maximize creativity in design and then temper that creativity with an assessment of the concept functionality and feasibility. Eight different system designs were collectively generated and assessed by the team using a Pugh Matrix, as shown in Figure 2 on the following page.

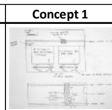
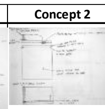
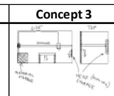
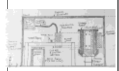
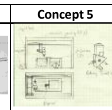
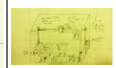
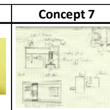
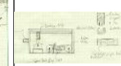
Parameter Number	Multi-process 3D Printer / Judgement Criterion \ Conceptual Image	Mutli-Proto Lab	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6	Concept 7	Concept 8
										
1	Cost	-	-	+	-	-	-	-	D	-
2	Technical Difficulty	-	-	+	-	-	-	-	A	+
3	System Extensibility	+	+	-	+	+	-	+	T	-
4	Number of Safety Concerns	+	S	+	-	-	-	-	U	-
5	Utlizes pre-existing parts	-	-	S	-	-	-	S	M	-
6	Motion Control Precision	+	-	-	+	+	-	S		+
7	Maximum Number of Processes in Machine	S	-	-	+	+	-	+		-
8	Active Material Storage Volume	?	+	S	-	-	+	+		S
9	Maintenance Frequency	?	-	+	-	-	-	-		-
10	Material Replacement Difficulty	?	+	S	S	S	+	+		S
11	Number of Actuating Elements (↓)	S	-	+	-	-	S	-		-
12	Ease of assembly/Open source capability	-	-	+	-	-	-	-		+
13	Visual appeal of system	+	+	-	+	+	+	+		S
14	Power Consumption	-	+	-	+	S	-	S		-
	Total (+)	4	5	6	5	4	3	5	0	3
	Total (-)	5	8	5	8	8	10	6	0	8
	Net Score	-1	-3	1	-3	-4	-7	-1	0	-5

Figure 2. Pugh Concept Selection Matrix for the Overall System Design. Eight generated system ideas are compared against each other and the existing Multi Prototype Lab system using 14 assessment parameters.

Concept seven from the Pugh Matrix was selected as the assessment datum because it was conceptually one of the more straightforward system designs, utilizing design elements which were fairly consistent with existing systems, according to prior research by the team. The system sketch of this concept is shown in Figure 4.

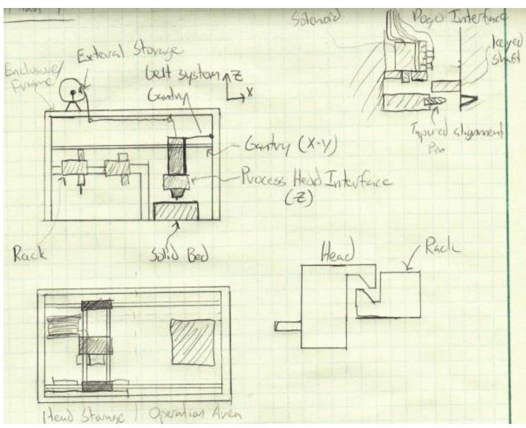


Figure 4. Pugh Matrix Concept Seven: A planar gantry system with vertical movement controlled by a vertical element mounted to the gantry.

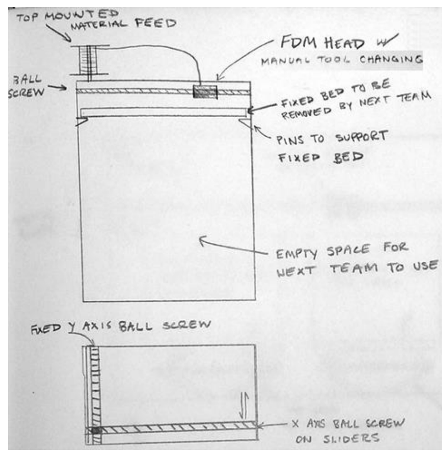


Figure 3. Pugh Matrix Concept Two: A two-axis FDM with rudimentary system design elements.

From the results summarized in Figure 2, the design concept two (shown in Figure 3) appears to have the highest score. However, this design is not actually capable of motion along three dimensions and was designed only as a simplistic "last resort" solution. The fact that it scored more highly than all other options indicates that the selection criteria used in this matrix fail to capture all relevant system parameters. Taking this into account, concept two was discarded from consideration, and the team selected concept seven to move forward in design, as no other design was determined to be relatively superior.

After determining the system design, the next step was to identify and repeat the same brainstorming and selection process for critical subsystems. In considering the system layout, the following critical subsystems were identified: motion system, EMHI, and storage system. It was also at this point in the project that the team decided to implement two basic process heads: an ABS plastic FDM extruder as an additive process head and a rotary tool as a subtractive process. These two processes were chosen after benchmarking approximately 20 different possible process heads. They were selected due to ease of implementation and prevalence in the field of additive manufacturing.

PHASE 3 – SUBSYSTEM AND DETAILED DESIGN

Following the Systems Design phase, the team started developing subsystem concepts and began modeling components within those subsystems. What follows is short description of each subsystem design and some component functionality within the subsystems. For each subsystem, a CAD model showing the system design is included.

EMHI AND UMB

The EMHI consists of four machined plates, a solenoid arm, a rotational solenoid, a "pull" solenoid, 6x 3mm dowel pins, and a male electrical pass-thru on the Motion System. This subassembly mates with the UMB subassemblies which consist of a machined back plate, a tapered pin, 3x 6mm ball bearings, a female electrical pass-thru, and 4x 6mm dowel pins. The rotational and X-Y degrees of freedom the UMB and EMHI front plate are controlled by arranging the 3mm dowels and 6mm ball bearings in an evenly spaced circle around the taper pin and taper pinhole, with the dowels at ninety degrees to the tangent of the circle. When this mate is achieved, the taper pin extends into the box formed by the EMHI plates, and the male-female electrical pass-thru is connected. The rotational solenoid is then activated, which clamps the solenoid arm down onto a machined flat on the taper pin. This secures the UMB assembly firmly in the Z-direction. The "pull" solenoid is then shifted to an unpowered state, which releases a rod over the solenoid arm, effectively locking it into place if a power loss occurs. The Process Head is then able to perform operations through the mechanical and electrical mating.

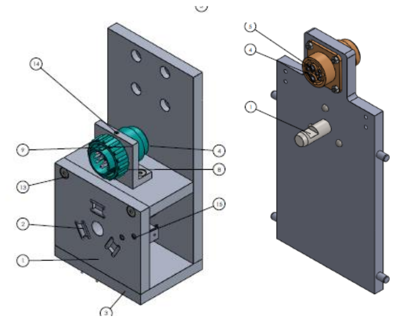


Figure 5. EMHI (left) and UMB (right) Subsystem CAD Models.

MOTION SYSTEM

CNC costs can largely be attributed to expensive machining required in order to achieve high accuracy linear motion. In order to reduce costs, the team elected to use the open source Makerslide rail system on the X and Y axis, in a double-rail "I" configuration (two short axis are "Y", a single long axis as "X"). This configuration was chosen to reduce the total amount of linear rail needed, and maximize the operating area of the system. Both the X and Y rails are powered by integrated motor/controllers with encoders for additional accuracy. These motors operate three lead screws, which were chosen over belts and similar linear motion drives due to high accuracy potential, low feedback deflection, and minimal backlash. The Z-axis requires more precision than the X and Y axis due to 3-D printing layer width tolerances, and using a more traditional hardened linear rail and carriage. The Z-axis is also powered by an integrated motor/controller which drives a smaller pitch lead screw with an anti-backlash nut to allow for a more accurate step resolution. The Z nut block was custom made to mount the EMHI assembly as well.

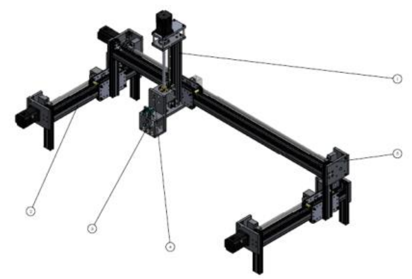


Figure 6. Three-axis motion system CAD Model.

STORAGE SYSTEM

The storage system was designed to be as simple as possible to operate, accessible by the operator and EMHI, and gravity operated, preventing the need to run any electrical lines to the subsystem. The system consists of double width 80-20 support beams that connect to the enclosure frame and the storage mounting brackets. The storage mounting brackets screw into the 80-20 supports, and mate with the 6mm dowel pins present on the UMB subassemblies using slots cut in the bracket, which open to the front and back of the machine, offering the needed accessibility.

Figure 7. Storage system with storage bracket detail CAD Model.

ENCLOSURE

The enclosure system includes both the 80-20 frame and operator safety system in one convenient subsystem. Hardboard was chosen as the main enclosure material due to it moderate strength, low cost, and surface finish. Polycarbonate sheeting was used in the doors and windows on the sides and top of the enclosure for its transparency and strength. The doors have magnetic latches with an included safety sensor, allowing detection of operator intrusion into the machine. An Emergency Stop is also mounted to the enclosure to cut all power to the system.

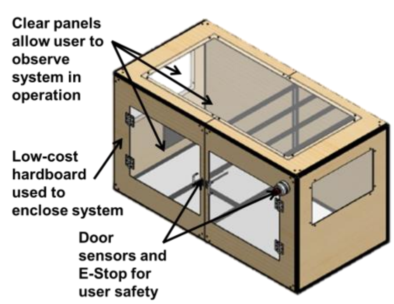


Figure 8. System enclosure CAD model with identified system elements.

PROCESS HEADS

The initial process heads to be implemented where selected based on simplicity of integration into the system. An FDM Extruder and a Dremel Tool spindle where selected as the first additive and subtractive processes for these reason. The extruder head was designed to mount a third party MakerBot StepStruder to a UMB subassembly using a single mounting plate attached to the bottom of the UMB. There was debate on whether to carry filament on board the process head or pipe it in through the EMHI. Ultimately, on-board storage was selected due to fewer possible complications and easier filament reel change out. The rotary process head was designed to mount a Dremel 3000 rotary tool using 3-D printed ABS clamps, which is a proven method used on other open source CNC machines.

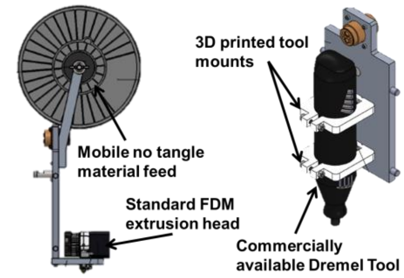


Figure 9. CAD models of two implemented process heads with added callouts.

BED SYSTEM

During the system design phase, the team opted for a simple heated bed in order to reduce complexity and focus on our core customer needs. This simple bed still needs to be level-able to the system in order to 3-D print and route parts. Adjustability in this regard is completed with 3adjustment bolts with mounting blocks, which control the height at three key points on the bed. This bed then mounts a heater and mirror printing surface.

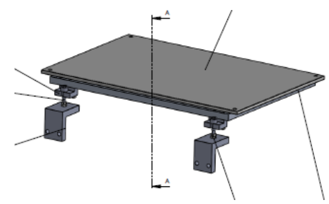


Figure 10. Bed CAD model. Two of the three leveling feet are visible.

ELECTRICAL SYSTEM

The electrical system was one of the last systems designed due to its necessity to be integrated throughout many of the other systems. This design process included considerations of power requirements, wire flow, safety components and control system requirements while keeping the system low cost and open-sourced. The system design began with the selection of the Arduino Due as the microcontroller due to its open sourced nature, 32-bit architecture, and higher clock speed capabilities. The power requirements of the entire system were analyzed to determine the various power supplies needed. This analysis identified the need for two high current, regulated power supplies, a 300W 12V and a 350W 24V, as well as a low current, 5V supply. The safety requirements of the system led to the need for various limit switches as well as an emergency stop system. The emergency stop system was designed to cut off power to solely the 12V and 24V power supplies which stops all motors the heated bed as well as the Arduino. Limit switches were also incorporated as dual purpose soft stops and zeroing points. Once all the major components required were identified, wire routing throughout the system was identified. The wires were planned to be routed along the outer edges of the system as much as possible to eliminate clearance issues. In the cases where the wiring is needed on the interior of the system, such as the motors and EMHI in the motion system, cable carriers were utilized to avoid tangling and damage.

BASIC SOFTWARE/FIRMWARE

While this project focused heavily on the physical design of the system, in order to demonstrate and test its capabilities some rudimentary software needed to be written for the Arduino microcontroller. The implemented firmware executes simple control of motors, switches, and solenoids to demonstrate functionality of the system. Work was undertaken to identify existing open source 3D printer firmware packages which are compatible with this project's Arduino Due microcontroller. Since the Due is a newer Arduino board there is limited scope of documented Due compatible development. Fortunately, Repetier Host and Firmware has recently been updated to include Due support. The current software is capable of controlling the three axes, managing heating elements and extruders, slicing models, and executing g-code commands. The software currently drives the dual Y-axis motors with mirrored step commands, so software misalignment correction is not currently possible. The software, while useful for initial testing of the system, has not been fully adapted to the system and could benefit from more intensive development efforts.

SUBSYSTEM AND COMPONENT ANALYSIS

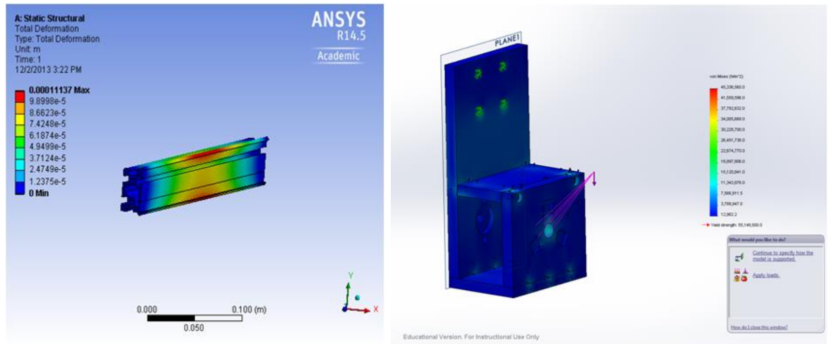


Figure 11. Example Finite Element Analysis conducted to determine deflection under loading for key system components. Left is deflection of a motion rail and right is deflection of the EMHI.

In order to insure high dimensional accuracy for parts built with the system, rigidity of the motion system and EMHI was critical. The team conducted finite element analysis on critical parts in the motion system, using mass and center of gravity information tabulated from accurate mass property CAD models. This information was used to build worst-case loading FEA models of the X-Y rails, supports, and carriages, as well as the EMHI Frame and Taper Pin. The Z axis was not investigated, as it is by far the strongest component in the system. The stack-up of these worst case scenarios showed favorable results and the subsystems where theoretically validated.

PHASE 4 – SYSTEM CONSTRUCTION AND PROTOTYPING

The first step of this phase of the project was the purchasing of all components from the compiled system Bill of Materials (BOM). Long-lead items including the stepper motors and the rotary solenoid used in the EMHI were ordered at the end of MSD I (prior to the winter break) and all other system components were ordered at the start of MSD II. The parts ordering process resulted in many substantial delays which were not anticipated or accounted for in the project plan developed in MSD I. Delays were the result of a variety of causes, including a high level of activity in the Industrial Engineering office (which was the office the team had to work through to order materials) and difficulty in establishing accounts with new vendors. As a result of these delays, the team had to combine purchasing from different vendors to consolidate orders down to existing relationships wherever possible, sometimes resulting in component purchasing at sub-optimal prices.

One specific instance that caused difficulties at this phase was the acquisition of aluminum plate for use in the system. Many system components were designed to be cut from 10 mm plate, which was substantially more expensive than 3/8” in the United States. Consequently, many system elements had to be quickly redesigned to accommodate the updated plate thickness. Fortunately, this did not result in any major design issues and was readily accomplished.

One of the customer needs of the project was the capability of the system to be assembled by hobbyists. It was assumed that the hobbyists who would be interested in this project are medium to highly skilled individuals with access to various machines including standard machine shop equipment (mill, drill press, etc…) and a 3D printer. While not all of the tools equipment used by the team to complete this project were absolutely necessary (less sophisticated equipment could be used to accomplish similar results), the advanced manufacturing capabilities of the Brinkman lab were utilized to reduce part production time to compensate for ordering delays and to generally minimize machining man hours.

A large portion of the machining was simplified by the availability of a CNC water-jet cutting tool in RIT’s Brinkman Lab. Almost all of the aluminum plate parts were cut on the water jet, substantially reducing number of machining man hours required by the team. Additionally, the geometries of the storage brackets and the interfacing surfaces of the EMHI are not easily produced with milling equipment, so these components were produced using 6-Axis CNC machines in the Brinkman Lab.

In machining system components, the team heavily utilized the resources available in the RIT Mechanical Engineering Machine Shop. Many system components were produced using Bridgeport Vertical Mills. Of particular importance to the design of the system was the precise mating and alignment of system components, which is critical for precision motion. To accomplish this, all mating surfaces had to be flush and squared up relative to one another. It is for this reason that milling almost all system components was necessary.

At the conclusion of MSD II, the machine has roughly 250 unique parts excluding fasteners and electronic components. While it is possible to assemble the system with one person, two or more people make the assembly safer and faster. In putting together and testing the system, this and the following two phases (Problem Identification and tracking and Troubleshooting and Issue Resolution) tended to be rather cyclic. While they are presented here in a more linear fashion, there was a lot of iteration in the construction and testing process.

PHASE 5 – PROBLEM IDENTIFICATION AND TRACKING

As component machining was completed, subassemblies were constructed to check for any design or fabrication issues. A substantial amount of time was spent in this project resolving various errors. A substantial percentage of these errors were a result of last-minute design changes implemented due to material or part availability (as described in Phase 4 above). As issues were identified and addressed, a working document was generated to track system issues. Furthermore, emphasis was placed on continually updating the system CAD models and the BOM to reflect the updated system design. These actions were taken to ensure that future development on the project can build on the existing content without having to resolve inconsistency in the documentation. Figure 12 shows a snapshot of some of the issues and the actions taken to correct them.

Issue Description	Date Identified	Subsystems	Components	Date of Remed. Identification	Description of Remediation	Owner	Parts to buy	Parts to machine	FIXED Y/N?	Further Explanation
Shaft Couplings for XY do not fit motor shafts	3/5/2014	XY MOSYS	XY Shaft Couplings	3/5/2014	Bored out coupling. Make a split bushing to bridge the size gap. Update BOM with the correct parts	Nick	N/A	XY Shaft Coupling, Split Bushing	Y	Updated to correct coupling
Z Nut Block carriage side mount holes machined incorrectly	3/7/2014	Z MOSYS	Z Nut Block	3/7/2014	Moved Hole Location, Updated in Model	Matt	N/A	Z Nut Block	Y	Updated in Model
Z Motor Mount holes not large enough	3/9/2014	Z MOSYS	Z Motor Mount, XY Motor Mount, Z Fixed, Z Simple	3/9/2014	Drill to correct size	Austin	N/A	Z Motor Mount	Y	N/A
Z Nut Block Hole Position out of alignment	3/9/2014	Z MOSYS	Z Nut Block	3/11/2014	Remove material from the bottom to reach alignment	Austin, Jeremy, Matt	N/A	Z Nut Block	Y	Not Updated in Design Yet
M5 Ordered for M6 XY Nut Block Holes	3/9/2014	XY MOSYS	N/A	3/9/2014	Order M6 Button Heads	Austin, Nick	M6 Button Heads	N/A	Y	BOM Updated

Figure 12. Issue tracking document snapshot with five of the identified issues noted. The tracking spreadsheet includes information on the nature of the issue, the owner, and the means taken to resolve the issue, along with other details.

PHASE 6 – TROUBLESHOOTING AND ISSUE RESOLUTION

A direct approach to issue troubleshooting was used for this project. As the issues in the system were discovered, the team would immediately collaborate and investigate to determine the root cause of the issue. Once the root cause was discovered, the team began brainstorming and testing resolutions to the problem and verifying that the error was corrected. The team utilized this process in many cases throughout the systems build and test phase. Much of the issue resolution process was closely tied to the problem identification and tracking phase, so that this and the previous phase are closely related.

Over the span of the construction and testing process of MSD II, the general troubleshooting process implemented by the team involved iteratively: assembling systems, checking for fit, and checking for functionality. Initially there were multiple sources of fit error, due either to system redesign to accommodate new parts or initial errors in component geometry. After resolving all system fit issues, it was next necessary to resolve issues with the functionality of each subsystem and the system as a whole.

A subsystem for which the iterative construction, identification, and resolution process was particularly crucial was the motion subsystem. Initial construction of this subsystem revealed that some of the mounting brackets needed to be redesigned slightly to resolve some fit issues. After making these corrections and updating the system model, it was later found that the process of aligning the axis is both crucial and cumbersome. This became a major identified system flaw, which does not currently have an easy solution. Finally, at the end of the MSD II cycle, there remains some level of uncertainty about the functionality of the stepper motors on this system, indicating an unresolved problem in the system.

CONCLUSIONS AND FINAL SYSTEM STATE

Over the course of the MSD course, substantial progress has been made in the design and development of a Multi-Process 3D printer. Working from the initially defined customer needs and engineering requirements, an overall system was successfully designed and planned for implementation. The system was designed in such a manner that all needs and requirements could be theoretically met; however the current state of the project limits the testing of certain aspects of the design. A visual reference which is useful in understanding the current state of the system is shown in Figure 13 below.

rqmt. #	Importance	Source	Function	Engr. Requirement (metric)	Unit of Measure	Marginal Value	Ideal Value
S1	9	CR1	Cost	Cost of System Operating Software	USD		0
S2	1	CR3	Performance	Useability Time	% Up Time	low	high
S3	3	CR3	Performance	Tool Change Time	Seconds	high	low
S6	9	CR4	Performance	Enclosure Dimensions (LxWxH)	Inches		
S7	9	CR2, CR5	Cost	System Cost	USD	$\leq$ 5000	$\leq$ 2000
S8	1	CR7	Cost	Quantity of Recycled Parts			
S9	3	CR3,CR9	Performance	Quantity of Implemented Additive Processes		1	
S10	3	CR3,CR9	Performance	Quantity of Implemented Subtractive Processes		1	
S11	3	CR11	Performance	Manipulatable (Print/Remove) Part Volume	Inches		12"x8"x8"
S12	9	CR12	Safety	Ability to physically interact with parts during operation	User Score	Very Hard	Impossible
S13	9	CR13	Ease of Use	Development Extensibility (Improvement by Future MSD Teams)	User Score		
S14	9	CR8	Safety	System halt on physical intervention	Boolean	FALSE	TRUE
S15	1	CR6	Performance	Intuitive Interface	User Score		
S16	9	CR3,CR10	Ease of Use	Human Interaction Time during tool change	Seconds	$\leq$10	0
S17	9	CR15	Performance	Maximum Tool Head Weight Supportable	Kilogram	$\geq$2	$\geq$5
S18	9	CR11,CR14	Performance	Motion Control Accurately zeroes	mm	$\leq$0.25	$\leq$0.1
S19	3	CR11,CR14	Performance	Motion Control Consistently zeroes	%	$\geq$95	100
S20	3	CR11,CR15	Performance	Motion Control Translation Speed at maximum load	mm/second	$\geq$50	100
S21	9	CR16	Performance	Tool Head/Interface Dimensionality	cm	$\leq$10x10x20	
S22	3	CR2	Ease of Use	Time Required to Remove access panel	Minutes	$\leq$5	$\leq$0.5

Figure 13. Summary of project Engineering Requirements f at the conclusion of the MSD course. Items in Red are unachieved specifications (or specifications which cannot effectively be tested and are equivalently unmet) and items in Green are specifications that have been met.

Reviewing the highlighted requirements in Figure 13 it is clear that a significant number of the engineering requirements have not been met at the conclusion of this project. Many of the unmet specifications are related to either the testing of system elements during operation or performance of the motion system. A clear path was identified to continue development and testing of the motion system to resolve those unmet requirements. However, Figure 13 demonstrates that the system has met requirements related to cost, extensibility, and appearance. Taking all of these factors into consideration, the project team believes that the intent of this project was met. The team successfully designed and constructed a hardware framework which future teams can build upon. In further development, it is hoped that the system will reach a fully automated state and all performance requirements currently not met will be tested and resolved.

RECOMMENDATIONS

While working on design and construction of the system, many areas for improvement/ expansion of the system were identified. A small list of recommendations for continued system development is as follows:

- Expand the number of implemented processes
  - Metal additive process head
  - Measurement process head
- Integrate 3D scanner into system
- Fully test additive and subtractive processes
- Design and add features to more readily align axes
- Add independent control of the dual y-axes
- Implement encoder feedback in firmware
- Replace front panel with a more solid and visually appealing material
- Apply UV and IR blocking plastic film to Polycarbonate windows

REFERENCES

[1] https://edge.rit.edu/edge/P14551/public/Home

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