FAMU-FSU COLLEGE OF ENGINEERING

GD&T Process for Additive Manufacturing in the Aerospace Industry

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A report submitted to Ms. Beth Gray
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This report is the third of five progress reports. It defines the opportunities and constraints of this project following the Six Sigma methodology of "Define, Measure, Analyze, Design, Verify" (DMADV). The team's approach, deliverables, and in-depth analysis of customer requirements are provided as well as measurements and analyses that have been performed regarding the process developed in this project.

Contents

List of Figures

List of Tables

Abstract

Additive manufacturing (AM) has become increasingly popular in the aerospace industry in recent years. The AM field is an innovative and rapidly advancing industry. Because of this, there is lack of uniformity in geometric dimensioning and tolerancing (GD&T) for AM parts in aerospace. Some standards do exist for AM parts in the aerospace industry, such standards can be found within the American Society for Testing and Materials (ASTM) and The American Society of Mechanical Engineers (ASME) standards literature, however they are specific to certain AM methods. The aerospace industry already has intense certification and validation procedures in place for aircraft parts. Precision and attention to detail are of paramount importance for safety and sustainability in these aircrafts. Since there is a lack of a clear GD&T process, these AM parts can take up to four years to be certified and used on an aircraft. In-house procedures, as well as out-of-house procedures on the government side, have to be carried out.

This report will outline the define phase through the analyze phase of this project. The problem has been identified, and as a result of the team's analysis of customer needs, it was determined that the scope of the project will be to develop and integrate a GD&T process for AM parts in the aerospace industry by checking for inherent error based on dimensional differences in the final part versus the theoretical model. Issues in the printing process are the primary causes for error in final products. The dimensional difference can be measured in terms of XYZ location as the printer is given a G-Code, which is a file format, that tells the extruder head where to print on the printer bed. It was determined that a Renishaw probe would be utilized, integrated with a FANUC delta-style robot, to perform touchdown measurements on the part once it has completed printing. However, the team discovered the probe required a machine controller in order to operate. Instead, a new scope was developed that focuses on quantifying variability of 3D printed parts through executing a 3D print and measurement test plan. This test plan consisted of printing two cylinders of different heights on three 3D printers and then the measurement of diameter of the cylinders. The team was not strictly focused on variability in the prints but quantifying the variability of the printers themselves. Doing so has allowed the team to begin statistical analysis of the diameters of the cylinders. Initial analysis showed that the printers themselves had the most effect on the dimensional deviations. In the analyze phase, the team was able to utilize a function of the scanning software that overlays the scans with the respective CAD model, and automatically provides a color map of deviation. From the results, the team identified root causes for variability in all three printers. In the following phases, the team will execute a similar test plan, however, the FANUC will be integrated with a mechanical gripper that will pick up a pseudo-probe in order to measure the parts. This pseudo-probe will be developed by the team and will mimic the Renishaw probe. Finally, an initial system design was developed. A micro factory will be contained within an enclosure, consisting of the FANUC integrated with the gripper and pseudo-probe, a Selective Compliance Articulated Robot Arm (SCARA) printer integrated with a robotic printing arm, and a linear-motion assembly used to transport the print bed. The part will remain on the bed and be moved into the working range of the FANUC in order to collect the dimensional data.

1. Introduction

The Northrop Grumman Corporation (NGC) is a world-renowned company that is known for being a leader in the global security industry with innovative solutions and products in the autonomous systems sector, cyber, C4ISR, space, strike, and logistics with modernization of products brought to customers worldwide (1). Most notably, NGC is known for their innovative manufacturing processes and has a future outlook with applications and uses in the additive manufacturing (AM) industry. Currently, NGC does not use any additive manufacturing processes (3D printers) in their manufacturing process, but rather for the design and engineering side for fast prototyping. This is due to the various problems that arise throughout the AM field. Additive manufacturing (3D printing) is a relatively new and innovative field with many different solutions and methods, which is where problems arise. Some of the problems with additive manufacturing are a lack of verification for parts, a lack of set processes for geometric dimensioning and tolerancing (GD&T), but also various problems with equipment reliability, environmental hazards and the human element which leads to slight differences with verification.

The team's silent sponsor, Northrop Grumman Corporation (NGC), has awarded the FAMU-FSU College of Engineering and Dr. Tarik Dickens money from the NGC higher education fund to enhance research but also to build upon existing standards and development of a process for the additive manufacturing and geometric dimensioning and tolerancing field. A silent sponsor is a sponsor who chooses to remain hands-off (silent) in regard to the project, and instead provides funding to the team's sponsor, Dr. Dickens, to overview and help lead the team. Dr. Dickens is known for his research in the materials and industrial manufacturing field and is the main sponsor for the additive manufacturing and GD&T team.

The overall problem at hand, is that there is no clear process for geometric dimensioning and tolerancing of additive manufacturing parts. ASME provides some standards for additive manufacturing, such standard can be found in ASME Y14.46, which serves to provide a product definition for additive manufacturing. However, these standards do not cover the specifics of additive manufacturing GD&T. Through customer needs questions and statements, the team was able to confirm that the silent sponsor and team sponsor are looking for an extremely detailed and well-documented process toward achieving GD&T readings for a 3D printed part. The end goal of this project is to be able to validate a part within a set tolerance, in which this solution and process gathers the necessary data to draw comparisons between theoretical and actual parts. The current process for certification with NGC is the use of molds and tools to provide comparisons and validation. A mold is often times made, and if the part fits properly within the mold or mold shell than the part can be considered verified. With tooling, the part is compared to the tool set, which is theoretically ideal, to check for dimensional differences and tolerancing. Another solution used in the field for verification is a coordinate measuring machine (CMM) machine. A typical run-time for verification of a part using a CMM machine is roughly 50 minutes (3). The team's solution hopes to minimize the run-time for the GD&T process and optimize the process in which this occurs. Typical CMM machines can be upwards of $20,000 and are relatively outdated due to operation time and cost. With the human factor in consideration as well, removing the need for a human within the GD&T validation process improves cost efficiency. With a hard budget of $2000, the team hopes to accomplish a verification process for GD&T of additive manufactured parts, that is both cost efficient (in terms of cost reduction for human labor and CMM machine) and time efficient, to provide numerous benefits to the receiving industry.

The team's role with this project is to address the various problems with current AM GD&T processes and to form, improve, and successfully integrate a process which helps to develop said standards. The plan to fix this problem can be broken down into sequential steps. Concurrently within the define phase, the team has been broken into sub-section teams to work on the project and also capture the proper and detailed documentation along the way. One sub-section team is addressing the design of a "micro factory" in order to both print and validate a part within one enclosure. The first step with this process is ordering and assembling the enclosure to be a suitable solution for GD&T verification with environmental concerns addressed. From here, a breadboard will be created in order to integrate the 3D printer and FANUC with probe (validation tool). Future considerations are kept in mind which involves multiple printers and their concurrent configurations. Another sub-section team is working on probe readings and integration, whereas the first step here is to receive data from the Renishaw probe in use to eventually configure a GD&T process. The last sub-section team is working on detailed documentation and process plan to support the define and design process along the way. Ultimately, the team hopes to come up with a clear process plan for the system and touch upon standards within the AM GD&T industry while also improving upon cost efficiency, automation techniques, and efficiency of the overall system. With future improvements, the system could potentially be sold as a standard, sit-alone unit which could print parts under environmentally safe conditions while also validating said part under GD&T defined standards.

Within the analysis phase, the data collected from the measure phase was analyzed in order to identify potential problems within the system itself. Various tools, such as the 3D scanning software, were utilized in order to provide quantifiable data and see were errors occur through the 3D printing experiment conducted in the measure phase. This included revamping the value stream mapping, process analysis, and data analysis for critical errors. In addition to this, the pareto chart of standardized effects was devised along with the process capability report in order to quantify which printer had the most errors along with the analyzation of which printer performed the best under the specified test conditions. Concurrently with these analyses, improvements on design were made within the analysis phase. This included the completion of the breadboard, the FANUC robotics stand, and the Dexter^{TM} arm mating piece which connects to the breadboard. The next phase will be the improve phase, where the root problems of the system are addressed, and solutions are put in place in order to improve the system as a whole.

Overall, the team's progress through the analyze phase has been substantial and will continue to ramp up as the project comes to an end. Future work includes improving upon the problems identified, creation of a pseudo probe to measure GD&T, creation of a mating piece for the SCARA robotic 3D printer to mount to the breadboard, and the creation of a stand for future probes and tools.

2. Project Charter

2.1 Project Overview

2.1.1 Objectives (Customer Requirements)

The requirements expressed by the stakeholders for this project are:

1. Provide a certification process for additively manufactured parts
2. Integrate Six Sigma approach to the project
3. Increase capacity
4. Create a more precise and efficient method
5. Decrease waste and defects

The current process NGC follows for the certification of these parts takes about two to four years. They currently white master cast some parts and also compare the parts to certified molds and tools. This starts by creating a mold or tool and obtaining approval from the Federal Aviation Administration (FAA), then they also require vendor approval. Once the mold or tooling is certified, they can start producing parts and comparing them. This process incurs in additional time and cost as it requires man-hours.

The main objective of this project is to provide a better method for the certification of AM parts. The team will try to achieve this by implementing a micro factory that includes a SCARA (Selective Compliance Assembly Robot Arm) which will 3D print a part, a probe which will read measurement data of the printed part based on a cloud system, a FANUC M-1iA in which the probe will be integrated, and linear motion assembly used to move the part from the SCARA to the FANUC. The following objectives listed after this are steps that need to be taken to ensure the completion of this main purpose. This objective is designed based on all the customer requirements that need to be met.

This project will integrate the Six Sigma approach. It is divided into five different phases of DMADV; which stands for define, measure, analyze, design, and verify. This is an improvement cycle tool used in Six Sigma, which is a "disciplined, statistical-based, data driven approach and continuous improvement methodology for eliminating defects in a product, process or service".[2] The recommendations based on this methodology will be followed in each phase.

First is the define phase, which purpose is to determine the objectives and scope of the project, understand the process, and determine the deliverables required by the stakeholders. Second is the measure phase, in which the issue is quantified. The steps to complete in this phase is to map the process, gather data, validate measurement systems and assess the process performance.[3]

Third is the analyze phase, in which the goal is to evaluate and reduce variation in the project. The current state and potential states are compared to identify and eliminate gaps. Fourth is the design phase, in which choices on how to implement the ideas for the project are drawn. Fifth is the verify phase in which the method will be tested.[3]

In general, implementing this method will benefit the project as it will help the team follow steps that will optimize the process by increasing capacity and decreasing waste and defects.

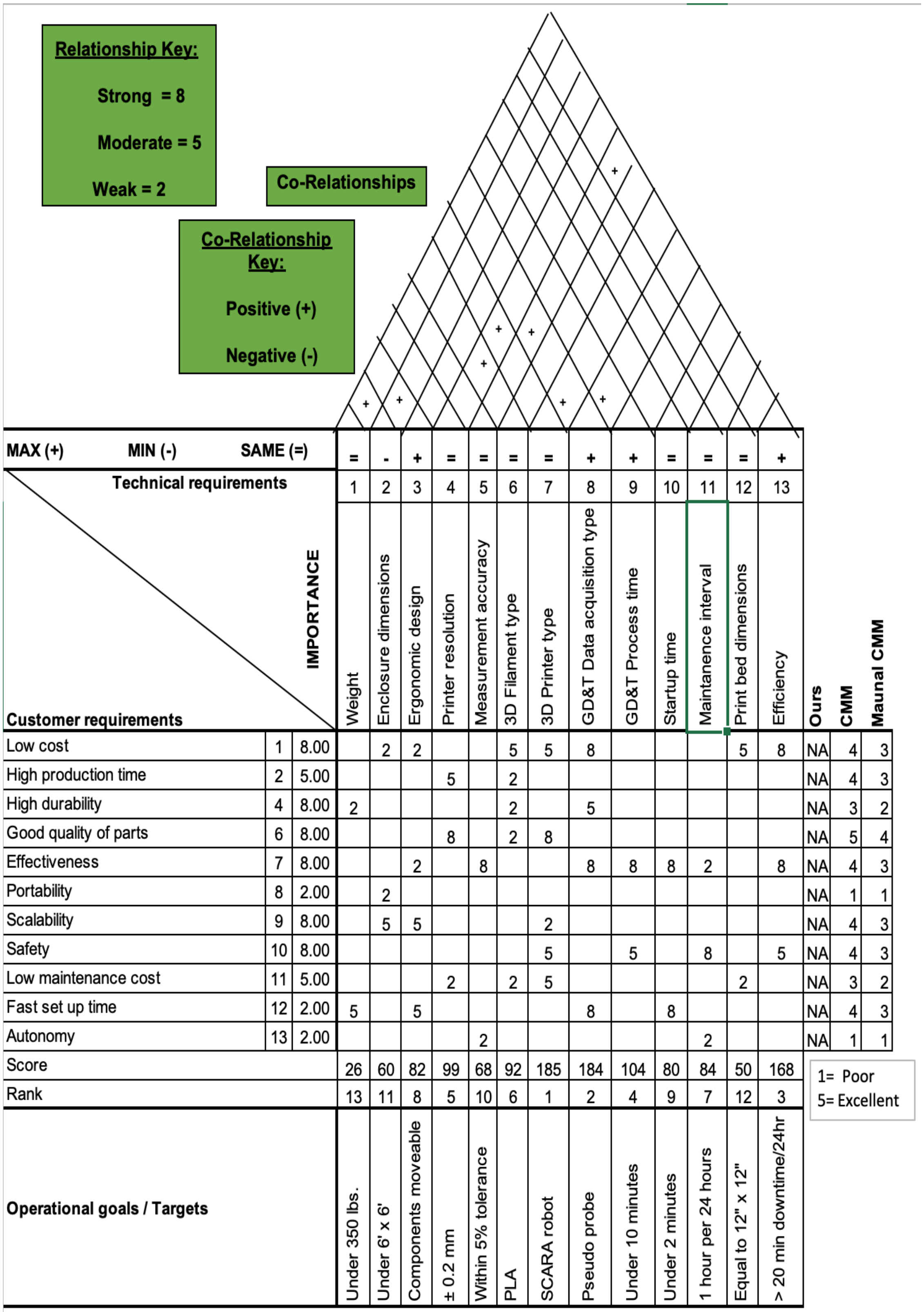
2.1.1.1 Deliverables (Technical requirements)

The deliverables that will be presented to the stakeholders of this project include:

1. Team contract
2. Initial project completion form
6. Fishbone diagram
7. Optimal design of each part that integrate the micro factory and present it in a CAD drawing
8. Bill of materials
9. Initial script of the standard operating procedure for FANUC programming
10. House of quality
11. SWOT matrix
12. Poster
13. Assemble an enclosure for the micro factory
14. Manufacture a breadboard for the micro factory
15. Manufacture a movement system for the micro factory
16. Define phase report
17. Design and implement a micro factory based on customer requirements
18. Test micro factory
19. Measure phase report
20. Analyze phase report
21. Improve phase report
22. Control phase report

To evaluate and take into account all of the customers' requirements and weight them against the technical requirements, the team created a House of Quality (Figure 1). Each customer need was assigned a number based on its importance, with 2 being the lowest and 8 being the highest. Then, technical requirements were added, and they were assigned a number based on each of their co-relationship with the customers' requirements. The roof of this house represents the relationship between each technical requirement. A plus (+) sign placed in the box where two technical requirements intercept indicate positive effect between them, and a minus (-) sign represents a negative effect. This is important to understand how each factor affects another to know how the process can be improved effectively.

Additionally, the score for each of the technical requirements was calculated by multiplying the relationship value (between the technical requirement and customer requirement) to the importance value of each customer need and adding the column. The sum of these values is the score of the technical requirement. These were then ranked from lowest to highest score. The rank shows the technical requirements importance to the project, the most important are the SCARA robot and the pseudo probe. These two have the highest rank since the variability of the parts depend on the printer and the pseudo probe is what measures the part and allows for accurate analyses to be done. Additionally, the goals or targets for each of the technical requirements are shown in the lower part of the house of quality. Also, on the right side of the image, the performance of other methods such as CMM and Manual CMM were rated. As of now, the method cannot be rated as the team is not certain of the performance it will have. However, once it is tested it will be possible to rate and compare the new method against CMM and Manual CMM.



Relationship Key:

Strong = 8

Moderate = 5

Weak = 2

Co-Relationships

Co-Relationship Key:

Positive (+)

Negative (-)

MAX (+) MIN (-) SAME (=)

Technical requirements / Customer requirements		IMPORTANCE	Weight	Enclosure dimensions	Ergonomic design	Printer resolution	Measurement accuracy	3D Filament type	3D Printer type	GD&T Data acquisition type	GD&T Process time	Startup time	Maintanence interval	Print bed dimensions	Efficiency	Ours	CMM	Maunal CMM
MAX (+) MIN (-) SAME (=)			=	-	+	=	=	=	=	+	+	=	=	=	+			
			1	2	3	4	5	6	7	8	9	10	11	12	13			
Low cost	1	8.00		2	2			5	5	8				5	8	NA	4	3
High production time	2	5.00				5		2								NA	4	3
High durability	4	8.00	2					2		5						NA	3	2
Good quality of parts	6	8.00				8		2	8							NA	5	4
Effectiveness	7	8.00			2		8			8	8	8	2		8	NA	4	3
Portability	8	2.00		2												NA	1	1
Scalability	9	8.00		5	5				2							NA	4	3
Safety	10	8.00							5		5		8		5	NA	4	3
Low maintenance cost	11	5.00				2		2	5					2		NA	3	2
Fast set up time	12	2.00	5		5					8		8				NA	4	3
Autonomy	13	2.00					2						2			NA	1	1
Score			26	60	82	99	68	92	185	184	104	80	84	50	168			
Rank			13	11	8	5	10	6	1	2	4	9	7	12	3			
Operational goals / Targets			Under 350 lbs.	Under 6' x 6'	Components moveable	± 0.2 mm	Within 5% tolerance	PLA	SCARA robot	Pseudo probe	Under 10 minutes	Under 2 minutes	1 hour per 24 hours	Equal to 12" x 12"	> 20 min downtime/24hr			

1= Poor
5= Excellent

Figure 1: House of Quality

2.1.2 Expected Benefits and Business Case

Time and money would be saved if this process is correctly developed and implemented. This method would eliminate the need for creating a mold or tooling to evaluate the GD&T of the part. It would also avoid the complications that occur when a mold or tooling wears off, since that also increments the time it takes to certificate a part.

Furthermore, the different risks that may arise in this project are represented through a Threats/Opportunity Matrix (Table 1). It states the short and long term risks. These could be positive risks that are considered opportunities to deliver an optimal project or negative risks which are threats that might threaten the completion of this project. A short term threat that may arise is that the sponsor would need to keep using the current method, instead of testing and implementing a potentially more effective process. The second threat that may occur, if there is little to no improvement of the current process, is that the sponsor would lose the time and money invested in the project. On the other hand, short term opportunities would be that the increased of quality and capacity of parts is immediately present and this would save cost and time.

Additionally, a long term threat would be that NGC could lose potential contracts to other companies as it would be limited to using the current method. On the contrary, long term opportunities would be that the company would be able to implement an innovative process that would potentially increase their contracts and therefore their profit margin.

Table 1: Threat/Opportunity Matrix

	Threat	Opportunity
Short Term	• Sponsor would be limited to current method • Loss of time and money invested in developing a new process	• Increased quality and capacity of parts • Cost and time will be saved
Long Term	• Sponsor could lose potential contracts	• Sponsor could implement standards for additive manufacturing • Increase in profit • Increase in contracts

2.1.3 Project Stakeholders and Team Organization

The Additive Manufacturing and Geometric Tolerance project is sponsored primarily by Dr. Tarik Dickens and Northrop Grumman Corporation. Dr. Dickens is an industrial and manufacturing engineer. He has previous research on additive manufacturing and one of his current research interests is integrative additive manufacturing. For this reason, the team will benefit by having Dr. Dickens as a sponsor and advisor for this project and vice versa. Furthermore, the second advisor for this project is NGC which is a leading global security company that provides products to mainly government but also commercial customers. Currently, NGC only uses additive manufacturing for prototyping parts. However, as this innovative field expands NGC could benefit by creating additively manufactured parts for their products and having set standards for this process. The team will also benefit by the information that NGC can provide them about how processes are conducted in the industry.

Additional stakeholders of this project include Professor Beth Gray (senior design professor), Lucas Braga Carani (teaching assistant), Ryan Adams (teaching assistant), and Sean Psulkowski (graduate advisor). Team members, their roles, and their skills are:

Kelan Green – Project Manager and Quality Engineer

Kelan is the define and verify phase team leader. He will work towards ensuring the desired quality is achieved in this project and that the project is developed successfully. His major and skills are:

- Industrial and Manufacturing Engineering major
- Six-Sigma Green Belt
- MatLab, MiniTab, Tecnomatix, C++, SQL
- Leadership/communication

Leonardo Tellez – Process Engineer & Webmaster

Leonardo performs as the measure phase team leader. He will work towards optimizing the method that is being developed. He will also assist with the webpage of the project and will be responsible for keeping it updated. His major and skills are:

- Industrial and Manufacturing Engineering major
- Leadership, teamwork
- MatLab, SolidWorks, C++
- Project management

Carlie Cunningham – Quality Engineer

Carlie serves as the analyze phase team leader. She will work towards ensuring the desired quality is achieved in this project. Her major and skills are:

- Industrial and Manufacturing Engineering major
- MatLab, SolidWorks, MiniTab, Tecnomatix
- Supply chain logistics experience

Samantha Bell – Process Engineer

Samantha is the design phase team leader. She will work towards optimizing the method that is being developed. Her major and skills are:

- Industrial and Manufacturing Engineering major
- MatLab, SolidWorks, MiniTab
- Six-Sigma Green Belt

Dillon Mathena – Mechanical Design Engineer

Dillon will work towards designing, developing and testing the micro factory. His major and skills are:

- Mechanical Engineering major
- MatLab, SolidWorks, Creo Parametric
- Finite Element Analysis (FEA)
- Computer Numerical Control (CNC) Machining, Design Engineering experience

Matthew Emerick – Systems Engineer

Matthew will work towards designing, developing and testing the micro factory. His major and skills are:

- Mechanical Engineering major
- 3D printing experience
- Machine design
- Project management

2.2 Approach

2.2.1 Scope

The scope of this project is to develop a GD&T process for additively manufactured parts. This will be achieved by designing and integrating a micro factory which will contain a FANUC, a SCARA, and a linear motion assembly. Additionally, a probe will be implemented in this project. The scope will be updated as necessary as the project progresses. For example, some parts of the scope had to be adjusted. When the micro factory was designed at first the team planned on purchasing a linear motion assembly; however, to reduce cost the team decided to design and manufacture the linear motion assembly. Similarly, the team and advisors decided not to integrate the Renishaw probe that was provided since it needs a machine controller that costs $3000.00. The group will instead purchase a mechanical gripper that will be integrated with the FANUC along with building a pseudo-probe that will mimic the Renishaw. This will allow the group to still implement a probe in this project which will be used to measure the dimensions of the 3D printed parts in order to compare this to a scanning method that has been used to measure samples in the second phase of the project. The main goal of the project still remains the same, even though the work needed to achieve the goal has been updated as stated previously.

All decisions of changes in the work need to be approved and discussed with the advisors, which include Dr. Dickens and Mr. Psulkowski. These will be discussed during an assigned meeting that should be set via Basecamp (a project management app the team and stakeholders use to communicate). Northrop Grumman do not need to be notified of changes in the work as it is a silent sponsor and is only interested in the final product, which is the process the team will try to develop.

On the other hand, there are some aspects not required by the customer but that may develop as work is done on the project. These would be considered out of scope. One of those aspects would be to test if the process performs as well if it is scaled. For industry this is very important since the method needs to perform the same way at a higher scale in order for them to be able to implement it. However, this is not a required aspect as this method is not expected to be used in industry as of now.

Additionally, this project is not expected to be fully autonomous. It is only expected to be semi-autonomous as it will need to be set up by a person. These aspects would surpass the customers' expectations for the project. Nevertheless, achieving out of scope aspects would benefit the team and the sponsors.

2.2.2 Assumptions & Constraints

An assumption that must be made in order to be able to test if the project is scalable, is that the process the team is creating could be implemented in industry. This also entails that it must be assumed that the probe will also work for larger size and more complex AM parts. If not it must be assumed that a different tool will be used in industry. It must also be assumed that workers will be trained to set up the machines for this process.

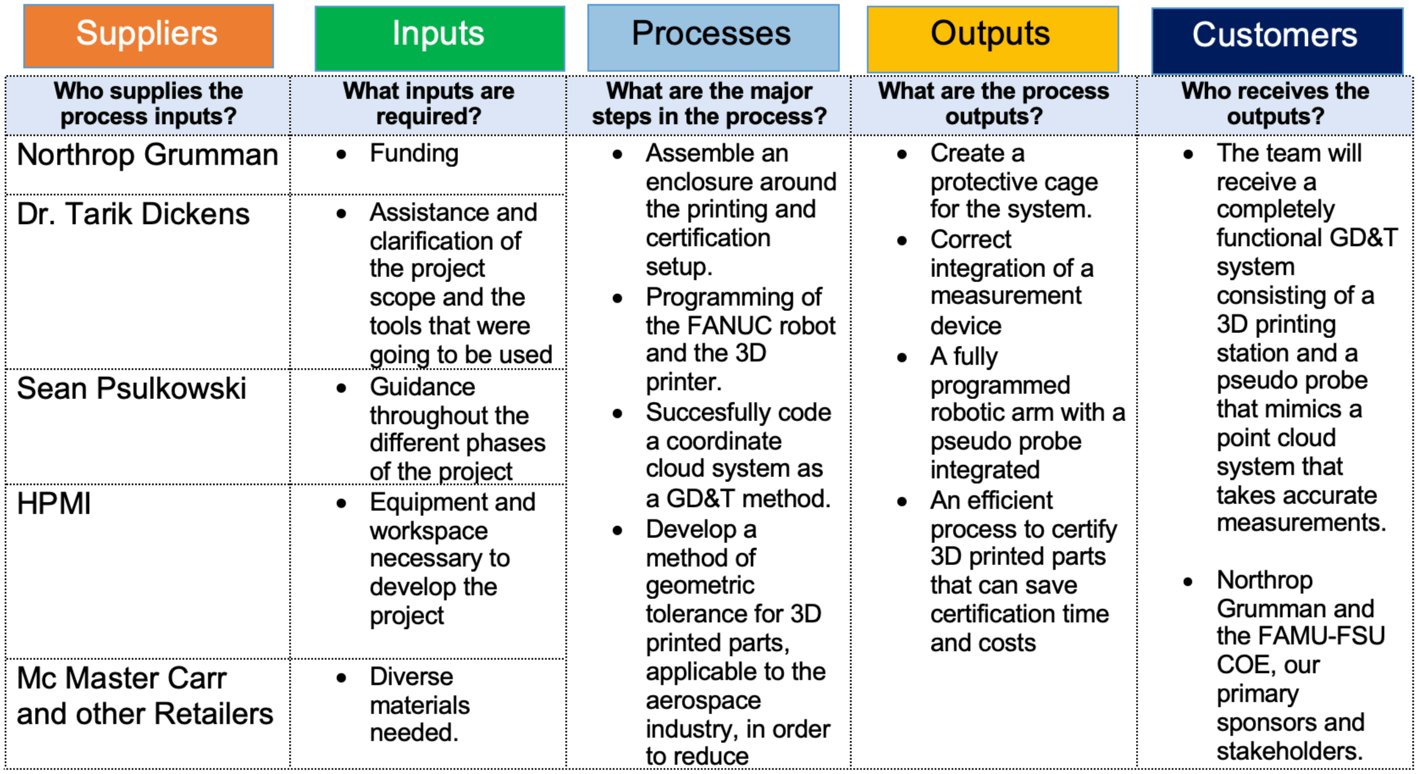
Some constraints the team faces are the timeline and available funding. The project is limited to eight (8) months approximately. Therefore, the team's priority is to focus on achieving the customers' requirements. After this, if time permits it, other aspects of the project can be developed. Another constraint would be available funding. The micro factory's structure and all of its components could be optimized by buying all of them from a vendor. However, due to budget restrictions, the team has to fabricate some of the parts required in this micro factory.

An additional constraint is that the size of the part that will be printed and measured is limited to a 1 feet x 1 feet print bed and confined to the size of the structure that has been proposed for the enclosure. In order to assess the customers' requirements it will be assumed that the process will work at a larger scale. After customers' requirements have been met, if possible, the team will test if the project is scalable.

2.2.3 Project Process

Table 2 shows the SIPOC diagram for the project, which consists of five sections. Suppliers are the institutions or people that provide help to team, either with funding, assistance, tools, or resources in general. The help given by the suppliers, in any of its forms, constitutes their input. The processes column, represents the steps needed to achieve all of the outputs, these outputs are the goals that the team need to meet in order to deliver them to their customers, which is the last column of the chart, and represents all the people or institutions that will benefit from the outputs achieved.

Table 2: SIPOC Diagram



Suppliers	Inputs	Processes	Outputs	Customers
Who supplies the process inputs?	**What inputs are required?**	**What are the major steps in the process?**	**What are the process outputs?**	**Who receives the outputs?**
Northrop Grumman	- Funding	- Assemble an enclosure around the printing and certification setup. - Programming of the FANUC robot and the 3D printer. - Succesfully code a coordinate cloud system as a GD&T method. - Develop a method of geometric tolerance for 3D printed parts, applicable to the aerospace industry, in order to reduce	- Create a protective cage for the system. - Correct integration of a measurement device - A fully programmed robotic arm with a pseudo probe integrated - An efficient process to certify 3D printed parts that can save certification time and costs	- The team will receive a completely functional GD&T system consisting of a 3D printing station and a pseudo probe that mimics a point cloud system that takes accurate measurements. - Northrop Grumman and the FAMU-FSU COE, our primary sponsors and stakeholders.
Dr. Tarik Dickens	- Assistance and clarification of the project scope and the tools that were going to be used			
Sean Psulkowski	- Guidance throughout the different phases of the project			
HPMI	- Equipment and workspace necessary to develop the project			
Mc Master Carr and other Retailers	- Diverse materials needed.			

3. Defining the Current Process

As mentioned previously, there are several resources needed for this process to function successfully. The components involved in the micro factory include the enclosure, the FANUC

M-1iA and stand, the SCARA 3D printer and the linear motion assembly. In addition to these, other materials/resources include the filament for the 3D printer, the software needed to design the product and the slicing software.

The way that the team knows the process is working is by comparing the physical printed part with the theoretical CAD design and/or the G-Code for the system which displays each layer as XYZ coordinates. The process of comparing either of the two validation methods is through the use of a point cloud created by the Renishaw probe. One way to approach this, is to assess each layer of the part is being printed and probed, the measurements can be recorded and can be compared to the original design to ensure the part is being printed properly. Another, more feasible method, would be to approach the process like traditional CMM machines, where the part is first printed and finished, and then moved to the final GD&T validation area. This will likely be the approach for the team. This theoretical 3D print/probing process is outlined in Figure 2.

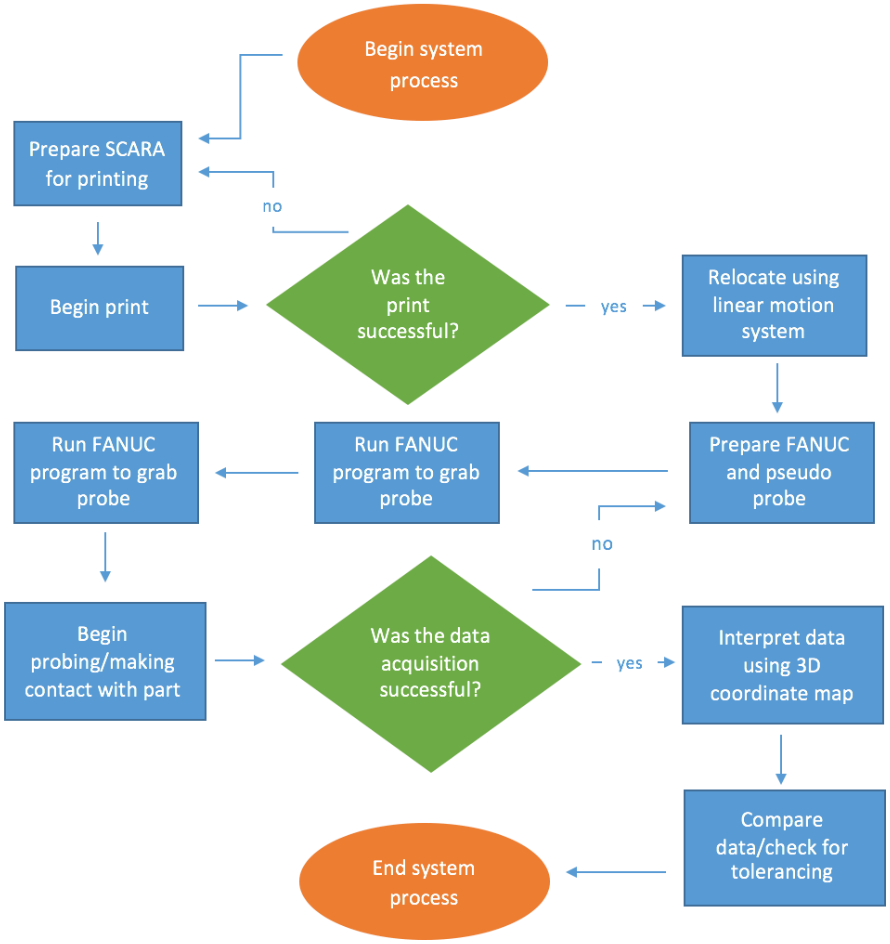


Figure 2: Process Flow Chart

The response variable that the group is measuring is the placement of the PLA filament and determining whether or not it has been placed correctly. The main issue that is being faced is that the product is being printed incorrectly and thus, failing GD&T certification and wasting valuable time and money. Using the measurements collected from the data acquisition process, the team can compare these to the theoretical model and attribute any discrepancies to the issues noted in the fishbone diagram. The various causes that could attribute to the product being printed incorrectly are outlined in Figure 3.

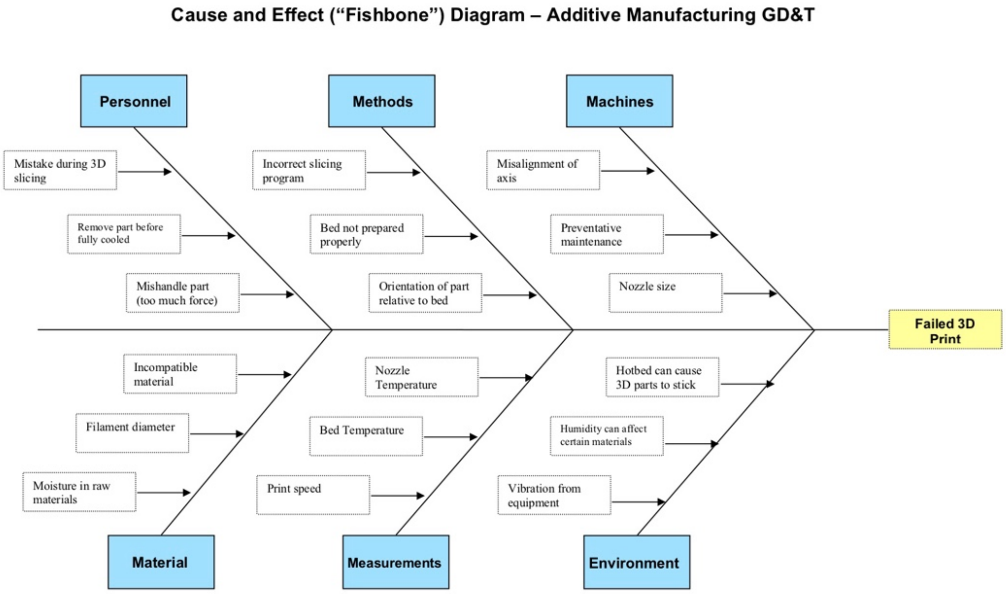


Figure 3: Fishbone Diagram

Figure 4 shows the work-breakdown for the define phase developed by the team. The Team decided to divide all tasks into four main categories: project initialization, evidence manual, concept generation and selection, and the final deliverables for the define phase. The initialization phase basically included meeting with the advisors, brainstorming and setting the project´s scope, and developing a team contract in which appointment times, group policies, and roles were defined. The evidence manual included most of the deliverables that were required throughout the phase, such as the project hazard assessment, fish bone diagram, and project schedule. The concept generation and selection consisted of defining what parts, tools and approach the team will use to develop a solution. The last category included the report, presentation, and poster of the project required at the end of the phase.

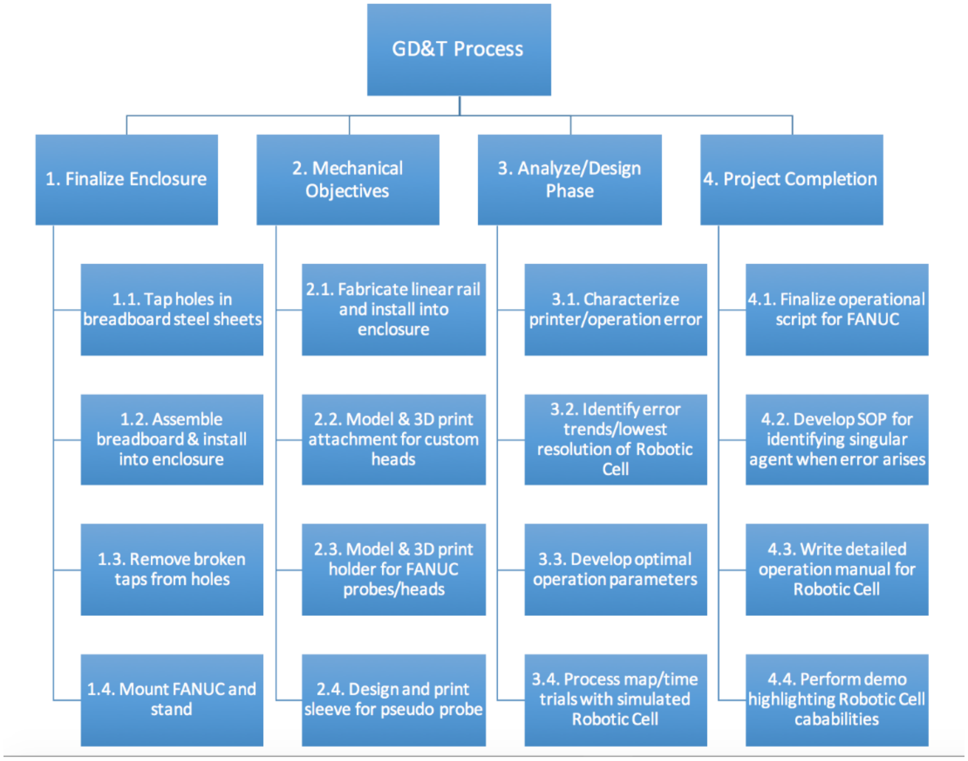


Figure 4: Deliverable Based Work-Breakdown Structure

4. Measuring the Baseline Performance

For the measure phase of this project, the team decided to design an experiment in order to measure quality of printing among different printers. The main purpose for this experiment was to eventually compare the results with the team's micro factory setup and show how the team's solution will provide improved benefits for customers compared to the traditional GD&T methods. This brought a big challenge which was to quantify the measurement of quality of printing in order to analyze results. The experiment designed consisted in printing two-cylinder batches in three different models of 3D printers and measure the differences in diameters using a 3D scanner provided by Dr. Dickens.

The three printers used were the LulzBot TAZ 6, the Ender Pro 3, and the Dexter^{TM} robotic arm at HPMI. The first cylinder had a height of 0.5 inches and the second cylinder had a height of 1 inch. They were printed along the centered y axis, with a separation of 100 mm between each other, as shown in Figure 5. Both cylinders had a diameter of 0.5 inches.

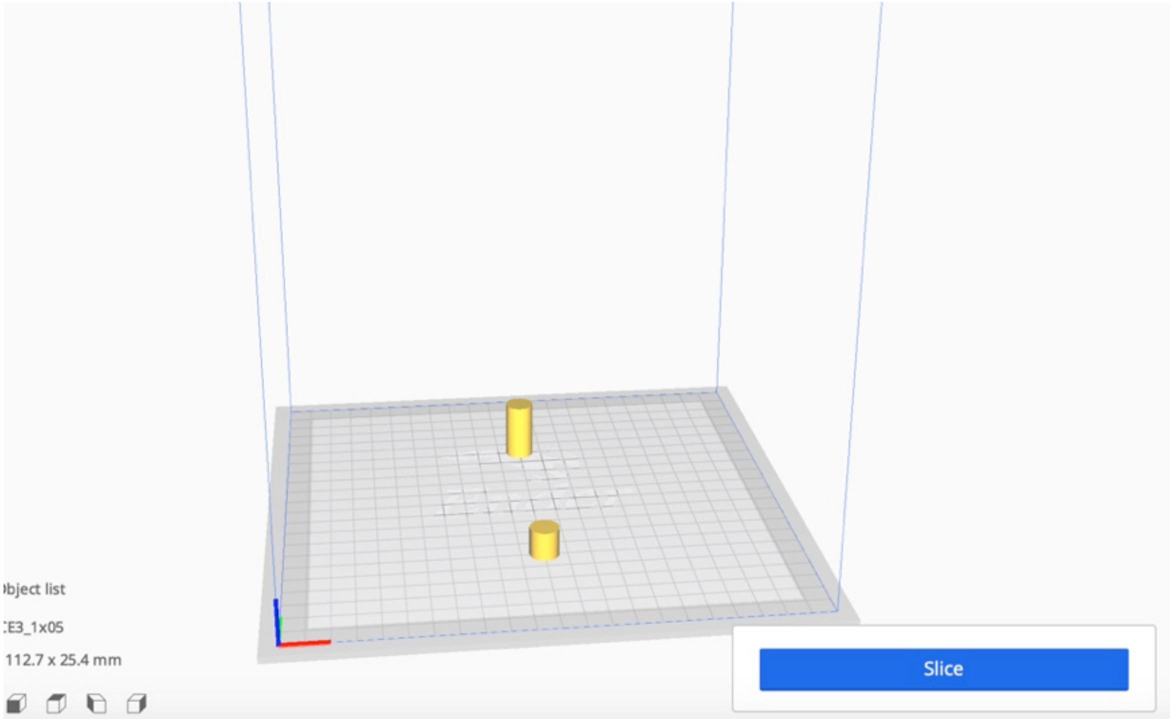
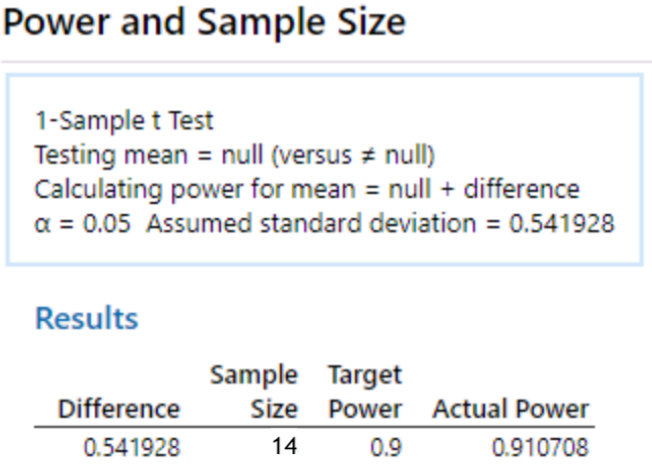


Figure 5: Cylinders Prepped for Slicing

In order to determine how many batches should be printed (sample size), an initial run was performed, and initial measurements were taken in order to obtain the deviance and standard deviation to be used as a baseline to determine the sample size that will yield an appropriate confidence level. The collected preliminary data was analyzed using the MiniTab software and a sample size of 42 was obtained, as shown by Figure 6. This confirmed the initial inference, since the experiment was a 3x2x7 design (3 printers, 2 sizes, 7 batches).



Power and Sample Size

1-Sample t Test
Testing mean = null (versus ≠ null)
Calculating power for mean = null + difference
α = 0.05 Assumed standard deviation = 0.541928

Results

Difference	Sample Size	Target Power	Actual Power
0.541928	14	0.9	0.910708

Figure 6: MiniTab 1-Sample t-Test

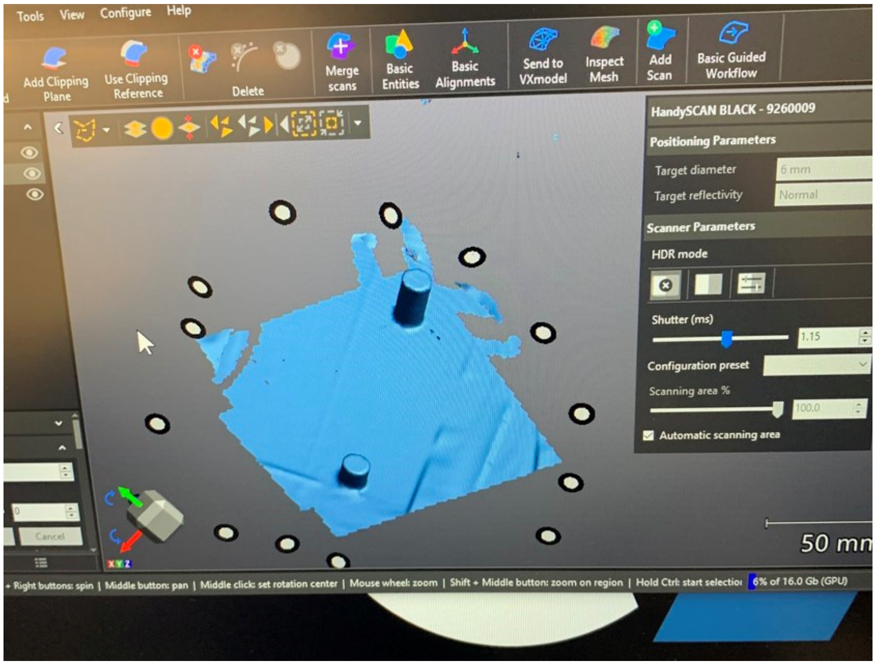
Before the printing began, the team developed a test plan to make sure the same conditions were met between the three printers, and that each member tested for the correct conditions.

First, the CAD files were converted to STL files by using SolidWorks, to make sure there were no conversion errors. When printing, each team member checked if the printing bed had an inclination level and balanced it if necessary. The material used for printing all the samples was PLA, and the team make sure that nozzle and printing bed temperatures were the same for each batch. Finally, the STL was sliced using the CURA software for each printer, inputting the same layer height, infill percentage and printing speed for each printer.

The printing with the LulzBot was very fast and easy since the machine is very user friendly, and thanks to the CURA software specially designed for this model of printing, setting it up was straightforward. There were also no notable printing errors or failures with this printer.

The Ender printer had a similar CURA software, therefore initial settings were also straightforward. However, in the first few trials the nozzle was not releasing any material at all. The team tried restarting the machine, re slicing the CAD file, and changing the PLA spool without any success. After reading the manufacturer´s suggestions, the source of the problem turned out to be that the printing bed had some level of inclination, instead of being perfectly aligned, causing the printing to fail. Once the printing bed was aligned, the team resumed printing with this machine. Most batches were successfully printed with the exception of two 1-inch cylinders that for some reason, the printer skipped some layer in the middle of the structure, causing them to be very fragile and eventually broken. The factors that could have caused this error will be analyzed in further depth in the next phase.

Printing with the Dexter^{TM} arm was definitely the biggest challenge for the team. Since this robotic arm was built completely at HPMI, it is still in experimental phase, having some eventual problems and breakdowns. Because of this, Mr. Psulkowski suggested to just print 4 batches, and change the previous experimental model to a 3x2x4 model, and then finish printing the missing batched for the Dexter^{TM} printer in the next phase, since he will be working during the holidays break to fix the issues with the Dexter arm. When the printing part of the experiment was concluded, measurements were taken using the Creaform 3D scanner and the VXelements software included, as shown in Figure 7. To compare the printed parts with the theoretical model, the VXelements software had to be used, however the license for this software was expired so the measurements were taken using calipers and will be taken again using the software in the next semester when the license issues are solved.



HandySCAN BLACK - 9260009

Positioning Parameters

Target diameter 6 mm

Target reflectivity Normal

Scanner Parameters

Shutter (ms) 1.15

Configuration preset

Scanning area % 100.0

☑ Automatic scanning area

+ Right buttons: spin | Middle button: pan | Middle click: set rotation center | Mouse wheel: zoom | Shift + Middle button: zoom on region | Hold Ctrl: start selectio 6% of 16.0 Gb (GPU)

Figure 7: Final 3D Scan Result

A Design of Experiment analysis (DOE) was performed in order to see which factors played a more significant role in printing issues. The pareto chart of effects is shown in Figure 8. As it can be observed in the chart, the main effects causing deviation from theoretical values are the printer itself, followed by the interaction of the three factors analyzed which were, printers, height, and batch. This data will be furthered analyzed in the analyze phase.

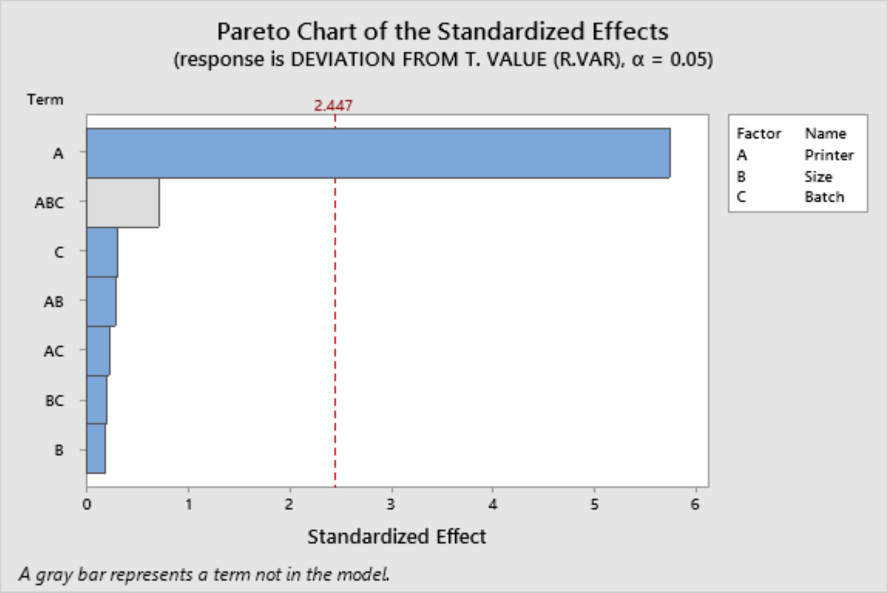
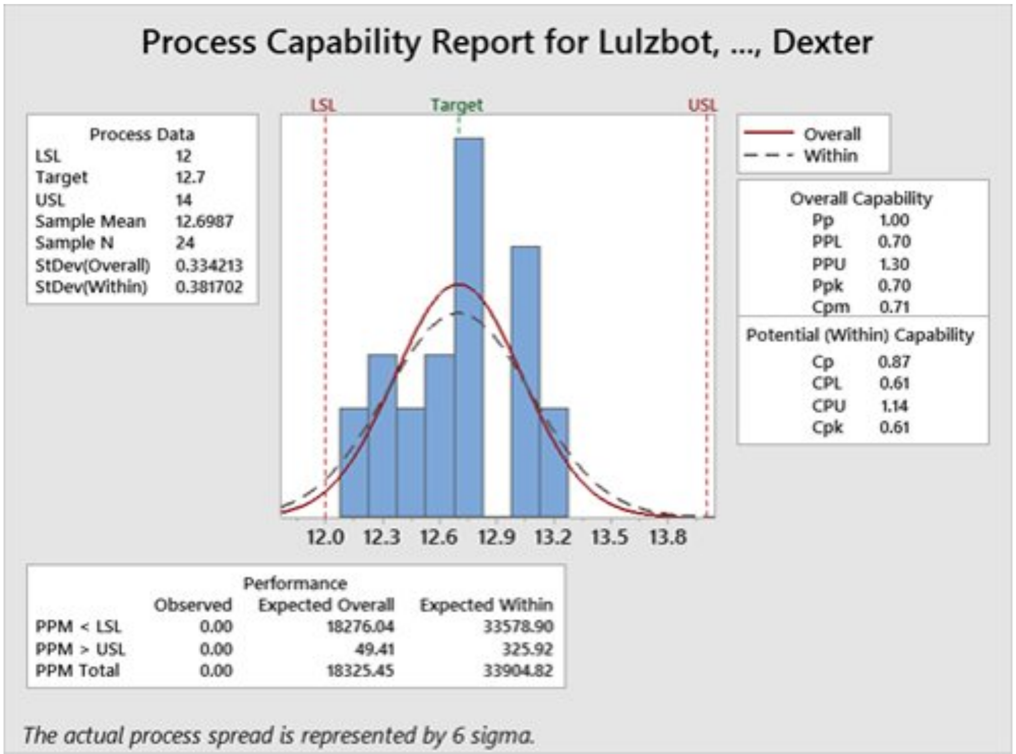


Figure 8: Pareto Chart of Standardized Effects

Additionally, the performance of each printer was analyzed through a Process Capability Report by using Minitab, shown in Figure 9. This showed that the process is normally distributed. The Within and Overall curves are closely aligned, meaning that there is some variability, but the process is not out of control. The peak of the distribution curve is somewhat centered with the target value, however some values exceed the target. The potential capability (Cpk) value is 0.61, this means that the team needs to improve the process by reducing the variation or shifting its location. Cp (process capability) and Cpk do not have the same value, therefore the process is not centered. This conclusion can also be drawn by comparing Ppk and Pp. Ppk is the overall capability of the process, its value is higher but still needs to be to be improved as well.



Process Data	
LSL	12
Target	12.7
USL	14
Sample Mean	12.6987
Sample N	24
StDev(Overall)	0.334213
StDev(Within)	0.381702

Overall Capability	
Pp	1.00
PPL	0.70
PPU	1.30
Ppk	0.70
Cpm	0.71

Potential (Within) Capability	
Cp	0.87
CPL	0.61
CPU	1.14
Cpk	0.61

Performance

	Observed	Expected Overall	Expected Within
PPM < LSL	0.00	18276.04	33578.90
PPM > USL	0.00	49.41	325.92
PPM Total	0.00	18325.45	33904.82

The actual process spread is represented by 6 sigma.

Figure 9: Process Capability Analysis

Moving into the evolution of the design, the team developed various working ranges with respect to the FANUC. One of which was the working area of the FANUC in terms of the printing plate’s height. The working area has an elliptical, bowl shape as pictured in Figure 10.

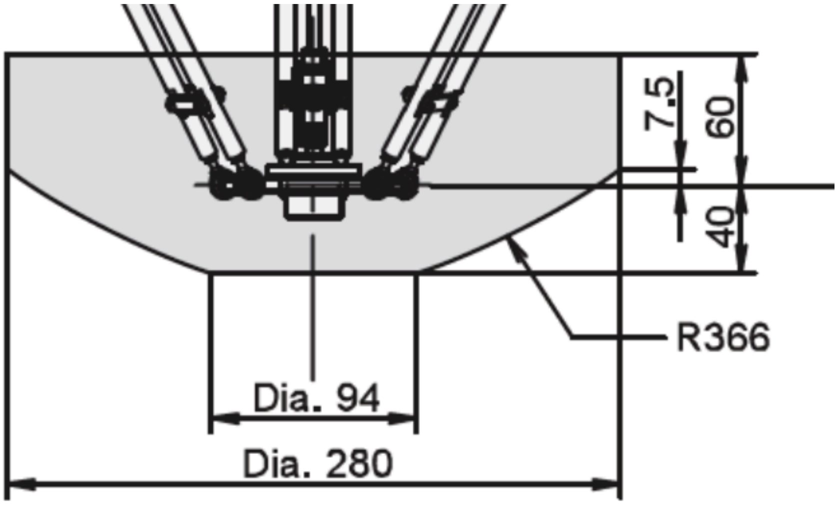


Figure 10: Technical Drawing of FANUC Working Area

The printing plate height can be viewed as that flat portion on the bottom of the shaded area. As the printing plate moves up, the working width and height changes. The equation of this parabolic portion was calculated and then the working range, in respect to printer height and part dimensions, was found. Figure 11 and Figure 12 display graphs of this working range. Figure 11 expresses the range as a ratio of working height to working width. Figure 12 displays the working height and width plotted over the printer plate height as two separate lines. From these two graphs, the team is able to determine working height and width at any given printer plate height.

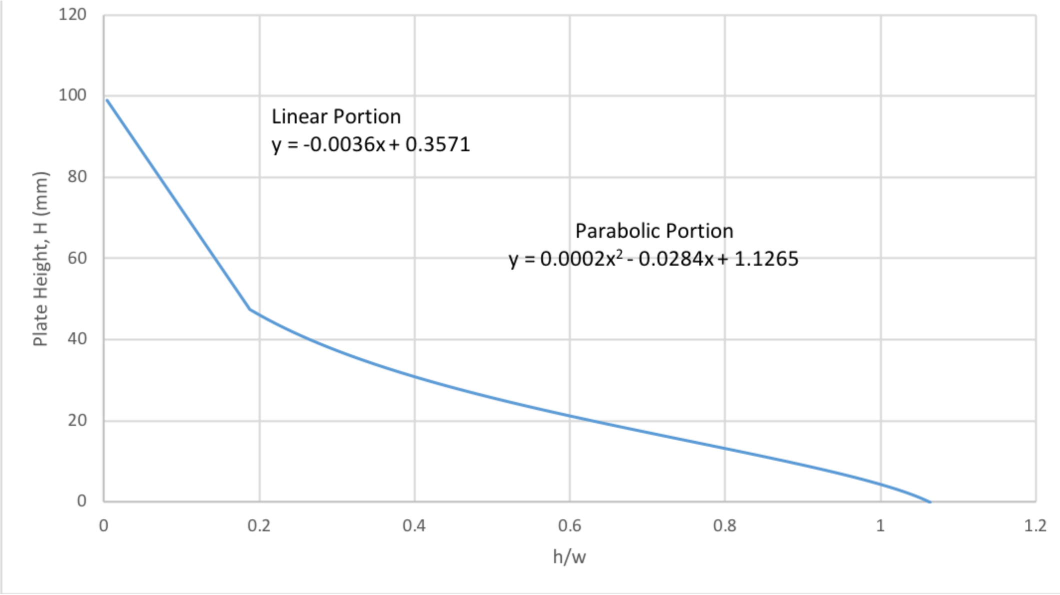


Figure 11: FANUC Working Height – Working Width Ratio versus Plate Height

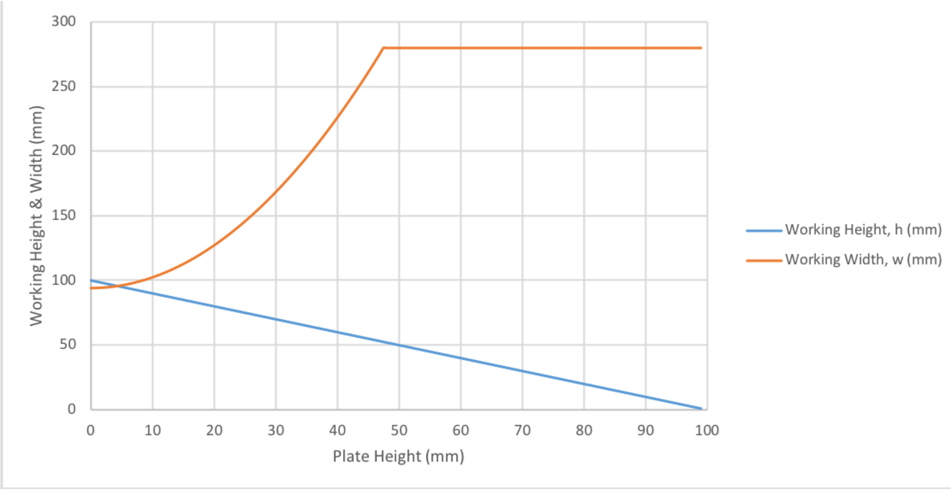


Figure 12: Working Height and Width as Independent Lines versus Plate Height

Through the concept generation portion of the project, in addition to the design evolution, several concepts were generated and brought into higher fidelity stages through 3D CAD development using SolidWorks. Each design was chosen through initial ideation, customer requirements, and sponsor coordination, in which eventually lead the team to finalize a design with the approval of the team's sponsor and silent sponsor. In choosing a design, several factors were taken into account, which vary from cost and material strength, to ease of manufacturing and production along with working area optimization of the FANUC robot, SCARA robot and 2x Dexter^{TM} 3D printers.

To preface the designs and concepts, one of the most important customer requirements was maneuverability and ability to move components within the designated work area. The designated work area in this case, is the enclosure which includes acrylic windows to allow for safe operation and viewing of the system process. To be able to move components, each design features a breadboard layout which is used to adjust the various robots and subsystems within the enclosure. From this, various mating pieces for the FANUC robot, SCARA robot, Dexter^{TM} 3D printers and the 3D printing hotbed were created which allow for a universal mate for each component wherever on the breadboard, which is comprised of two steel sheets with a hole pattern which is roughly (2.21" x 2.21" distance apart from hole to hole). 4130 steel firstly was chosen, which eventually was switched to A36 steel for the breadboard, over other metal alloys such as Aluminum, because of its higher tensile strength versus Aluminum 6061. The concern here was that the shear force introduced by the weight and operation of the components could cause bending upon the plate. However, to mitigate against this, steel was chosen as the material of preference. The breadboard will also feature supports running along the edges and underneath in order to mitigate against potential deflection.

The material and fastener selection for the breadboard and mating pieces was verified through a Finite Element Analysis (FEA) study under static loading conditions. The loading for this study used a 37.5lb (17kg) remote mass placed at the centroid of the FANUC robot. A remote load was chosen instead of the complete robot assembly and mounting piece to simplify the computational complexity of the study. This loading was chosen on the basis that the FANUC Robot would be the heaviest component mounted to the breadboard. Parameters for this study included non-penetrating surfaces with the remote load evenly distributed over the top surface of the FANUC mounting piece, the breadboard was fixed on all sides, and two- ¼-20 hex bolts were used to secure the load to the breadboard. A visual depiction of the remote load and resulting displacements can be seen in Figure 13.

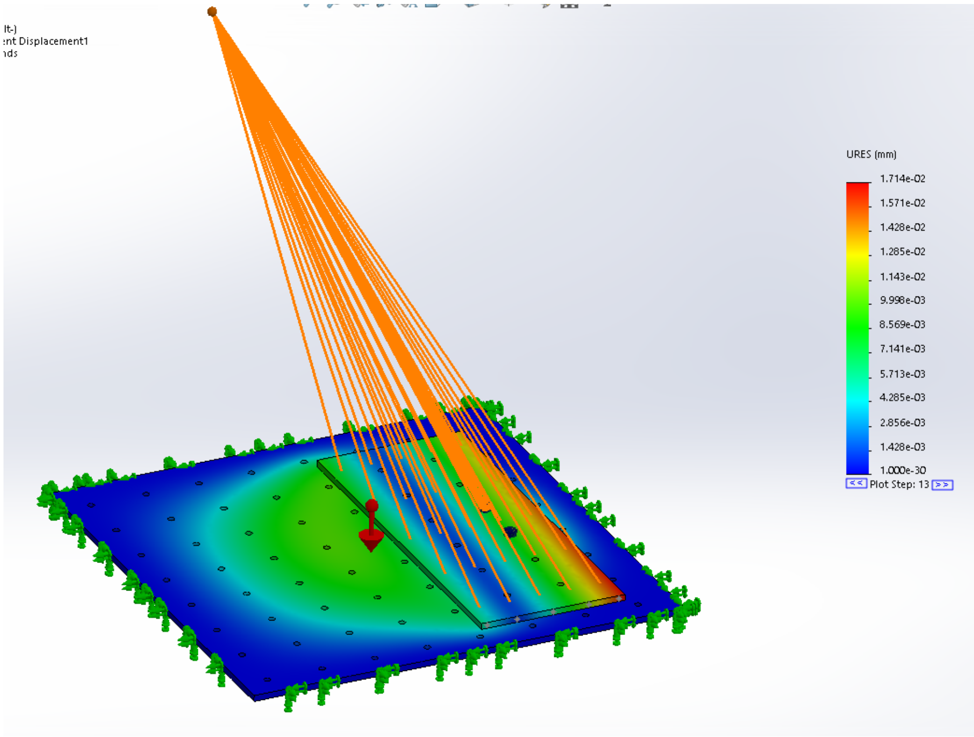


Figure 13: Displacement Results from Fastener Study

The combined load across a single fastener was determined to be 5,587 psi, well below the yield strength of the alloy steel which is 60,200 psi. This will provide a factor of safety of 10.75 which is more than sufficient for the application of this system. The deflection of the steel breadboard was found to be no more than 0.0003" (0.0085 mm). This deflection will introduce a minor variance in the measurement of the parts given that the FANUC robot can only position the measurement tool within 0.0008" (0.02 mm). A full breakdown of the fastener loading can be seen in Table 3.

Table 3: Fastener Loading from FEA Study

Type	Resultant	Connector
Shear Force (lbf)	0.32961	Hex Screw-1
Axial Force (lbf)	137.68	Hex Screw-1
Bending moment (lbf.in)	0.58778	Hex Screw-1
Torque (lbf.in)	0	Hex Screw-1
Stress (psi)	2809.8	Hex Screw-1
Shear Force (lbf)	0.33199	Hex Screw-2
Axial Force (lbf)	136.06	Hex Screw-2
Bending moment (lbf.in)	0.52808	Hex Screw-2
Torque (lbf.in)	0	Hex Screw-2
Stress (psi)	2776.7	Hex Screw-2

Moving forward, the original design of the system included the enclosure, robots, and linear motion system with a Renishaw probe mated to the FANUC robot to allow for GD&T data collection. However, due to systems engineering constraints and a lack of equipment, the design and team ultimately had to head in a newer direction which will feature a probe made by the team. In the decision process, the Renishaw controller for the Renishaw probe was not provided to the team, which meant the team had to devise a way to integrate the probe without the controller, which introduces inherent error between communications, or design a new probe for the system. The controller is roughly $3,000, which is outside of the team's budget of $2,000. Although this Renishaw probe was a part of the early design proposal, ultimately due to budget constraints and communication errors, the team is opting to design a probe for roughly $50 which will integrate with an Arduino microcontroller provided by HPMI. This also allows for better signal communication between subsystems. For example, without the Renishaw controller the probe will send out unreadable signals to the computer. Whereas with an Arduino based probe, the signals will transmit out as readable byte data which can be read based off XYZ coordinates and then compared to FANUC robotic arm location.

With the preface discussed, design 1, Figure 10, features the FANUC with its designed stand (made from 4130 steel) and with the SCARA 3D printer adjacent to the FANUC. Between them is a 3D printer hotbed, which is connected to a mating piece which attaches to the breadboard. All of these components are featured within the enclosure.

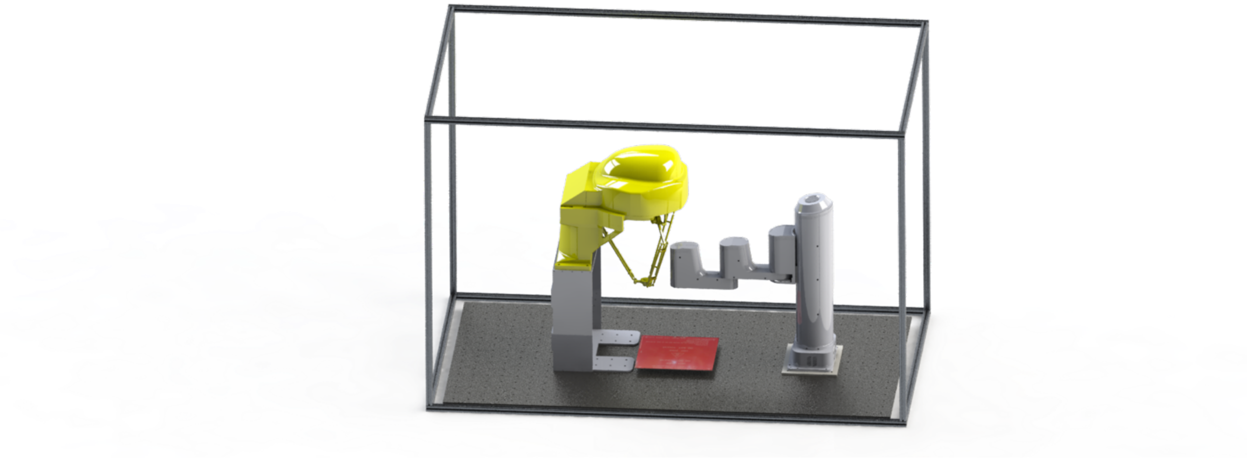


Figure 14: Concept 1 Featuring a FANUC Robot and a SCARA 3D Printer Configuration

The logic behind concept 1, Figure 14, was to be as minimal as possible, while still accomplishing the customer requirements at the same time. This is why the robots share a working area with the hotbed and do not utilize additional robots like in other concepts. A key advantage here lies with the minimalistic approach, which will require less maintenance whereas the key disadvantages here is that the system is not fully optimized, and there are problems with the working area between the robots. With the addition of a linear motion system and added robots, the theoretical process time for 3D printing parts and GD&T can be improved. However, the largest disadvantage of concept 1 lies with the working area between the robots. This leads into Figure 15.

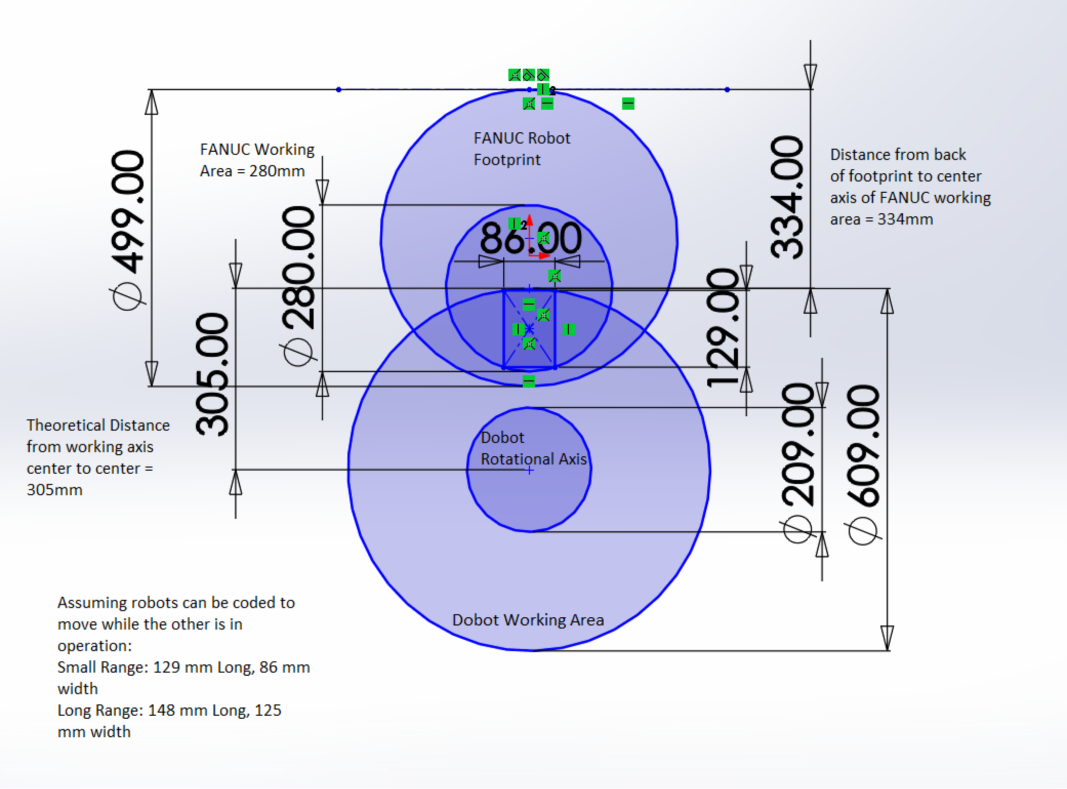


Figure 15: FANUC Robot Working Area vs. SCARA 3D Printer Working Area

Based off calculations shown in Figure 15, the working area can be considered roughly 6" length by 6" width for the FANUC robot and SCARA 3D printer configuration (shown as the rectangle between the robots), which is under the customer requirements of at least 12" length by 12" width working area or also 3D printing area. These calculations were conducted through analysis of the technical manuals for both the SCARA 3D printer and FANUC robot, in which dimensions were pulled and calculated from both. This leads to the conclusion that the 3D printing area should be 12" length by 12" width to be able to accomplish the customer requirement and improve overall working area. To accomplish this, a linear motion system can be implemented to allow for better optimization of working areas (by allowing for additional spacing between robots) and also allow for further calculations to verify optimization. This system, along with the addition of two Dexter^{TM} 3D printers is show in Figure 16.

Figure 16: FANUC Robot Working Area vs. SCARA 3D Printer Working area

Represented in Figure 16, concept 2 features the use of a FANUC robot with probe integration, two Dexter^{TM} 3D printers, a SCARA 3D printer and a linear motion system. The purpose of this configuration was to optimize shared working area between robots, while also covering the customer requirement of the robots being able to be modular while also allowing for multiple robots to be included. Theoretically, the implementation of several 3D printers allows for faster efficiency. While one robot prints, the other can be heating up or preparing for 3D printing. After the part is done printing, the linear motion system will carry the freshly printed part to under the FANUC robot where GD&T acquisition will occur. This system can then be reset once the user has identified if the part is within tolerance, and then remove the part, where the plate can return to one of the prepared 3D printers. With this configuration, the user increases efficiency by reducing downtime on a 3D printer between prints. While one printer is in operation, the other two can be prepared which ultimately increases manufacturing time of 3D printed parts. With concept 2 in consideration, concept 3 (shown in Figure 17) was created to improve upon the design layout of the robots featured in Figure 16. This was done in order to improve working area optimization and satisfy further customer requirements.

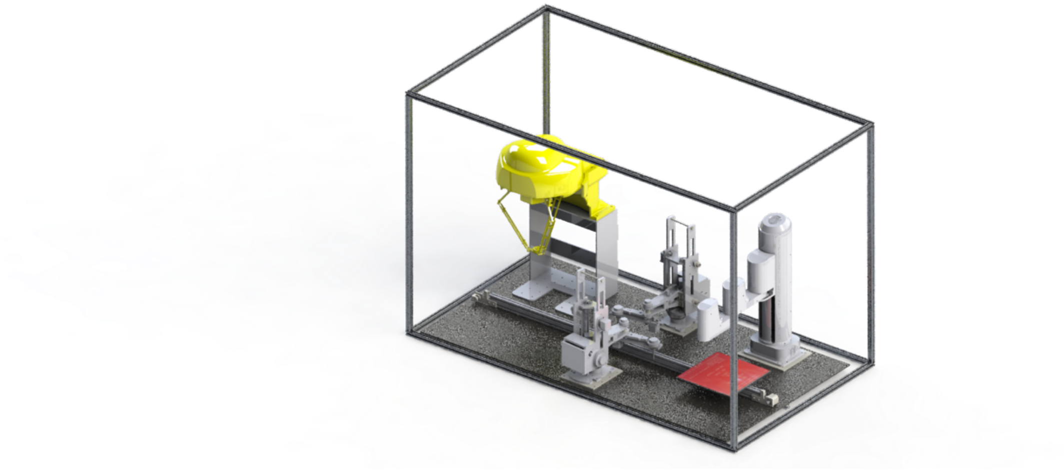


Figure 17: Concept 3 (Final Concept) Featuring Linear Motion, SCARA Robot, 2x Dexter^{TM} Arm and FANUC Robot

Concept 3, Figure 17, was chosen to be the final concept, based on varying improvements over concepts 1 and 2. Ultimately, concept 3 improves upon concept 1 by including three possible 3D printers. This increases reliability of the system as a whole, due to the notion that if one robot were to become dysfunctional, then two robots are available to maintain the system process. When all three 3D printers are operational, then the system can improve manufacturing capabilities of 3D printed parts due to lower downtime between 3D prints. A 3D printer extruder nozzle typically requires a period of roughly 1-2 minutes to reach proper extruding temperature, so therefore with several 3D printers in operation this time can be theoretically cut-out if one printer heats while the other is in operation and then cooldown phase. Another improvement lies with the utilization of the linear motion system pictured above which is not pictured in concept 1. With the addition of a linear motion system, the robots can be placed to optimize working area between them. This is shown with Figure 18, where the working area is pictured for the FANUC robot, 2x Dexter^{TM} arm and SCARA 3D printer.

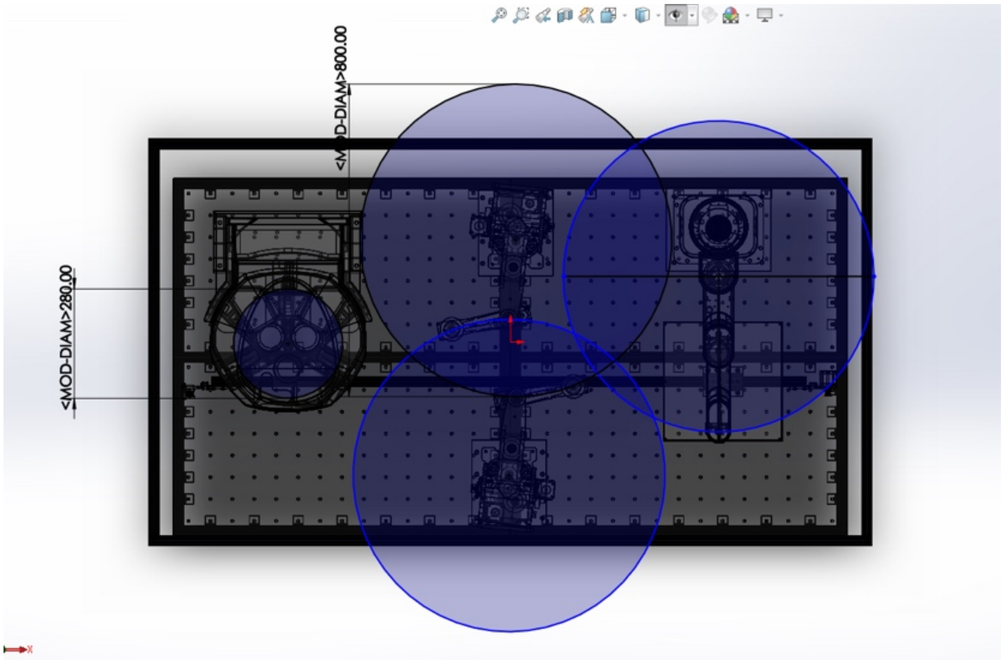


Figure 18: Working Area Optimization of FANUC, 2x Dexter^{TM} Arm, and SCARA Robot

Shown in Figure 18, a brief mechanical analysis was conducted in order to visualize the working area of each robot. With this configuration, there is improved working area as each robot is free to operate without conflicting with another robot. Shown on the right-side of Figure 18, the SCARA can operate on the hotbed without knocking into either of the Dexter^{TM} arms pictured in the middle, where the Dexter^{TM} arms are free to operate without confliction either. This is where the main improvement from concept 2 to concept 3 derives, as with concept 2 the robots are more likely to collide with one another, whereas concept 3 improves upon this by better spacing out the robots based on calculated working area.

With the general operation of the system explained above, the evolution of design can be seen with the differences between early concepts, such as concept 1, and later concepts, such concept 3. Many of the design discussions were done in cooperation with the sponsor and silent sponsor (Dr. Dickens), which is why concept 3 was ultimately chosen as the final concept. To outline the requirements, the sponsors wanted a modular system with the ability to add additional components all in order to accomplish GD&T of a 3D printed part. This can all be accomplished through concept 3, as the breadboard allows for modularity and additional components to be placed, with the FANUC and probe allowing for GD&T acquisition. Purchase orders have been placed for each respective subsystem (FANUC stand, linear motion system, breadboard, enclosure and robotic fittings), and specific materials were chosen based upon the mechanical analyses (including FEA study). Predominately, for the metal alloy within the system, steel was often times chosen over aluminum due to mechanical property improvements such as tensile strength. This includes the material selection of acrylic over glass (for the enclosure walls), which can prove to be more reliable and safer for operation as acrylic is less likely to shatter in an explosive manner. Additionally, per use of SolidWorks, 3D models, universal fittings and coordination from manufacturers, the team was able to accurately ensure all parts fit together mechanically and can integrate together electrically. Ultimately, concept 3 was chosen as the final concept due to varying improvements over other concepts which was reinforced with mechanical analyses and 3D modeling.

Moving forward into the analysis phase, the evolution of the design continued to progress forward with concept 3, Figure 17, in mind. With the acquisition of materials complete, the team was able to use the waterjet at the high-performance material's lab, to properly use the A36 steel plates as a breadboard. A picture of this can be seen with Figure 19.

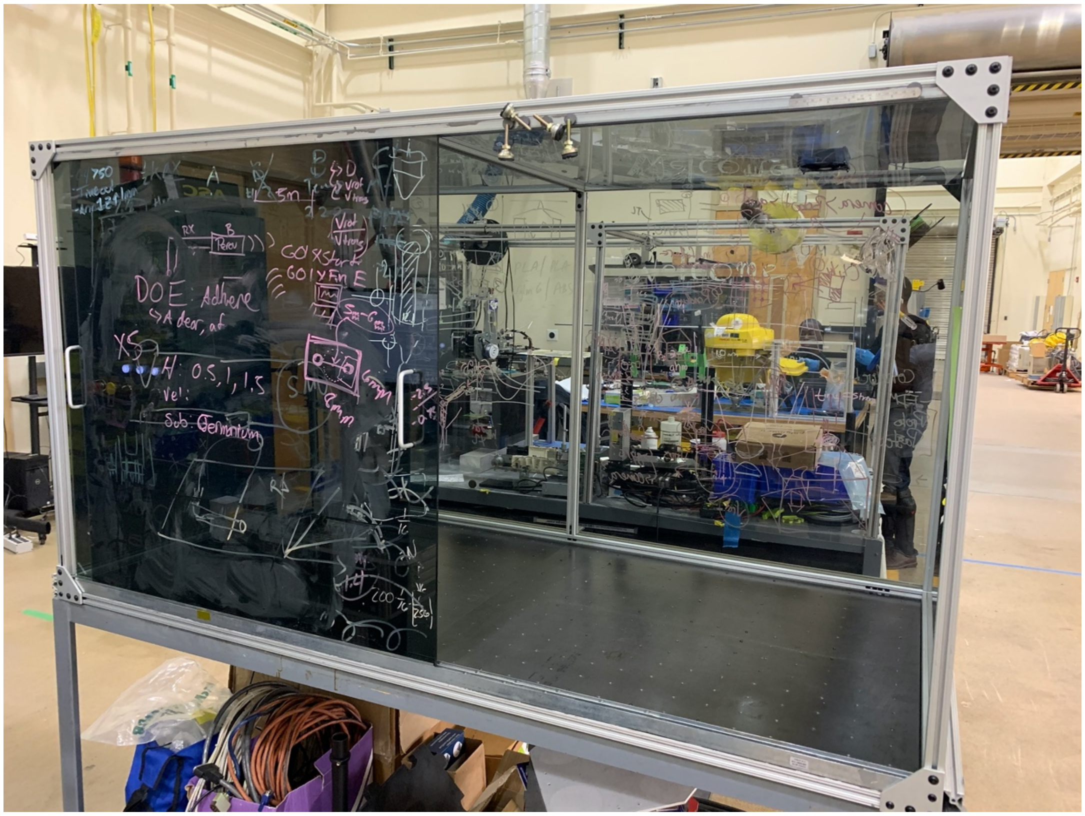


Figure 19: Enclosure Featuring the Breadboard on the Lower Portion

From Figure 19, the user can denote that the drilled and tapped holes are evenly spaced around the breadboard. This was done in order to properly move equipment around the enclosure in any configuration. With the breadboard properly installed into the enclosure, one of the big tasks was the manufacturing of the FANUC robotics stand. This stand was designed in SolidWorks, and later sent to the FAMU-FSU college of engineering machine shop in order to have the order fulfilled with the required parts given to the machine shop. This can be seen with Figure 20, after the stand was successfully manufactured.

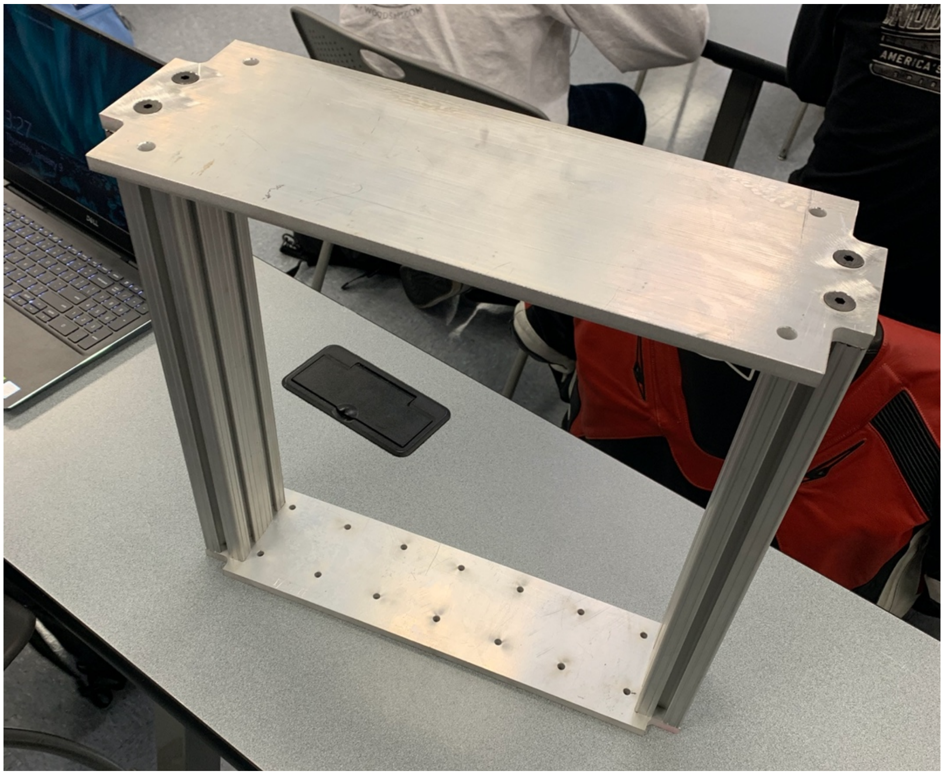


Figure 20: FANUC Robotics Stand After Manufacturing

Within the next phase, the team will install the FANUC robotics stand, Figure 20, into the enclosure pictured in Figure 19. From previous working area calculations done in the measure phase, the ideal height from the robot was calculated to stand at 16.5 inches above the ground, which is where the top part of the plate stands. This allows for full range of motion with the FANUC robot, in the XYZ directions, in order to accomplish the required GD&T readings, as the FANUC robot will be holding the probe which reads the data and then compares with the theoretical 3D CAD model. The hole pattern on the base of the FANUC stand allows for the FANUC to be moved anywhere within the enclosure pictured in figure 14, and will mimic concept 3, Figure 17, within the next phase. Concurrently with the progress of the breadboard and FANUC stand, the team was able to design a 3D printed mating piece for the Dexter^{TM} robotic 3D printer, in order to be able to mount the 3D printer within the enclosure. This 3D printed mating piece can be seen in Figure 21.

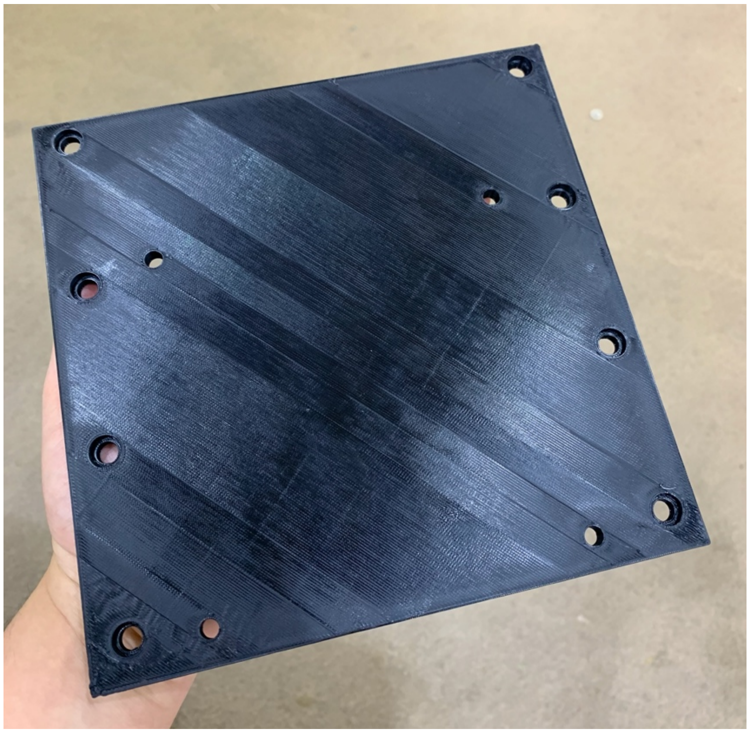


Figure 21: 3D Printed Dexter$^{\text{TM}}$ Robot Mating Piece

From Figure 21, the hole patterns for both the Dexter$^{\text{TM}}$ robot and breadboard can be seen. The holes located towards the interior of the 3D printed piece are for the Dexter$^{\text{TM}}$ arm, while the holes located towards the exterior of the part are for the connection to the breadboard. This will allow for the Dexter 3D printer to be utilized within the enclosure seen in Figure 19. These hole patterns were pulled from measurements based upon the respective robot and the breadboard hole pattern. Moving into future phases, this piece, along with the FANUC stand, will be integrated within the enclosure with their respective robots. In terms of parts that still need to be designed, a pseudo probe will need to be 3D printed and manufactured, a mating piece for the SCARA robotic 3D printer will need to be designed and 3D printed, and a stand for future probes and tools will need to be designed and manufactured in order to hold equipment for the FANUC robotic arm to pick and place.

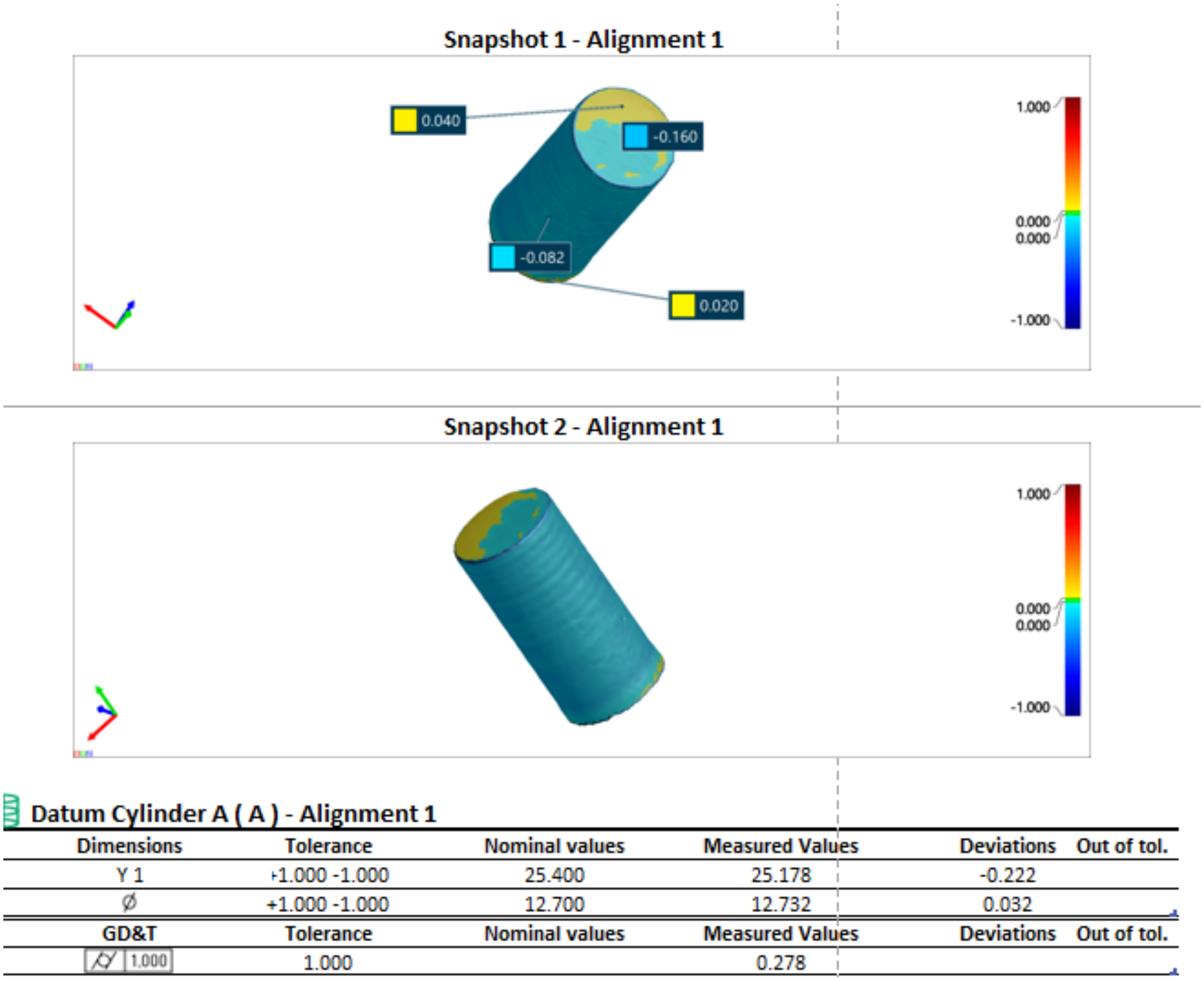
5. Identifying the Root Causes

During the measure phase, the team collected baseline performance data and actually began initial analysis of the cylinders. As discussed in Section 4, a process capability analysis and DOE were completed during the measure phase. This led to a pareto chart that identified the printers as having the most effect on the deviation from the theoretical CAD models. This conclusion was broad, so the team investigated further to identify the root causes behind printer variability. Issues with the scanning software during the measure phase were resolved, so the team was able to use VXelements to analyze the cylinders. There is a program within the software, VXinspect, that overlays a CAD model and a 3D scan, provides a color map of deviation, and allows for various automatic measurements. After the desired results are gathered, the software automatically generates an inspection report. The following steps were taken in order complete each inspection:

1. Since both cylinders were scanned at the same time, each cylinder was isolated and saved as new file from the original scan.
2. The scans were "cleaned up' by improving their resolution and removing isolated patches of unwanted objects the scanner captured.
3. The scans were sent to the VXinspect program, where a CAD model of the respective cylinder was imported.
4. A best-fit alignment was created.
    a. The scan and CAD model were moved into the same orientation with the top of the cylinder facing the screen.
    b. Three similar points on the scan and CAD model were selected.
    c. The software then performed iterations until the best-fit alignment was complete.
5. Once the alignment had been created, the color map and cylinder measurements are automatically created with reference to the CAD model.

It's important to note the orientation used in the best-fit alignment process. The software required the team to isolate the cylinders as their own scan file. In doing so, the bottom surface of the cylinder had to be removed. The top-view orientation was the only orientation in which the software was able to perform the best-fit alignment iterations. Therefore, the top surface was used as the reference, when in reality, the bottom would typically be aligned. The software provides measurements based on the alignment reference so any other reference could provide alternate results.

Figure 22 shows an example of a finalized inspection report of the cylinders. The first two images in the figure display the color map of deviation with respect to the CAD model. All values displayed are in millimeters. The colors indicate the magnitude of the deviation as well as whether the scan is over (red) or under (blue) the CAD model. The table at the bottom of the figure displays the various measurements the team gathered for each cylinder. The tolerances in the table are simply placeholders needed to collect the measurements and are not discussed in the report. The team is currently focused on the variability, and not whether the cylinders meet a certain tolerance. The team collected the height and average diameter of the scan compared to the nominal value, the CAD model. Also, a cylindricity measurement was taken. Cylindricity is essentially a combination of straightness and circularity. The units are in millimeters as well, but represents how much the cylinder deviates from the perfect CAD model. While circularity would focus use individual cross sections of the cylinder, cylindricity takes the entire cylinder into account and provides information on the overall straightness and roundness. A perfect cylinder would have a value of 0.0, meaning every point on the surface of the cylinder are the same radial distance away from the center axis. For example, the cylinder shown has a cylindricity of 0.278. Theoretically, if the team were to make a shaft for this cylinder to fit into then the shaft's diameter would need to be approximately 0.556 millimeters larger than the cylinder's.



Datum Cylinder A (A) - Alignment 1

Dimensions	Tolerance	Nominal values	Measured Values	Deviations	Out of tol.
Y 1	+1.000 -1.000	25.400	25.178	-0.222	
Ø	+1.000 -1.000	12.700	12.732	0.032	
GD&T	**Tolerance**	**Nominal values**	**Measured Values**	**Deviations**	**Out of tol.**
⌭ 1.000	1.000		0.278		

Figure 22: Finalized Inspection Report for One Cylinder

The team finished all inspections and compiled the data into one table, located in Appendix B. This table provides the diameter and height deviations along with the cylindricity values. To understand the nomenclature, the letter corresponds to the first letter of the printer's name. The first number, one or two, corresponds to the short or tall cylinders respectively. The final number corresponds to the batch number. From there, the team verified that the software inspection deviated from the manual inspection in the measure phase. This deviation is shown in Appendix C. Only the diameters could be compared since those were the only measurements taken in the measure phase. The team then moved on to analyzing the new data collected from the software inspections. First, the overall performances of the printers were quantified in Table 4. The printers' overall averages along with their respective cylinder averages (short and tall) were calculated. From this table, the Ender appears to be the most accurate and precise printer amongst the three. All of the Ender height deviations are the largest, however, there were issues with the printing bed during the first print. E11 and E21 have a height deviation of over one millimeter which caused the Ender averages to spike.

Table 4: VXinspect Average Measurements

Printer/Cylinder	Average Diameter MAD (mm)	Average Height Absolute Deviation (mm)	Cylindricity (mm)
LulzBot Short	0.645	0.441	0.392
LulzBot Tall	0.755	0.314	0.626
LulzBot Average	0.700	0.378	0.509
Ender Short	0.110	0.476	0.298
Ender Tall	0.114	0.519	0.352
Ender Average	0.112	0.498	0.325
Dexter Short	0.832	0.174	1.268
Dexter Tall	0.677	0.305	1.150
Dexter Average	0.754	0.240	1.209

Following the strictly quantitative analysis, the team used the software-generated color maps in attempt to identify the root causes for each printer's variability. In the following subsections, each printer will be discussed.

5.1 LulzBot TAZ

Figure 23 shows the color maps of the first two LulzBot prints, L11 and L21. Overall, the LulzBot performed poorly in terms of diameter precision and cylindricity, however, the color maps show some mild consistency across the prints. The LulzBot cylinders were slightly under the ideal diameter and height, and there were significant deviations around the top and bottom surfaces. The team had no issues with the printing bed and saw no delamination occur in all of the prints.

Due to consistency of the LulzBot cylinders, despite having the second most overall variation, the team has identified the environment to be the root cause of variation. These printers are located in A208 in the FAMU-FSU College of Engineering. This is a research room that sees heavy foot traffic and frequent use. The printers are on shelves with other printers. This combination results in vibrations from equipment in the room, individuals walking by, and potentially increased humidity depending on the number of individuals in the room. These plethora of environmental factors have been deduced as the cause of the variation.

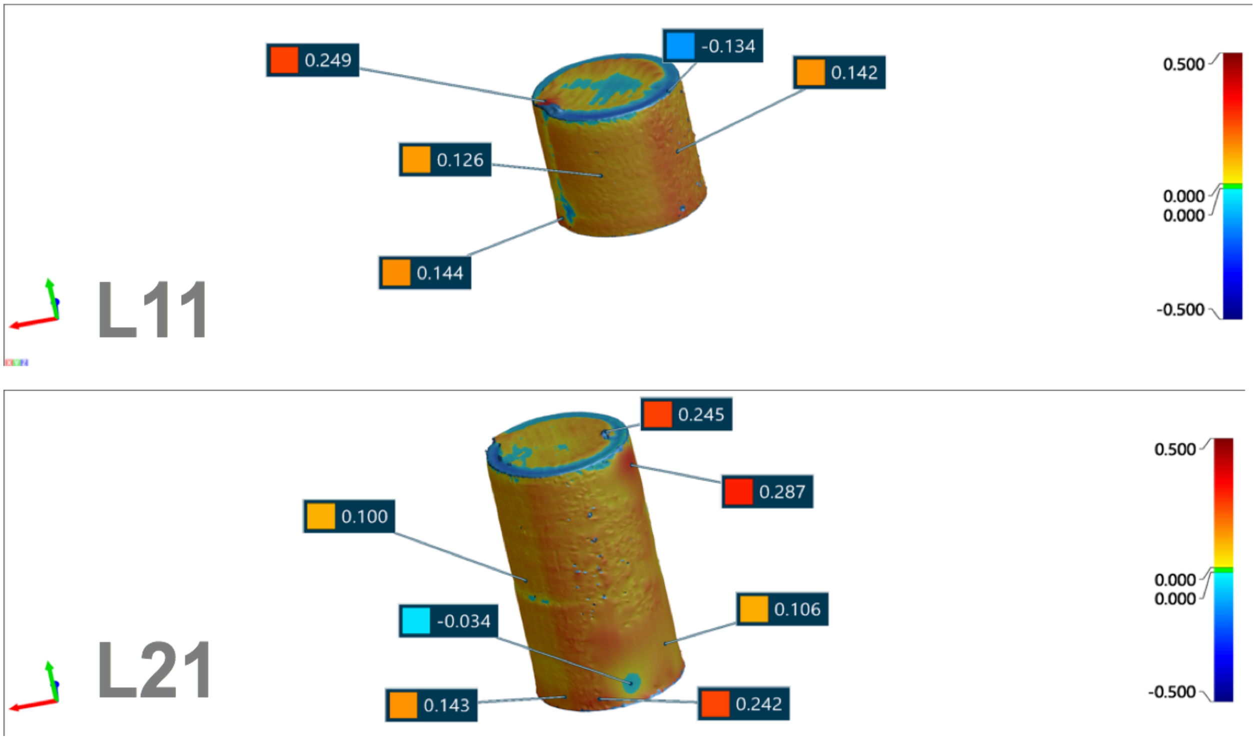


Figure 23: L11 and L21 Color Maps

5.2 Ender

The Ender, as mentioned previously, outperformed the other printers based on the quantitative analysis. However, there were visible delamination issues amongst the batches. Delamination in three different cylinders, two from the same print and one from another, are show in Figure 24. After inspecting the various cylinders with delamination present, it was determined that the delamination begins to occur at approximately 0.5 inches. Initially, the team struggled to level the printing bed in the first print, which could be attributed to the delamination present in E11 and E21. However, delamination still occurred after the bed was leveled properly for the proceeding prints.

Figure 24: Ender Delamination

Color maps of the Ender prints were then inspected, such as E15 and E25 shown in Figure 25 and Figure 26, respectively. There is clearly much less deviation across the entire cylinders as compared to L11 and L21 in section 5.2. The only exceptions are the dark blue notations on the E25 color map , where the was significant delamination.

E15 was the team's most precise print out of all batches amongst all printers. The most significant deviations are shown on its map, which are minimal. This cylinder had a cylindricity of 0.18, almost perfect, and a diameter deviation of only 0.031 millimeters.

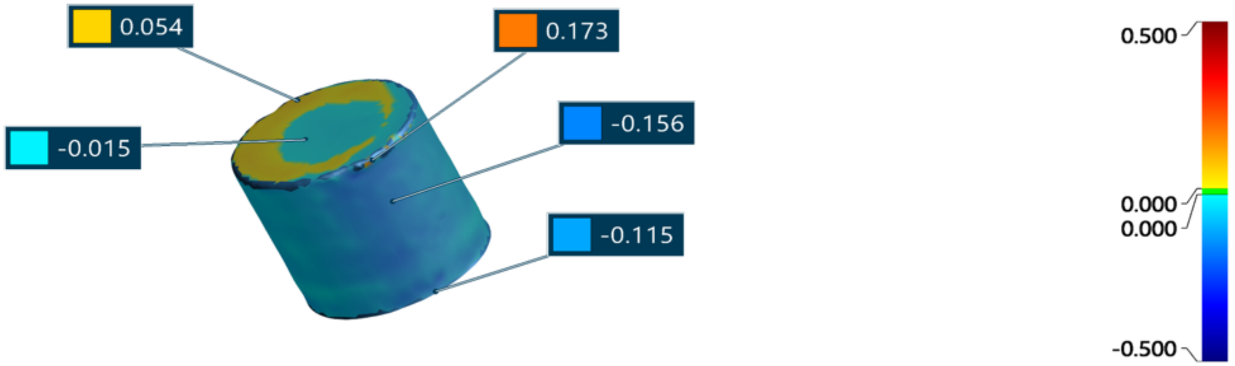


Figure 25: E15 Color Map

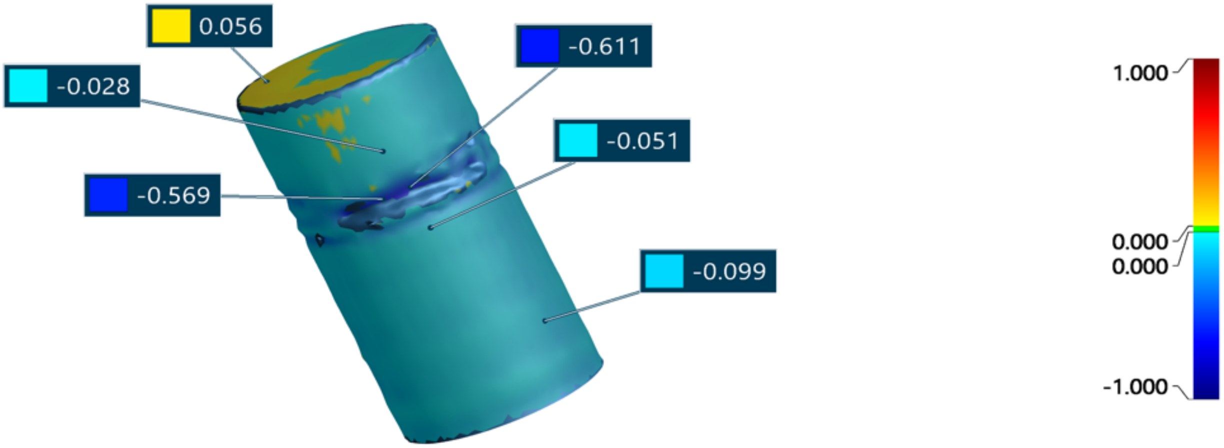


Figure 26: E25 Color Map

After considering the printing bed issue and noticing the level bed not making an impact on the delamination, the team concluded that yes, a level bed did impact the precision of the Ender. However, fixing this issue did not solve the delamination problem. Therefore the team concluded that an unleveled print bed along with environmental factors, similar to those affecting the LulzBot prints, are the root causes for Ender variability.

5.3 Dexter™ Arm

The Dexter™ Arm gave the team the most issues of all the printers. The results showed the Dexter™ last in performance compared to the Ender and LulzBot with significant variability in terms of cylindricity and diameter. Average cylindricity of the Dexter™ prints was 1.209, which is incredibly large. Figure 27 visibly shows the skewness in a Dexter™ batch, which is clear indicator of an imperfect cylinder. The same batch is shown in the color maps in Figure 28. The variability is extremely evident in these color maps, as the cylinder rapidly deviates from dark reds to dark blues at various points.

Variability in these prints was simply due to the Dexter™ print bed. The print bed was unable to be properly leveled as one of the corners could not be screwed down. This resulted in a constantly shifting print bed. Even though the team could not visibly see the bed moving during printing, it clearly was shifting as the cylinders have a curvature to them.

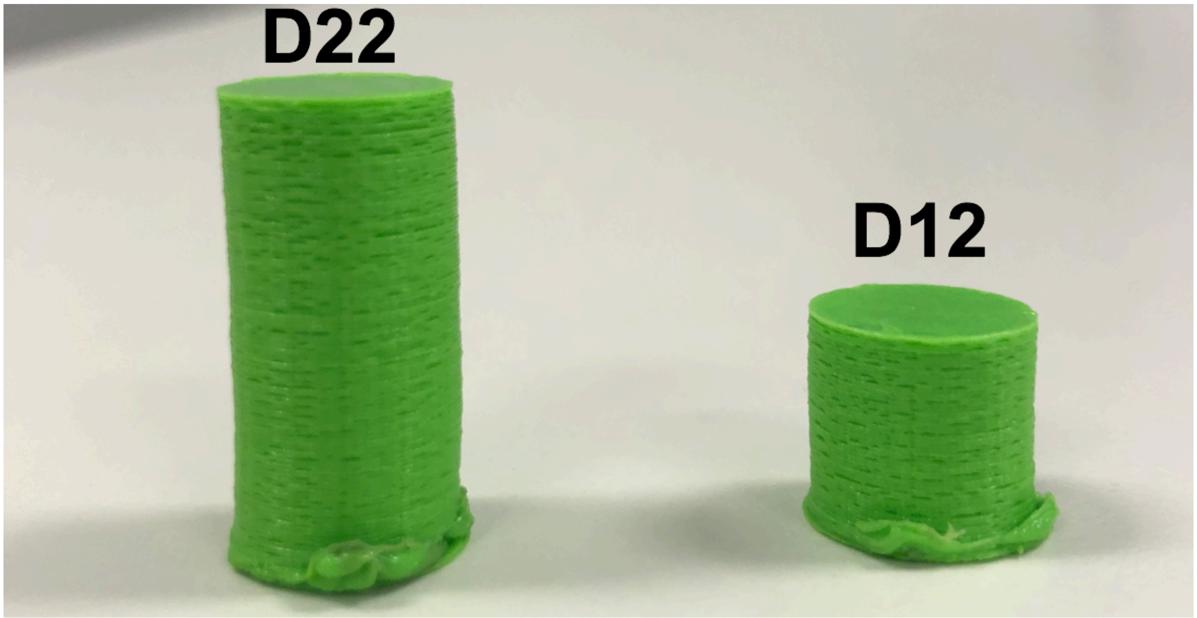


Figure 27: Actual Images of D12 and D22

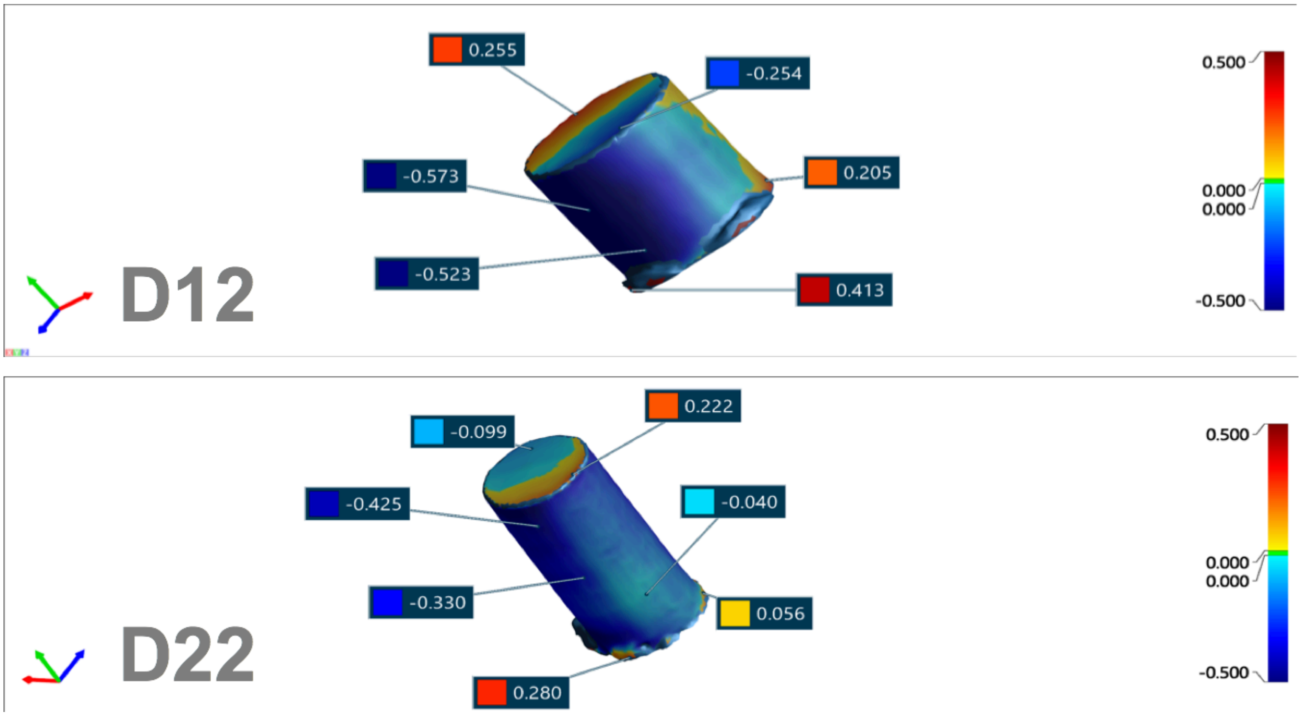


Figure 28: D12 and D22 Color Maps

6. Business Analysis

6.1 Economic Analysis

The team was assigned a budget of $2000 for the entire project. At first, the students considered building the whole enclosure that will surround the setup from scratch and have two different purchase orders for the materials needed. The team realized that those two orders were going to take most of the budget so they needed a cheaper solution in case more materials would need to be ordered in the future. After speaking with Dr. Dickens and Mr. Psulkowski about this issue, they suggested to reuse some materials that were available at HPMI from an enclosure that was previously built. This way a lot of costs could be cut, mainly in brackets, since the enclosure requires 32 brackets at a price of $4.00 each for a total of $128.00. This represents roughly 25% of the purchase order that the team submitted for $533.73, located in Appendix A. With this decision, the team was able to purchase all the materials needed for the enclosure and at the same time conserve 75% of the budget that was allocated for buying a gripper accessory for the FANUC robot, as well as materials to build the linear motion system.

It is important for any project to show not only that it can be done within budget, but also that it can actually save money in relation what it is actually used in the industry. Mike Bingham, in his article "CMM Justification" identifies the economic advantages of having an automated Coordinate Measurement Machine (CMM) over manual CMM. According to the text, there are three main aspects in which automated CMM saves costs: Inspection costs, scrap and rework, and downtime. The article estimates that approximately $187,500 can be saved yearly in inspection costs, $10,500 in downtime costs, and $15,000 in scrap and rework. The publication also estimates the return of investment to be above 350%, which makes this type of solution very profitable [4]. These numbers are really interesting, justifying the development of the team's project at least from an economic perspective. In this measure phase as well as in upcoming phases the team will use 3D scanning, an automated CMM technique, in order to quantify errors in printing

Since the solution will be at first in a smaller scale, the cost savings may not be as high as estimated, but they will be proportional to the budget of $2000.

6.2 Environmental Impact

The whole process is divided into two parts or stages, first the manufacturing of the parts to be certified, and second, the actual geometric tolerancing of the part, performed by a point cloud system. Since the team will use 3D printing as the method for manufacturing of parts it may be considered that this stage of the process has a low environmental impact, thanks to the fact that 3D printing uses less energy and resources in comparison to other common manufacturing methods [5]. Waste management is also improved with 3D printing, since there will not be much residual material left after printing the parts.

For the second stage of the process, the main environmental concern might be the energy consumption of the FANUC robot. However, according to its spec sheet it has an average energy consumption of only 0.2 kWh [6], making its environmental impact significantly low.

6.3 Ethical Considerations

With every new invention, and with technology focused on automation and reducing human workforce, the ethical issue of taking away jobs from human workers to replace them with machines begins to arise. This same issue is applicable to this project, since the team's primary objective is to create an automated GD&T method in order to reduce certification times and costs. By making a machine take care of the whole process, not only of manufacturing the part, but also making sure it has the correct standards, this approach will replace the human workforce that used to do the job. This can be beneficial for a company because they can save a lot of time and costs, such as salary and benefits, that do not apply to a machine, but at the same time they are taking away jobs from people that need them in order to earn a living. Depending of the company´s work culture and ethic, this situation may occur more frequently or not.

Considering this, one may be tempted to say that even though the project will bring important benefits in several aspects to the industry, sacrificing human jobs for these benefits might not be worth it. However, this is not true at all, in the sense that by implementing the team's process, human workers would not necessarily be replaced, or at least left without jobs.

Instead of eliminating jobs for humans, the team will say that they are transforming those jobs into different ones. In this specific case, a worker will probably not be needed to manually machine a part, but now there will be need for a worker that knows how to setup and code the 3D printer, as well as the FANUC. This solution will also be generating employment, since all these machines that will be used will need periodic maintenance in order for them to function optimally.

With this said, the team believes that this project will not only be beneficial for companies by implementing automation to save costs, but it will also consider the human workforce as an important component of the process balancing both sides of this ethical dilemma.

6.4 Health and Safety

It may seem at first glance that this project, since it is a process that works mainly with 3D printing which is relatively safe, would not have any risk factor for health and safety. However, there are always factors that should be considered to safely operate these types of machines and to work with them on a daily basis.

First of all, it is important to remember that the basic safety measures of the laboratory or facility in which the team's solution will be implemented must always be complied. That includes dressing code and personal protection equipment (PPE), such as plastic goggles, protective headwear, and gloves. It is also important to be aware of all the safety protocols in case of an accident, such as emergency number or the location of first aid stations.

It is critical that an ergonomic workstation is designed for the person that will be operating these machines. Even though it is not a job that requires a lot of force or physical effort, a poorly designed station may lead to musculoskeletal disorders (MSD) and other types of injuries. This station should be designed based on the Occupational Safety and Health Administration´s (OSHA) standards [7].

Another important health and safety factor to consider for this project is the assembly of the enclosure, in which safety measures must be followed at all times, since this activity involves moving heavy objects, and working at positions that may be uncomfortable. The same measures should be considered when fixing or working on maintenance duties, since those may involve working at inefficient angles or positions that may lead to MSDs. These safety measures will be described in more detail as the project progresses and the enclosure is built given the fact that at the time, the team is waiting for the ordered materials to arrive.

6.5 Social and Political Considerations

This project will not arouse any major political or social issues. The topic of replacing human workers with machines, which was vastly discussed earlier on this report, will also have a social impact as well as ethical. The social approach however deals with the fact that is not good to replace human workers with machines in a different way. As machines are assigned to take over human based tasks, they are not only taking jobs, but the income of each worker to satisfy their basic needs and sustain their families. A machine does not have any necessity for money, food, housing, and the other essential things that a human need for living comfortably. Society as a whole may disagree with this "technological revolution" fearing that it may take away thousands of jobs from people that actually need them to survive. The group believes this will not be the case, at least with this project, since, even though it is true that it may replace some human tasks with automated systems, it will also open new opportunities towards new positions and job openings for these workers to exert, and bring sustain to their homes with stable income and benefits.

6.6 Sustainability

Sustainability, despite being a popular concept in actual society, it is sometimes mistaken to only have an environmental connotation. Because of this, it is important to provide an accurate definition for this term before performing an analysis. Britannica Encyclopedia defines sustainability as "the long-term viability of a community, set of social institutions, or societal practices [8]". The concept of sustainability is all about being perennial without depleting all resources.

Having said this, the main question that comes up is if this project will be able to run in the long term. Since the project is a process, not an invention or a device per se, it is possible to keep it running for a prolongated time as long as the proper machinery is employed. If the process is successful, it should be applicable to any setup, not only using the specific machines used to develop it.

Since technology advances at a rapid pace, it is important that the companies that will implement this process are up to date with the latest machinery in order to keep improving it and making it work for years. Also, it is important to give proper maintenance to these machines in order for them to work optimally. Another important factor is to have qualified work force that can efficiently operate this machinery and have complete understanding of how the developed process works.

By making these considerations are correctly complied, the students believe that the process can be sustained for years, being fully functional and efficient, while bringing important benefits to the companies that decide to implement it.

7. Project Progress

7.1 Milestones and Schedule

Define Phase

The following tasks were completed during the Define Phase:

- Make initial contact with sponsors and stakeholders
- Develop team contract
- Perform background research
- Brainstorm deliverables
- Develop fishbone diagram on nonconforming AM parts
- Complete Project Hazard Assessment (PHA)
- Complete Initial Project Completion Form
- Design the micro factory within the enclosure
- Interpret customer needs
- Have weekly team meetings and bi-weekly conference calls with NGC
- Phase report
- Presentation
- Peer evaluations

Measure Phase

The following tasks were completed during the Measure Phase:

- Completed all purchase orders
- Finalized mating pierces for robots
- Finalized breadboard and linear motion assembly design
- Part dimensioning limits
- Optimization of the FANUC's working area
- Developed test plan
- Seven prints on LulzBot and Ender, four on Dexter™
- Initial statistical analysis of cylinders
- Poster presentations
- Phase report
- Peer evaluations
- Phase presentations
- Project completion form

Analyze Phase

The following tasks are required in order to complete the analyze phase:

- VXelements inspection reports of all cylinders
- Characterize/quantify printer variability
- Assemble breadboard
- Phase report (January 30th)
- Phase presentation (January 30th)

Completing the inspection reports is imperative so that the team is able to further analyze the cylinders. The reports provide much more information that the manual inspections from the measure phase and will allow for the team to identify the root causes of printer variability.

Design Phase

- Phase presentation (March 5th)

Verify Phase

- Phase report (April 9th)

Other

- Design day (April 23rd)
- Business analysis (April 19th)

A network diagram of tasks needed to be completed throughout the entire project is shown in Figure 29. The total expected duration of each task is displayed in the top cells. The four cells, surrounding the task, with numerical values refer to the earliest and latest starts and ends for each task. These values are in days. The top two cells refer to the earliest start and end durations, while the bottom two cells refer to the latest start and end durations. The float value below each task indicates the flexibility for that task. Notice the tasks that have float values of zero. These tasks are considered to be the critical path, meaning they must be completed on schedule.

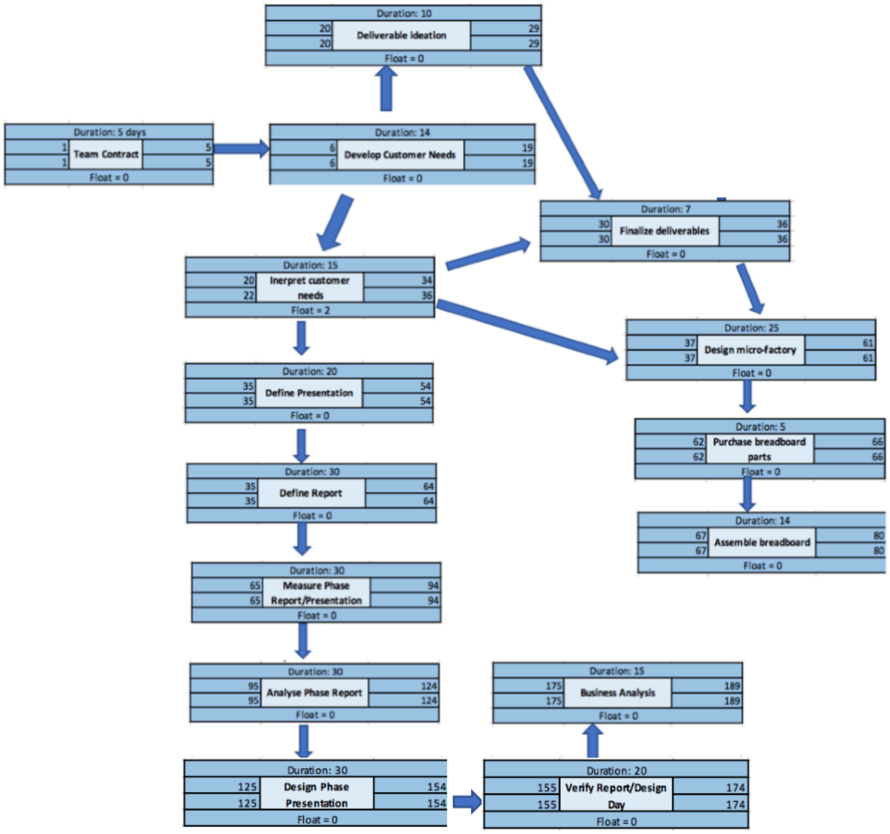


Figure 29: Project Network Diagram

Figure 30 shows a Gantt chart spanning from the beginning of the measure phase to the end of the analyze phase. The expected lengths of various tasks that were needed to be completed during the remaining Fall semester are outlined as well as major tasks for the Analyze Phase in the Spring. In the best-case scenario, the team will be able to successfully print all seven batches on each individual printer and performing an introductory statistical analysis. However, the worst-case scenario would be not being able to complete all seven prints. This would limit the ability to begin processing the various statistical analyses listed in the Gantt chart. To prevent this from happening, and maintain schedule, the team would reduce sample size to ensure some analysis could occur. The team could also limit the number of printers to only one of each kind (LulzBot, Ender, Dexter^{TM}).

Currently, the group is working to further analyze the initial measurement data collected from the cylinders.

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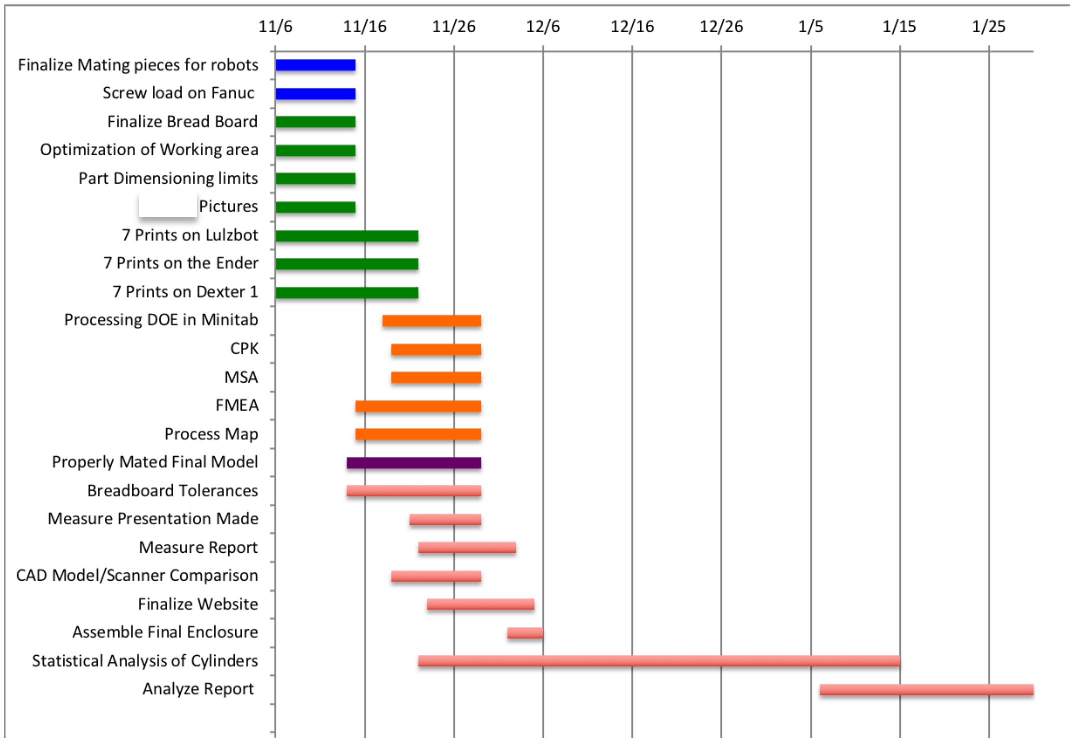
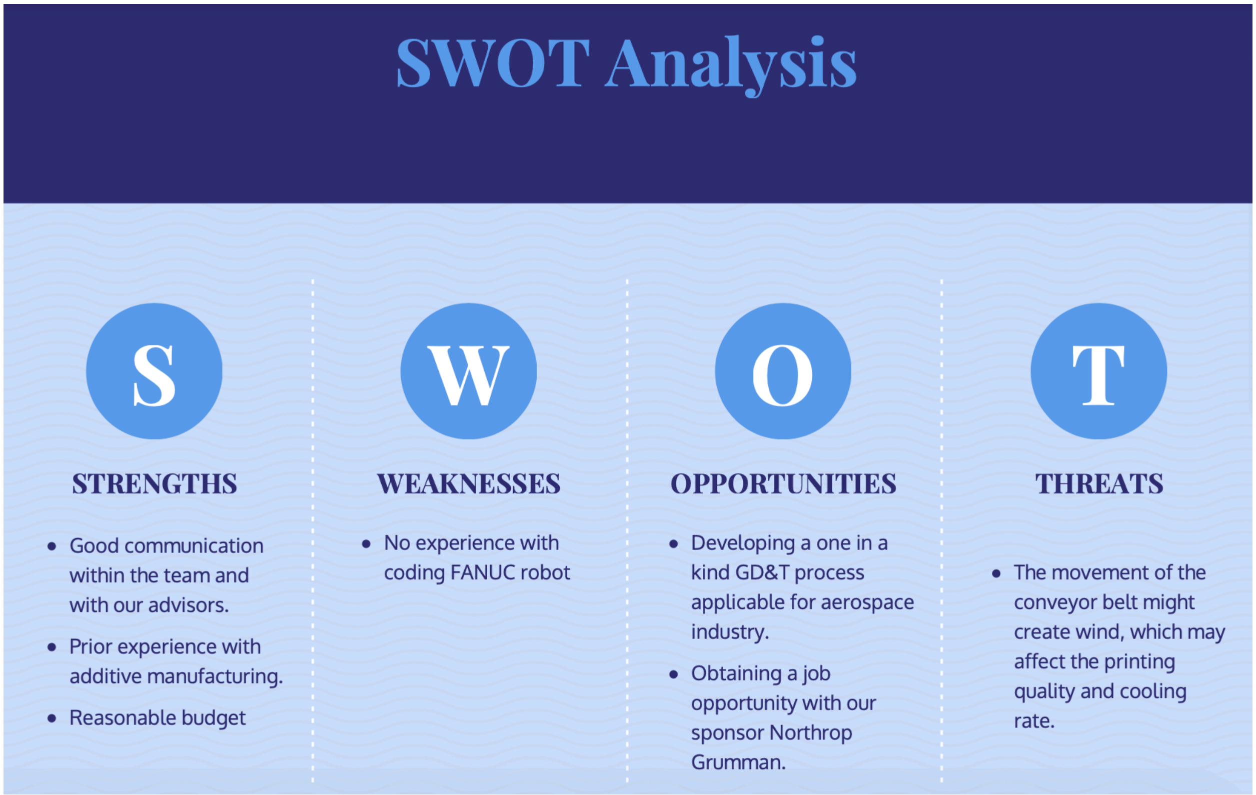


Figure 30: Gantt Chart

7.2 Risk Management

Figure 31 shows the strengths, weaknesses, opportunities, threats matrix, (SWOT) developed for this project. The main weakness is that students in this group do not have any experience with developing code for the FANUC robot, which will be one of the main tools for this project. This is a low-level risk, since the group has all the manuals and resources to complete this task. The strategy for this factor to not have a significant impact in this project, will be to start with a lot of anticipation, so in case it takes more time than expected, the project will not be behind schedule.

The main threat identified in the SWOT analysis is that after the part is printed, the movement of the linear motion assembly from the printing station to the GD&T station can create wind, which will affect the cooling rate of the machine, and may also affect the quality of the final product. This is considered to be a high-level risk since if this occurs, the assembly would have to be rearranged in order to avoid this from happening. In order to know if this will be a problem or the team plans on running simulations, apart from testing the setup when it is mounted. In order to prepare ahead in case this happens, the group will start brainstorming possible solutions, so when the time comes, if the problem occurs, there will be a solution already prepared to try to fix it.



SWOT Analysis

S

STRENGTHS

- Good communication within the team and with our advisors.
- Prior experience with additive manufacturing.
- Reasonable budget

W

WEAKNESSES

- No experience with coding FANUC robot

O

OPPORTUNITIES

- Developing a one in a kind GD&T process applicable for aerospace industry.
- Obtaining a job opportunity with our sponsor Northrop Grumman.

T

THREATS

- The movement of the conveyor belt might create wind, which may affect the printing quality and cooling rate.

Figure 31: SWOT Analysis

7.3 Budget / Bill of Materials

For the development of the manufacturing and certification system, the team was allocated a total budget of $2000 by Northrop Grumman, the team's sponsor. Northrop has required that a prototype be developed as well as the overall process. It was identified that the prototype would consist of five major categories including robotics, measurement, controls, fixturing, and process which includes any overhead or recurring cost such as consumables. Prior to the start of this project, all of the components encompassed by the process category were purchased and thus will not count against the $2000 allocation. At the culmination of the measure phase, the design of the implementation has been finalized. Therefore, a bill of materials was able to be developed reflective of the implementation pursued by the team. The breakdown of the expenses is illustrated in Figure 32. This breakdown is reflective of the most current bill of materials. Vendors were selected from a list of approved vendors provided by the university. Components were purchased from vendors with the most competitive price in order to keep in line with the project goal of designing an affordable system. The total cost of the preliminary design is $2000.00. This leaves $0.00 in the remaining budget should an unexpected cost be incurred.

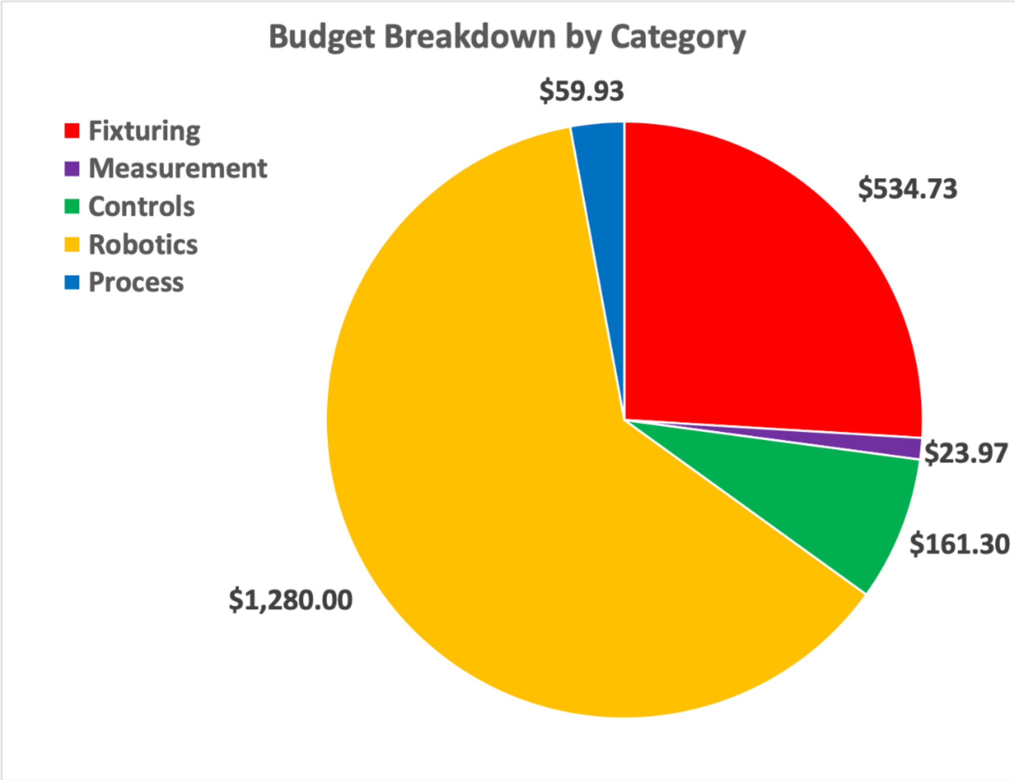


Figure 32: Budget Breakdown by Category

It was identified that the measurement subsystem was the most susceptible to miss performance expectations due to the highly experimental nature of the project scope. While the controls, fixturing, and process subsystems were identified to be at low risk of missing performance expectations. This is due to the high reliability of existing designs which are similar in function to the preliminary design. A contingency reserve was initially established by allocating 10% of the projects budget for unexpected expenses should the final design fail to meet expected performance. However, due to an update in customer requirements it was required to utilize the full amount of $2000.00 to purchase the required robotic components. In order to assure that the final implementation meets performance specifications, three budgets were created based on the most likely cost (C_m), the optimistic cost (C_o), and the pessimistic cost (C_p). A weighted average of these three budgets can be determined by $C_e = (C_o + 4C_m + C_p)/6$ to produce the expected cost (C_e). In Table 5 it is shown that the optimistic cost and most likely cost will be equal to or less than the expected cost as planned for in the budget. The pessimistic cost will exceed the budget allocated to the project.

Table 5: Budget Projections

Budget	Amount
C_m	\$2000
C_o	\$1800
C_p	\$2200
C_e	\$2000

8. Summary/Conclusion

During the measure phase, a data set was built from 3D scans of additively manufactured parts. This data set provided the basis for all of the work performed during the analyze phase. The collection of 3D scans was overlaid with the original CAD model corresponding to the part which was manufactured. The software automatically produces a color map that displays the deviation of the scan compared to the nominal, CAD model. This allowed for the determination a key GD&T parameter known as cylindricity. Cylindricity is 3D tolerance which describes the overall form of a cylinder to ensure it that it both round and straight along its longitudinal axis. 3D scans made the measurement of this tolerance possible by providing information across the entire surface of the cylinder rather than at localized positions as was measured with calipers during the measure phase. The results of this analysis showed that Ender produced the most precise cylinders compared to the LulzBot and Dexter^{TM}. The results also allowed for identifying the root causes of variability in each printer. It was concluded that environmental factors heavily affected the LulzBot and Ender, after examining the color maps of the cylinders. The team determined that the cause for variability in the Dexter^{TM} prints was due to an unleveled printing bed that could not be secured in a level position.

Furthermore, progress was made on the implementation of a automated coordinate measuring system for additively manufactured parts. This included the assembly of the breadboard which will serve as a construction base for robotic equipment, 3D printers, and a linear actuator. A stand for the FANUC robot was also assembled to raise the FANUC to a height which would allow the team to effectively use the full operational range of the robot to perform touch down measurements. The breadboard will ease the ability for future work to be carried out by allowing these components to be repositioned in different configurations to meet the needs of future project groups.

The next steps are to improve upon existing additive manufacturing methods by identifying issues which contributed to excessive variance in the parts which were scanned. Potential areas of improvement may include changes to the print settings used, upgrades to the 3D printing hardware itself, and environmental controls. In addition to making these improvements, an electromechanical system will be implemented which will be able to perform touch down coordinate measurements on additively manufactured parts. This system will provide the basis for future work into the automation of additive manufacturing. In regards to Northrop Grumman, the team expects to gain feedback on the final implementation of this system. Specifically, the team is wondering as to whether the system meets their expectations and also inquiring into potential ways to increase accuracy and improve the system. Beginning in February, the team will discuss with the sponsors Jennifer Tecson and Tarik Dickens, the conclusion of the analyze phase and the next steps in the improve phase.

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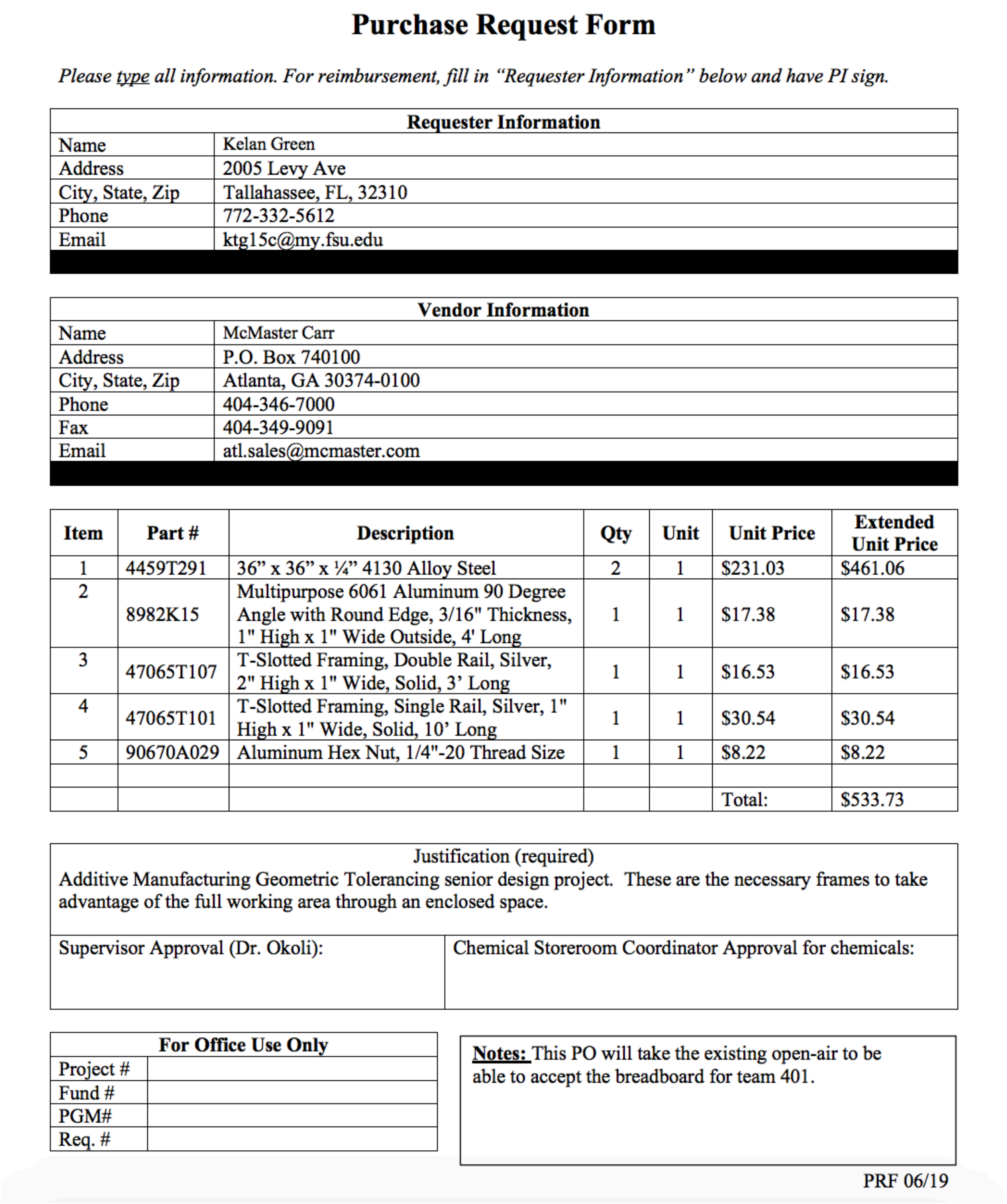
Appendix A

Below is the team’s purchase order to McMaster-Carr for the required materials for the enclosure.



Purchase Request Form

Please type all information. For reimbursement, fill in “Requester Information” below and have PI sign.

Requester Information	
Name	Kelan Green
Address	2005 Levy Ave
City, State, Zip	Tallahassee, FL, 32310
Phone	772-332-5612
Email	ktg15c@my.fsu.edu

Vendor Information	
Name	McMaster Carr
Address	P.O. Box 740100
City, State, Zip	Atlanta, GA 30374-0100
Phone	404-346-7000
Fax	404-349-9091
Email	atl.sales@mcmaster.com

Item	Part #	Description	Qty	Unit	Unit Price	Extended Unit Price
1	4459T291	36” x 36” x ¼” 4130 Alloy Steel	2	1	$231.03	$461.06
2	8982K15	Multipurpose 6061 Aluminum 90 Degree Angle with Round Edge, 3/16" Thickness, 1" High x 1" Wide Outside, 4' Long	1	1	$17.38	$17.38
3	47065T107	T-Slotted Framing, Double Rail, Silver, 2" High x 1" Wide, Solid, 3’ Long	1	1	$16.53	$16.53
4	47065T101	T-Slotted Framing, Single Rail, Silver, 1" High x 1" Wide, Solid, 10’ Long	1	1	$30.54	$30.54
5	90670A029	Aluminum Hex Nut, 1/4"-20 Thread Size	1	1	$8.22	$8.22
					Total:	$533.73

Justification (required)

Additive Manufacturing Geometric Tolerancing senior design project. These are the necessary frames to take advantage of the full working area through an enclosed space.

Supervisor Approval (Dr. Okoli):	Chemical Storeroom Coordinator Approval for chemicals:

For Office Use Only	
Project #	
Fund #	
PGM#	
Req. #	

Notes: This PO will take the existing open-air to be able to accept the breadboard for team 401.

PRF 06/19

Appendix B

Cylinder measurements gathered from VXinspect.

Cylinders	Diameter MAD (mm)	Height Absolute Deviation (mm)	Cylindricity
L11	0.727	0.094	0.456
L21	0.976	0.132	0.785
L12	0.457	1.462	0.269
L22	0.627	0.497	0.524
L13	0.419	0.373	0.269
L23	0.382	0.481	0.307
L14	0.482	0.574	0.27
L24	1.057	0.38	0.962
L15	0.921	0.206	0.634
L25	0.92	0.161	0.814
L16	0.809	0.157	0.469
L26	0.632	0.21	0.488
L17	0.703	0.223	0.375
L27	0.691	0.335	0.499
E11	0.284	1.319	0.356
E21	0.232	1.875	0.381
E12	0.123	0.625	0.537
E22	0.102	0.255	0.265
E13	0.032	0.273	0.268
E23	0.032	0.222	0.278
E14	0.19	0.285	0.268
E24	0.204	0.417	0.337
E15	0.031	0.337	0.18
E25	0.052	0.423	0.759
E16	0.087	0.331	0.266
E26	0.05	0.308	0.225
E17	0.021	0.16	0.213
E27	0.127	0.136	0.218
D11	0.295	0.199	0.839
D21	0.124	0.16	0.501
D12	1.342	0.07	1.456
D22	1.871	0.253	1.86
D13	0.923	0.184	1.718
D23	0.283	0.436	0.839
D14	0.767	0.242	1.059
D24	0.43	0.372	1.401

Appendix C

Diameter comparison of manual vs. software inspection.

Cylinder	Manual Inspection MAD (mm)	VXelements Inspection MAD (mm)	Inspection Deviation (mm)
L11	0.333	0.727	**0.394**
L21	0.420	0.976	**0.556**
L12	0.390	0.457	**0.067**
L22	0.407	0.627	**0.220**
L13	0.400	0.419	**0.019**
L23	0.523	0.382	**-0.141**
L14	0.487	0.482	**-0.005**
L24	0.377	1.057	**0.680**
E11	0.207	0.284	**0.077**
E21	0.247	0.232	**-0.015**
E12	0.053	0.123	**0.070**
E22	0.060	0.102	**0.042**
E13	0.087	0.032	**-0.055**
E23	0.023	0.032	**0.009**
E14	0.043	0.19	**0.147**
E24	0.060	0.204	**0.144**
D11	0.743	0.295	**-0.448**
D21	0.403	0.124	**-0.279**
D12	0.590	1.342	**0.752**
D22	0.460	1.871	**1.411**
D13	0.527	0.923	**0.396**
D23	0.517	0.283	**-0.234**
D14	0.360	0.767	**0.407**
D24	0.603	0.43	**-0.173**