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Hexagon -- On Machine Parallelism/Skew Check

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On Machine Parallelism/Skew Check

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Abstract

With industrial development, precision engineering has a wide range of application. However, in the precision machining of materials, Subtle changes can cause parts to exceed the tolerances. This project is to design a solution that measure the relative parallelism (skew) of 2 sides of the triangular beam during the final milling step. The tolerance of relative parallelism must less than 25 micrometers. The triangular beam is used in Hexagon's Global S, a coordinate measuring machine (CMM). The air bearings hold the triangular beam and move along with the beam's surface. The moving direction according to the machine self is X-axis. Therefore, the relative parallelism of 2 sides will affect the measurement accuracy of x-axis. The requirements of the solution need to mount on the milling machine and be non-contact. The parts cannot be moved or touched. Non- contact displacement sensors were considered to be the solution. After thorough and detailed researching and selecting, Omega inductive sensor LD 701-5/10 was be purchased and be tested. However, AR-700 laser displacement sensor from Acuity, LJ-V7060 displacement sensor from Keyence and CapaNCDT 6019 Capacitive sensor from Micro-epsilon were also be considered during the time. By comparing the advantages and disadvantages of displacement sensors from the performance, noise, accuracy, precision, the price and so on, the inductive displacement sensor was chosen. The displacement sensor will measure the side face of the triangular beam and need to be perpendicular to the side face during measuring process. The measuring process is very simple. Before measuring, the first surface needs to be milled. Assume that the first surface is completely horizontal and smooth. After milling first surface, rotating the triangular beam and do the measurement. The sensor will measure the skew of the first milled face. If the maximum and minimum difference displayed by the sensor is within 25 microns, then the position of rotated beam is correct, and the triangular beam can continue to be processed. If it is bigger than 25 microns, it means the position of rotated beam need to be adjusted. It is same principle for second and third face. Through improvement of the triangular beam measurements technology, the processing efficiency is improved, and material is saved.

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List of Acronyms

URI	University of Rhode Island
MCE	Mechanical Engineering
CMM	Coordinate Measuring Machine
2D	Two-Dimensional
PDS	Preliminary Design Specifications
PPT	Microsoft PowerPoint
um	Micrometer
QFD	Quality Function Deployment
3D	Three-Dimensional
CNC	Computer Numerical Control
CAD	Computer-Aided Design

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1 Introduction

An aluminum triangular beam will be mounted on Hexagon's Global S, a coordinate measurement machine (CMM). The Global S coordinate measurement machine from Hexagon has high precision, multi-probe and sensor and shop-floor capabilities. The triangular beam is held by air bearings on all three surfaces. The air bearings move x-axis according to the coordination along on beam surface. Therefore, the surface precision of the triangular beam needs to be very high. During the final milling process, the incorrect position of the triangular beam on the milling machine and other factors cause the parallelism to exceed the tolerances. Currently, Hexagon uses another CMM to measure the parallelism of the triangular beam. This measurement method has several disadvantages. First disadvantage is wasting materials. If the parallelism is over the tolerance, the triangular beam is a scrap. Second disadvantage is wasting time. The triangular beam needs to move from the milling machine to the CMM. Third disadvantage is the complicated operation. It is complicated to operate CMM to measure the parallelism. Therefore, it is necessary to design a solution to measure the parallelism (skew) of two sides of triangular beam during the milling step. The requirements for the solution are that the solution must be non-contact and mount on the milling machine, the part cannot be touched or moved. The tolerance of the parallelism of two sides must be under 25 micrometers. According to the design requirements, the displacement sensor was eventually decided to measure the parallelism of the two side of the triangular beam. The displacement sensor has several advantages, for example small standoff distance, sensitivity, Anti-interference, high precision and so on. The setup and operation of displacement sensor is also simple and efficient. After milling first surface, it will be served as the reference after milling. Assume that first surface is horizontally and flatness. Then rotating the triangular beam and do the measurement. The sensor will measure the skew of the first milled face. If the maximum and minimum difference displayed by the sensor is within 25 microns, then the position of rotated beam is correct, and the triangular beam can continue to be processed. If it is bigger than 25 microns, it means the position of rotated beam need to be adjusted. It is same principle for second and third face.

2 Patent Searches

- 10,083,844: Method of manufacturing bonded body
- 10,083,538: Variable resolution virtual reality display system
- 10,082,583: Method and apparatus for real-time positioning and navigation of a moving platform
- 10,082,392: Level device with inter changeable modules and digital features
- 10,082,380: Tool for measuring radial stacking angle of blades, measuring method and blade
- 10,080,672: Hybrid terrain-adaptive lower-extremity systems
- 10,080,136: Credibility token system for over the air multi-programming of a wireless device and method of operation
- 10,079,877: System and method for cloud aware application delivery controller
- 10,079,740: Packet capture engine for commodity network interface cards in high-speed networks
- 10,079,695: System and method for customizing packet processing order in networking devices

- 10,078,650: Hierarchical diff files
- 10,078,456: Memory system configured to avoid memory access hazards for LDPC decoding
- 10,078,133: Method and system for ladar transmission with closed loop feedback control of dynamic scan patterns
- 10,078,082: Detection of free and protein-bound non-human gal-alpha(1-3)-gal epitope
- 10,076,883: System and method for manufacturing off-axis prepreg material
- 10,076,624: Flexible structure for mask, and method and apparatus for evaluating performance of a mask in use
- 10,074,888: Accordion antenna structure
- 10,073,907: System and method of analyzing and graphically representing transaction items
- 10,073,701: Scalable and parameterized VLSI architecture for compressive sensing sparse approximation
- 10,073,532: General spatial-gesture grammar user interface for touchscreens, high dimensional touch pad (HDTP), free-space camera, and other user interfaces
- 10,073,166: Method and system for ladar transmission with spinning polygon mirror for dynamic scan patterns
- 10,073,043: Multi-axis positioning device
- 10,073,029: Sample measurement pool
- 10,070,974: Hybrid terrain-adaptive lower-extremity systems
- 10,070,936: Rod contouring apparatus for percutaneous pedicle screw extension
- 10,070,829: System and method for low x-ray dose breast density evaluation
- 10,070,084: Image sensor with multi-range readout

Several keywords were used for patent searches, for example Parallelism, Skew, Non-contact measurement, Air bearing. But the result of patent searches is not related to the problem in the project. Because the parallelism of the two sides of triangular beam is very specific problem. Normally, the patents are about measure the surface parallelism of two horizontal planes. If the patents or the related patents are used in this project, this should be the laser displacement sensor because the laser displacement sensor mounts on the milling machine and measures the distance between the sensor and the side surface of the triangular beam.

3 Evaluation of the Competition

Because of the customer-specific nature of our design, there is little market competition for our product. Alternatively, there is practical competition for our product in the form of the customer's current process of verifying skew on their specimen. This process, which involves verifying the specimen's dimensions using an over-powered CMM, wastes electricity and man-hours: both valuable resources. In this way, while understanding our product's low cost, the design beats the competition in every aspect.

4 Specifications Definition

When it came to a design, there were several constraints given by Hexagon that limited the directions in which a solution could be pursued. These constraints were that parallelism must be determined with a tolerance of 25 micrometers, the solution must be mounted to the milling machine, the triangular beam cannot be touched, and the solution cannot involve motion as this considerably reduces the repeatability factor. These constraints given by Hexagon are obviously physical constraints, as for numerical constraints, our group is yet to be given a financial budget as it was to be determined based off of our proof of concept. However, it is a goal of this project to choose the cheapest materials and sensors that still perform the required function at an optimal level. In order to fulfill the requirements stated, a logical choice would be to use some sort of non-contact linear displacements. There is a very wide range of these sorts of sensors on the market, many different companies and models were researched. Depending on the decided budget, there are many levels of accuracy, repeatability, and included features. This being said, in this particular market it appears that you get what you pay for, so to speak. Therefore the sensor chosen in the end will be by the choice of Hexagon.

Regardless of the sensor chosen, the real challenge of this design comes with the design of the system with which the sensor will be mounted. When one dissects this problem, there are several main constraints that hinder a variety of methods. This sensor is going to be installed inside mounting system that glides along two parallel metal bars via an air bearing glider. This being said, much research was done regarding air bearings, these are extremely smooth systems that severely reduce vibration due to sliding, this is how the milling machine is able to mill the beam down to a flatness of about 8 microns. This is one of the main benefits of using air bearings over many other bearings used in industry. Also note that when this measurement is taken, the mill will not be running; only gliding along the beam. Given the factors stated and the precautions already being made to reduce vibrations, our goal is to ensure an optimal accuracy and repeatability of the chosen sensor, this mount needs to work to reduce "noise" due to vibration as well. Noise due to vibration, is the outlying data or errors that occurs during a measurement due to vibration in this case. This goal once again leads back to the sensor that in the end is chosen. Some of the options explored, specifically via Keyence, had features known as vibration compensation filters. This feature may prove to be critical as it will make the design of the mounting system much more practical as well as a more refined guarantee of repeatability and accuracy.

In addition to the issue of vibration reduction, another issue stemming from the mounting system goes back to our problem definition as a whole. It is a common consensus of the group that any error that may occur to this triangular beam is most likely a result of a faulty installation of the beam into its mount on the milling machine. After much discussion with our sponsor, Mr. Singh, it is understood that after installation into the milling machine, the beam has zero degrees of freedom. However, if this beam is installed even a millimeter off in multiple of the six degrees of freedom, then there is automatically a potential for error. In this project, we are given very specific instructions. However, at the end of the day it is our goal to contribute in the development of a more efficient production of this triangular beam, which in turn is a key part of one of Hexagon's products. Efficiency in this case is referring to reducing money lost due to scrapped triangular beams, as well as reducing the time it currently takes to ensure perfect parallelism using a CMM after milling. In addition to ensuring the perfect parallelism of two sides of the beam, however, it would be ideal to establish perfect installation into the mount. This may even be possible with the linear displacement sensor discussed, but may in turn effect the method in which the sensor is mounted. This issue is still being discussed and may prove to be negligible to our purpose in this project but solutions for this potential issue are still being researched and discussed.

Table 1: Product identification

Product Name	Parallelism measuring instrument
Basic Function	Non-contact measurement system for the parallelism of the two side of a triangular beam
Special Features	Laser, non-contact, high accuracy 25 um, vibration reduction in sensor and mounting set up
Key Performance Targets	High accuracy: 25 um, non-contact
Service Environment	Part inspection
Training	No training requirement for our product, but there is most likely training required for Hexagon's milling process.

Table 2: Market identification

Current Customer/ Market	Market: precision engineering, metrology, industrial systems
Anticipated Market Demand	Not really a market product, but one will be required for each milling machine. The triangular beam being measured is required for each "Global S" system produced. Products that serve similar purposes exist, however none appear to exist for triangular beams.
Competing Products	Contact and optical measurement systems
Branding Strategy	Minimal competition

Table 3: Key product deadlines

Deadlines	End of Project: Late April 2019
Time to complete project	Approximately 6-7 months

Table 4: Physical description

Physical requirements	• Must be mounted to the milling machine • Parallelism must be determined with a tolerance of 25 micrometers • The triangular beam cannot be touched • Solution cannot involve motion as this considerably reduces repeatability • Maintaining exact dimensions from "Global S" design and housing.
Known or fixed prior values	• Perfect flatness of milled surface is guaranteed within 8 microns • Given design specifications and dimensions

Table 5: Lifecycle targets, financial requirements

The performance of the product over time	Non-contact, high accuracy, easy to operate, efficient in terms of cost vs functionality and performance of system.
Maintenance schedule and location	Maintenance as needed, goal is to reduce necessary maintenance due to proper management of the sensors exposure to debris.

Table 6: Manufacturing specifications, social, political and legal requirements

Which parts or systems will be manufactured by the team? Which parts may be outsourced	Sensor system chosen will be purchased from a company such as Keyence or Acuity. This system will include a triangulation laser, necessary hardware as well as the required software used to report recorded data. The mounting system prototype will be developed by the team. However, if and when this design is implemented into Hexagon's production process, the mounting system will most likely be outsourced depending on how many units they need.
Manufacturing requirements. Processes and capacity necessary to manufacture final product.	Standard metal working, wiring, laser & sensor calibration, etc.
Suppliers	Acuity Laser or Keyence

5 Conceptual Design

The images below display designs 1-30 generated by Greg Phillips during the concept generation portion of this project. Most of the designs below are quite similar; their main differences are in the design of the slider itself, the bearing and lubricant if applicable, as well as there are several different sensors used. All of which serve different functions. There are many faults with these designs. The main design errors being that the sensors are not mounted inside the milling machine. In this case, they are mounted to an air bearing glider or glider that uses various forms of bearing systems that acts as a separate entity from the milling machine itself. These designs were created prior to more detailed discussion with Mr. Singh in which the team was informed that the sensor had to be mounted inside the milling system. Despite this lack of communication, theoretically this design could work and be quite functional. Another flaw with these designs is that they involve un-necessary moving parts, which via discussion with Mr. Singh it was established that this extra movement could hinder repeatability. In addition, this route would be much more expensive than simply mounting the sensor onto the milling machine. These errors apply to virtually all designs generated by Greg Phillips at this stage of concept generation earlier in the semester.

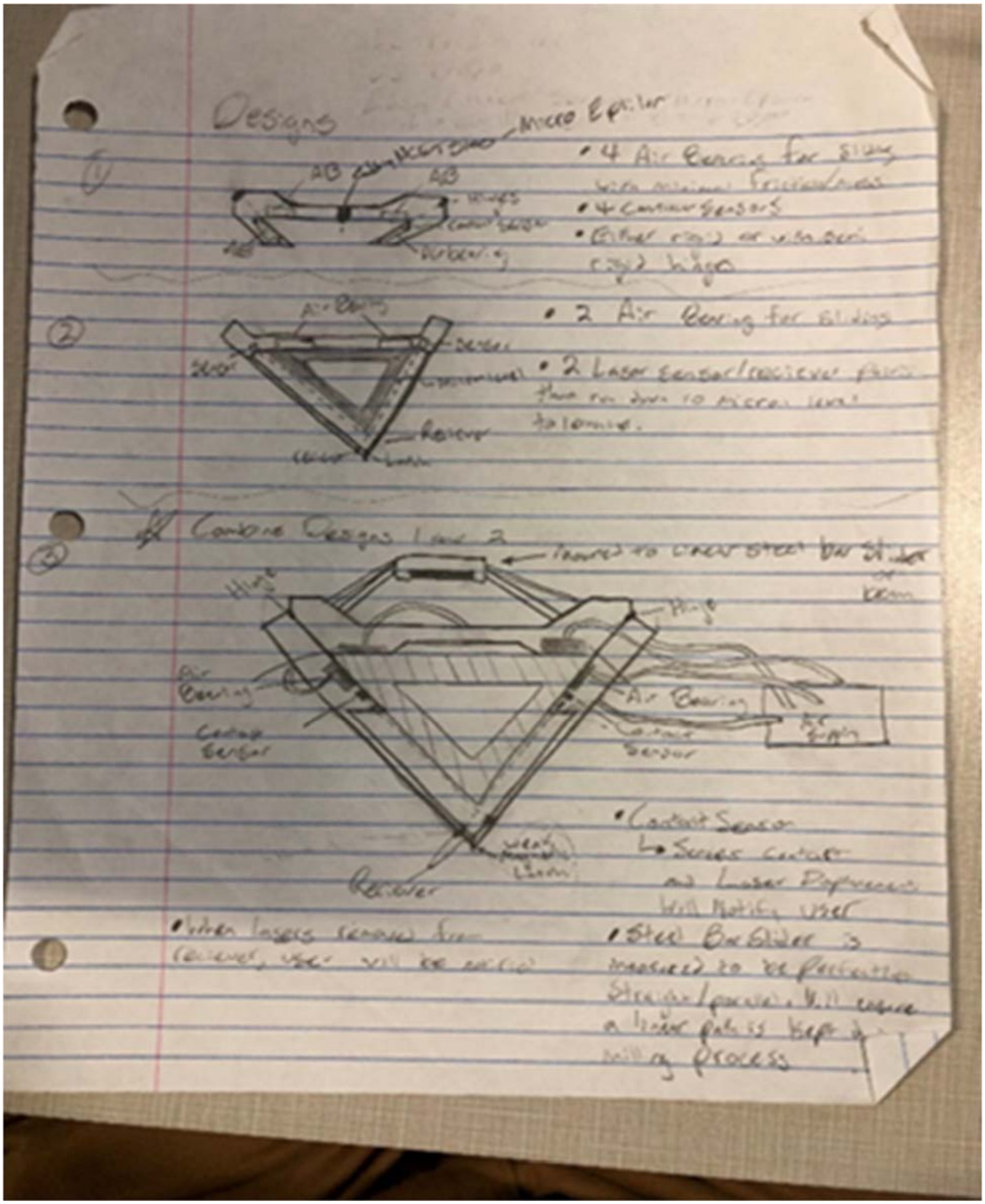

Figure 1: Greg Philips designs I

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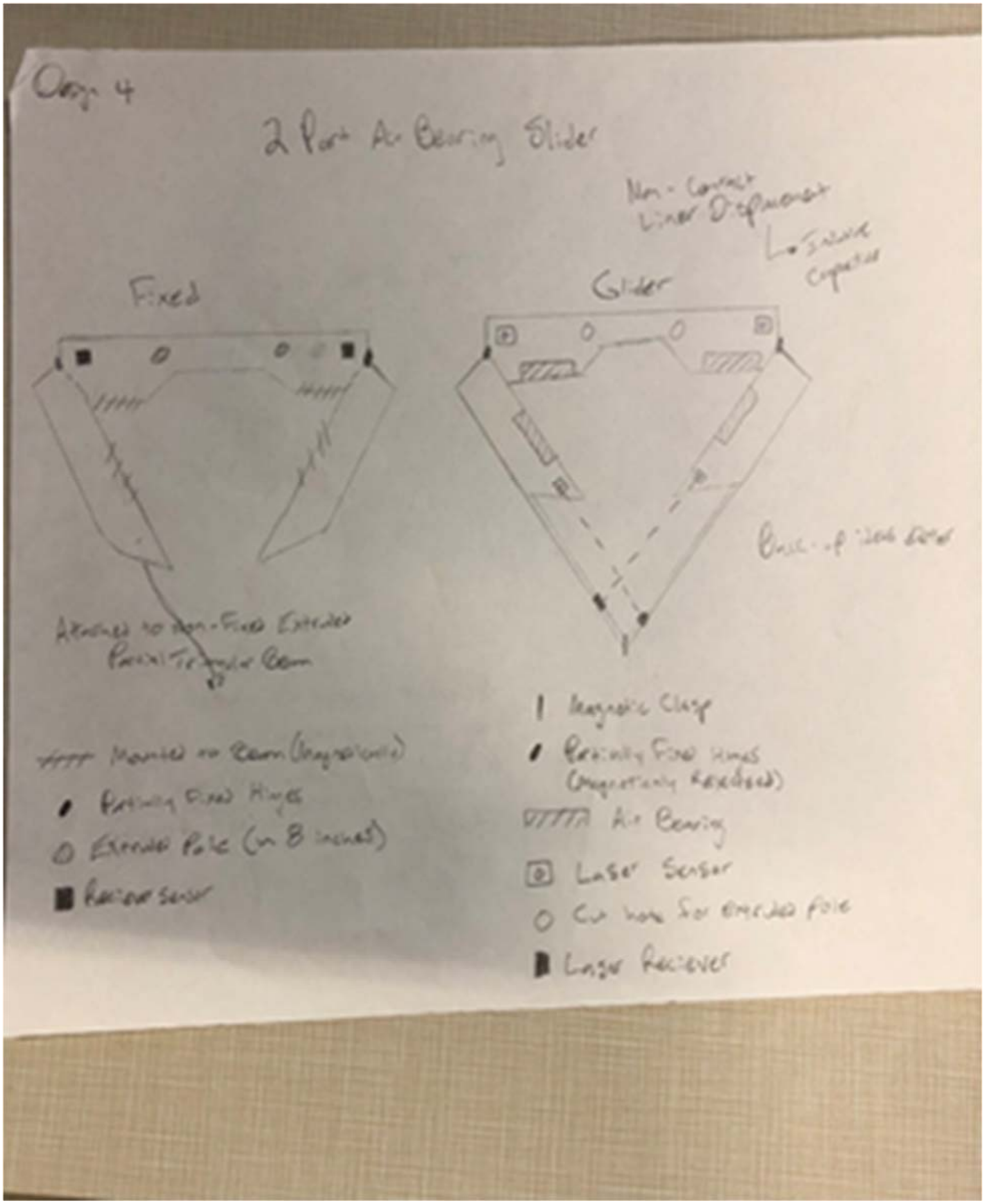

Figure 2: Greg Philips designs II

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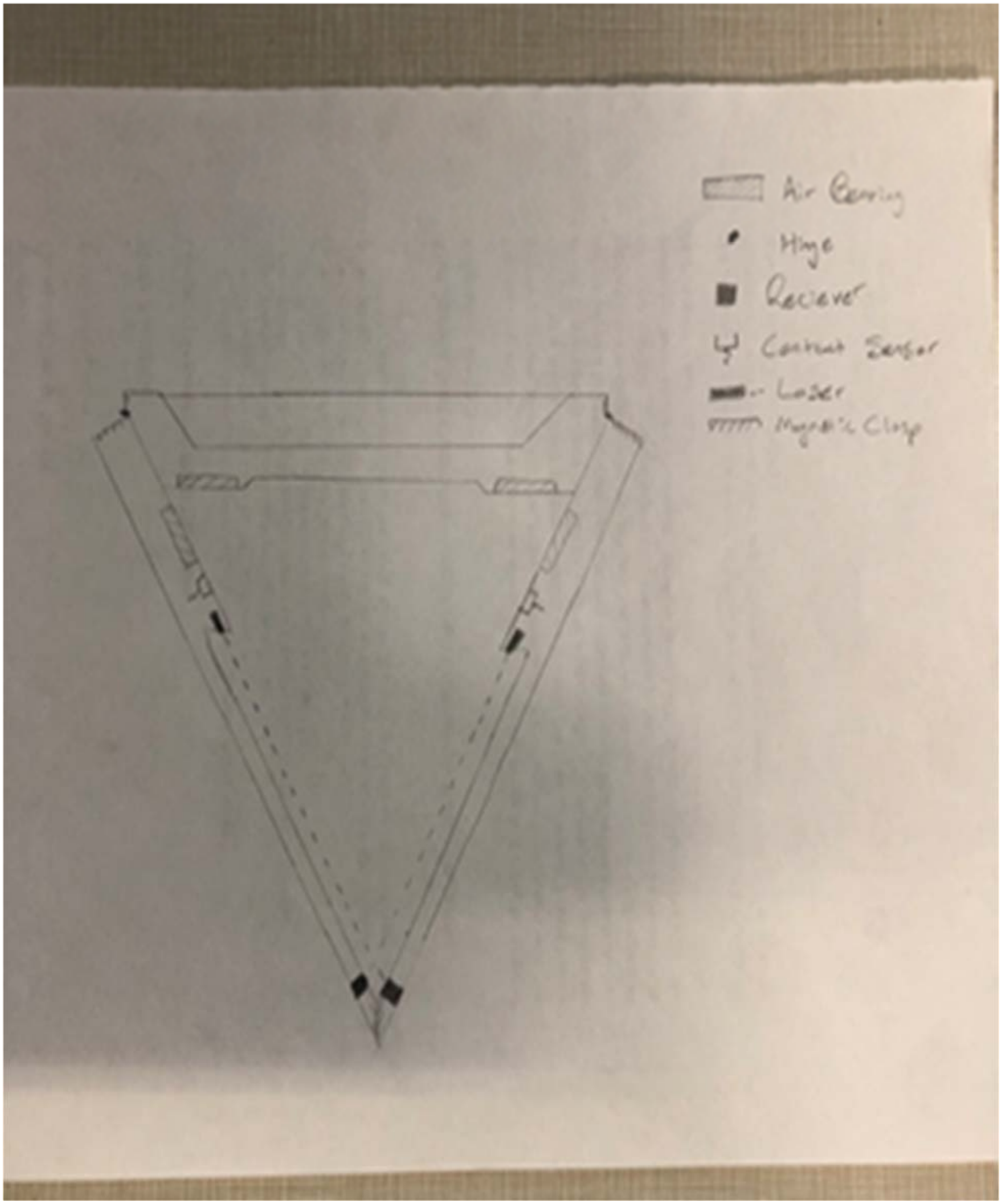

Figure 3: Greg Philips designs III

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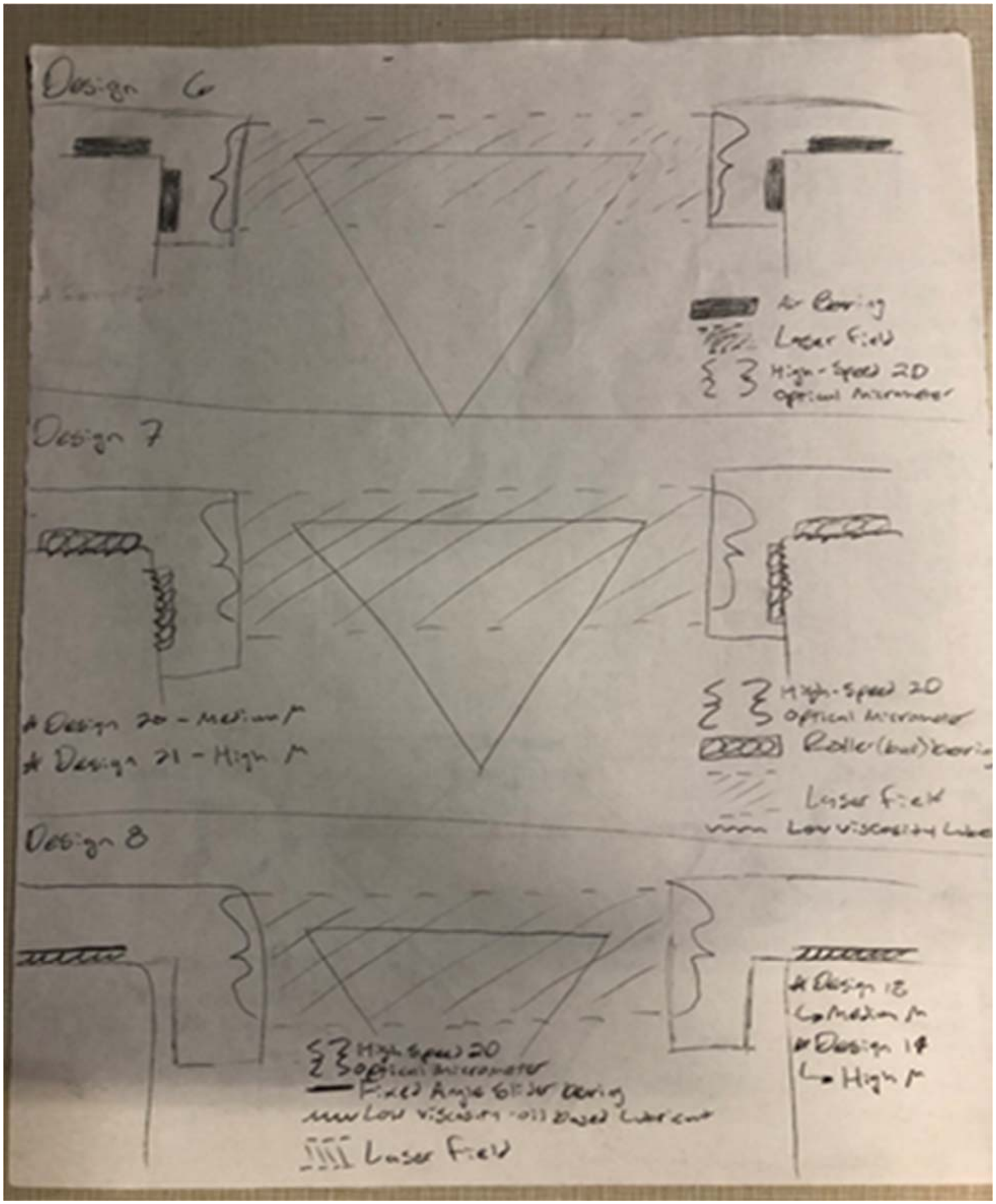

Figure 4: Greg Philips designs IV

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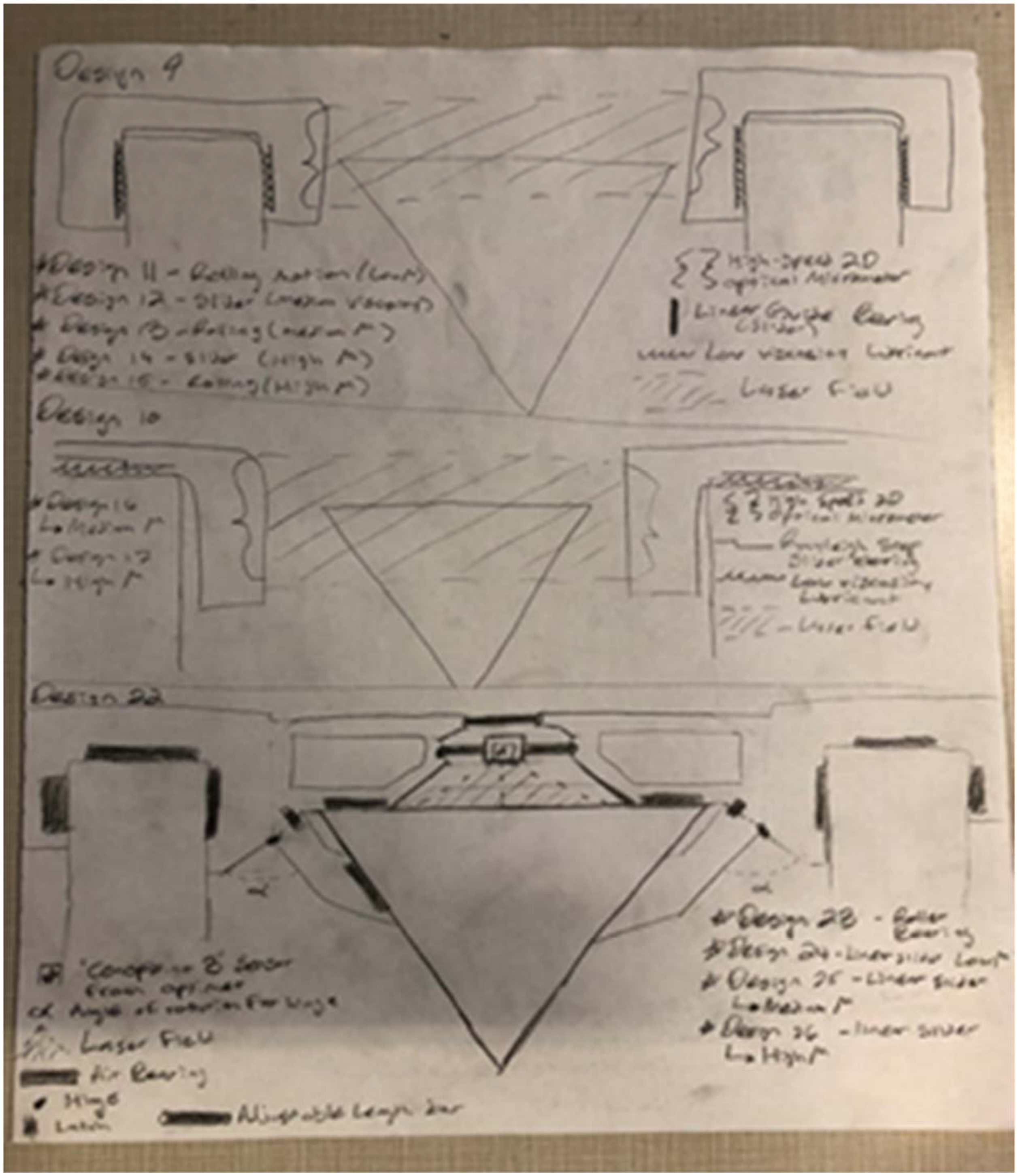

Figure 5: Greg Philips designs V

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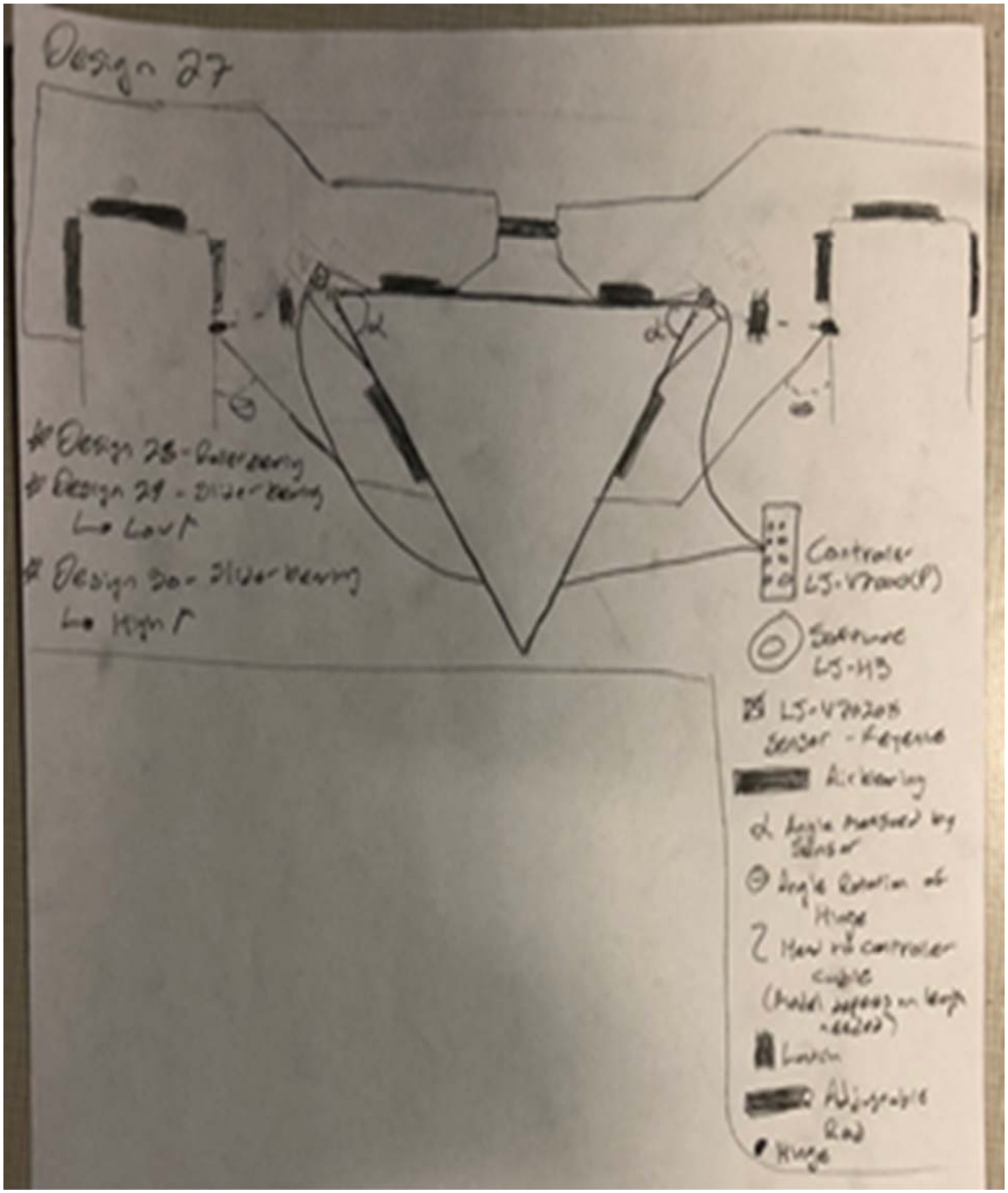

Figure 6: Greg Philips designs VI

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In addition to the 30 designs above by Greg, the Pugh chart below represents the analysis of 30 designs regarding the listed engineering criteria discussed in the design specifications section as a reference to design 6. Early in the design process, design 6 was viewed as a feasible design. Obviously, since then a very different approach has been taken to solving our given problem.

		Concepts																													
Engineering Criteria	Reference Concept	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Part must not be touched or moved; solution must be non-contact	6	-	-	-	-	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Parallelism must be within 25 micron: no point on either face must be out-of-parallelism by more than this tolerance.	6	s	-	-	-	s	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
No moving parts while performing key functions	6	-	-	-	-	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Adjustable to width of beam being measured	6	-	-	-	-	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Uses some form of non-contact linear displacement sensors	6	s	-	-	-	s	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Smoothest glide possible to reduce vibrations, and wear on side beams	6	+	+	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	+	-	-	-
Must be mounted to reduce room for error	6	s	s	s	s	s	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
# of Plusses		1	1	1	1	1	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	7	6	6	6	6	7	6	6	6
# of Minuses		3	5	5	5	3	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	0	1	1	1

Figure 7: Greg Philips Pugh chart

Like the issues that Greg Phillips faced with concept and design generation, many of the designs made by Yanchen Liu roughly displayed in the images below, simply do not work given the constraints given to the group prior to the creation of these designs. Fortunately, this issue mainly just applies to design 15, 16, 21, & 23-26. This being said, many of the designs below theoretically make more sense given our known constraints. However, most of the errors below are not feasible due to issues such as cost. For example, designs 2, 6, 7, 9-13, 17, 20, & 27-29 utilize sensors or optical measurement tools that are extremely expensive. After further research, it was established by the group that there are far cheaper options that theoretically should work as well as these options or even better in some ways. Cost is also an issue for designs 4, 5, 8 & 14 due to the fact that they utilize more than one sensor. It would be ideal to use more than one sensor as you could take multiple measurements of the triangle. This would indeed speed up the production process, but most likely not enough to make additional sensors worth it as they can be extremely expensive each. Further problems with the designs below stem from theoretical or practicality issues, despite the fact they do not violate the constraints of the previous designs. For design 1, despite the fact that this may work, it simply does not makes sense to only take measurements are the endpoints of the beam when data can be recorded for the entire length of the beam in the same amount of time. Referencing design 10, this design simply would not work with.

This is so because it has been established that a non-contact linear displacement sensor that utilizes a triangular beam would be ideal. This being said, in order to take accurate measurements, this triangulated beam needs to be perfectly perpendicular to the face of the triangular beam at which it is taking measurements. The further the angle strays from 90 degrees, the less accurate the measurements will be. Following the analysis of the early stage designs discussed above, this leaves designs 18, 19, & 22 as potentially valid solutions.

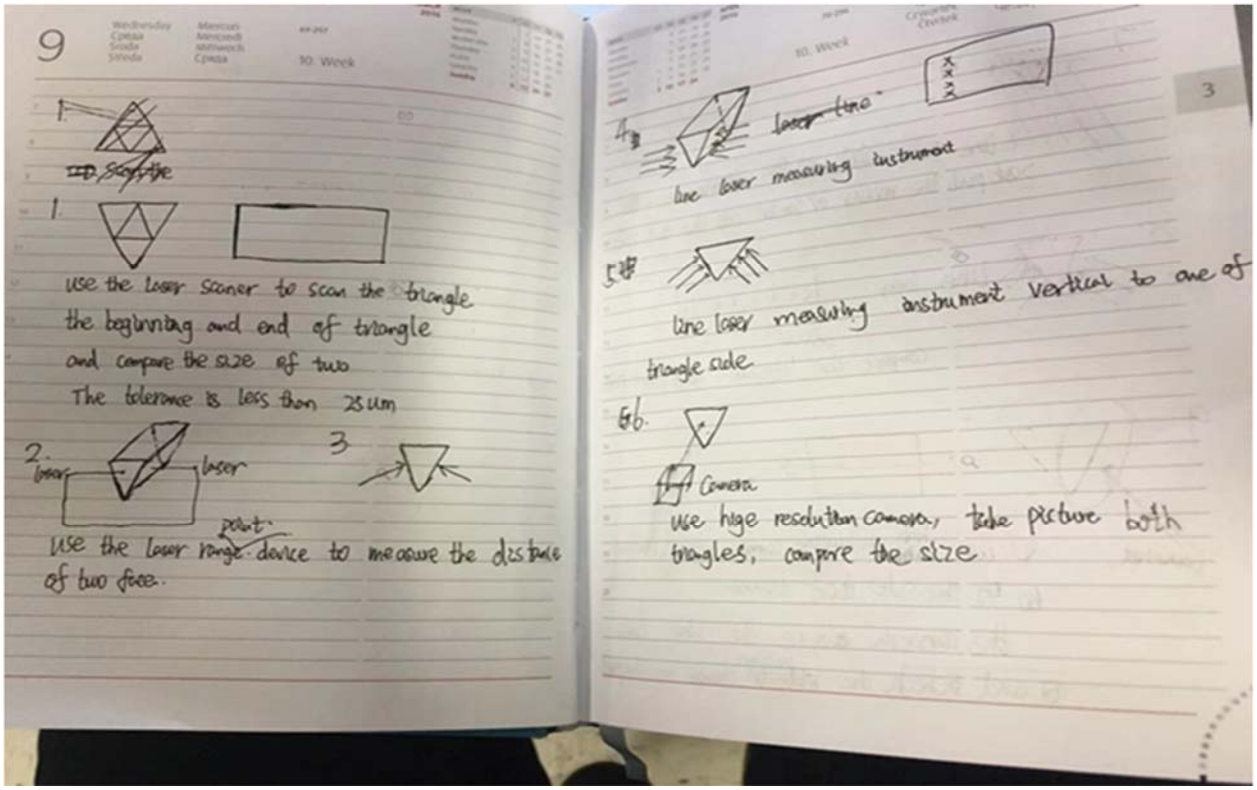

Figure 8: Yanchen Liu designs I

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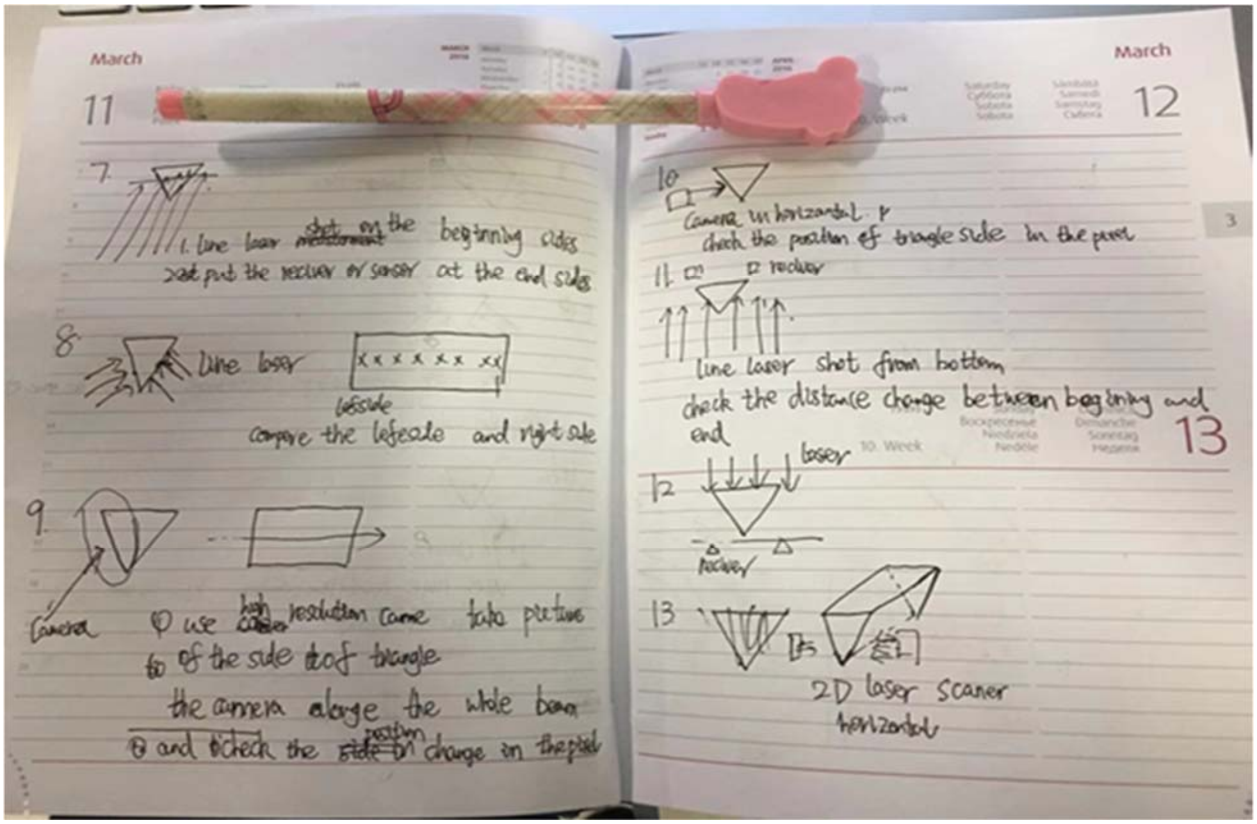

Figure 9: Yanchen Liu designs II

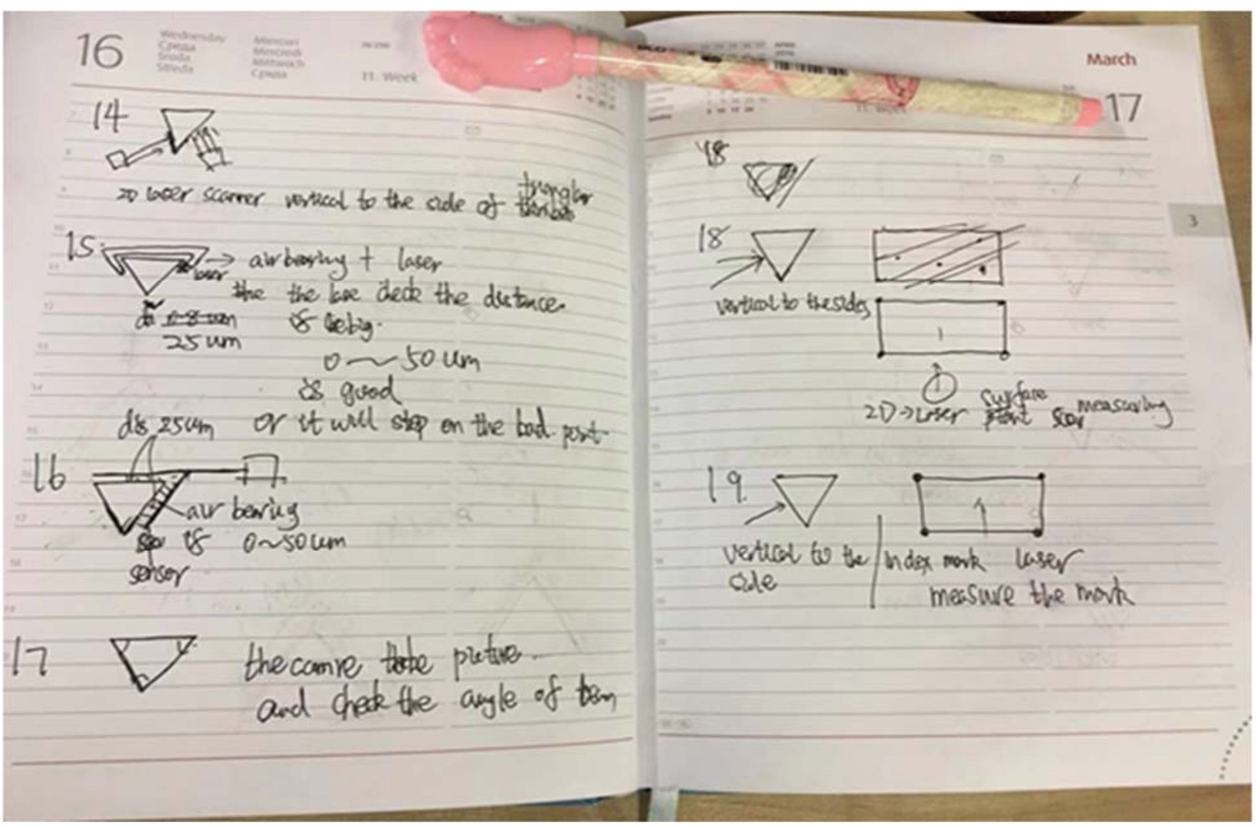

Figure 10: Yanchen Liu designs III

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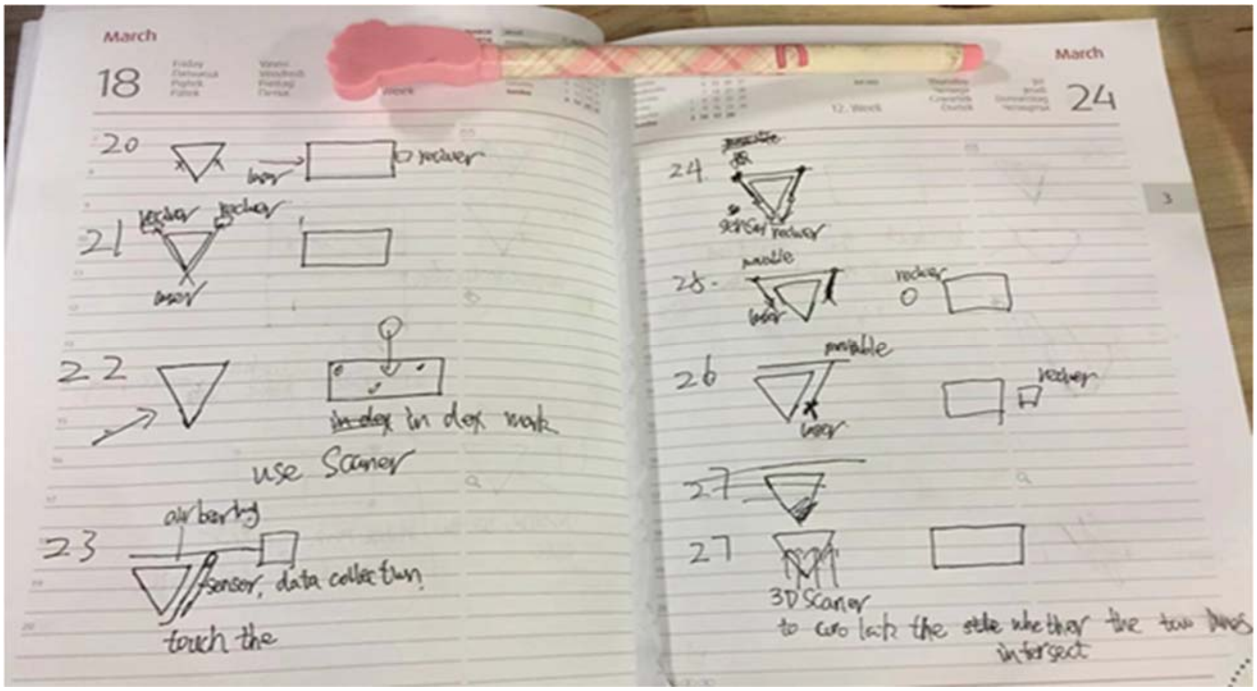

Figure 11: Yanchen Liu designs IV

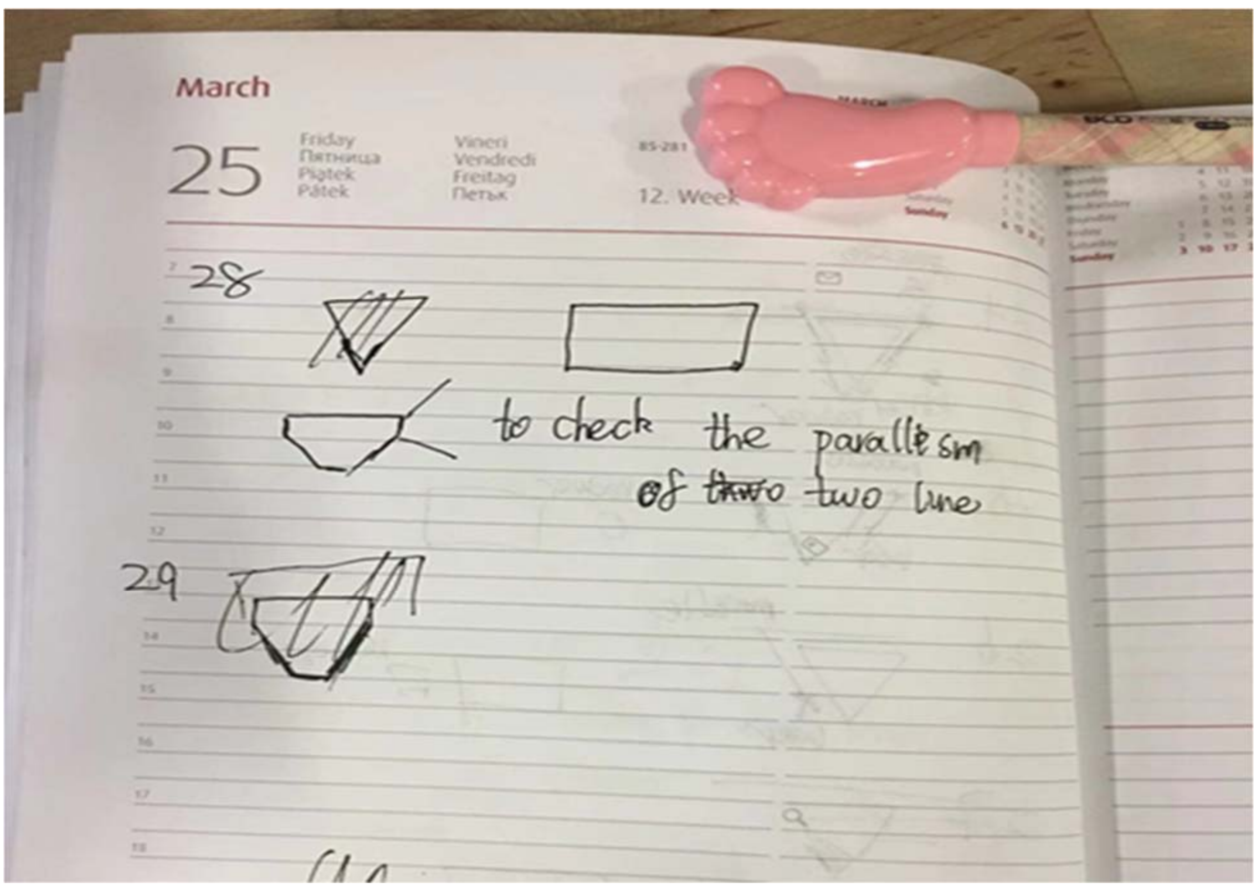

Figure 12: Yanchen Liu designs V

Below is the Pugh chart used to analyze and compare Yanchen's 30 designs to the listed engineering constraints. As stated in the previous section, this analysis was made prior to key information regarding the direction of this project. This being said, design 16 was taken as the reference design. This design contains many of the same features to that of the designs discussed in the previous section, and for the same reason this design is not valid. A true reference design would have been design 18, 19, or 22.

		Concepts																													
Engineering Criteria	Reference Concept	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Mass		5	5	5	5	5	3	4	5	3	3	5	5	3	3	3		4	5	5	4	4	4	4	5	5	5	5	5	4	4
Time to operate		5	5	5	4	4	4	5	5	4	5	5	5	4	4	4		4	4	5	5	4	3	3	5	5	4	5	3	5	3
Cost		5	5	5	4	4	3	5	5	4	5	5	5	4	4	4		4	4	5	5	4	4	4	3	5	5	5	5	5	3
Power consumption		5	5	4	4	4	4	5	5	5	5	5	5	4	4	4		4	5	5	5	5	4	5	4	4	5	4	5	4	3
Noise		2	2	2	4	4	4	3	3	5	5	3	4	4	5	4		3	4	4	3	5	5	5	5	5	5	5	5	4	4
Mess		2	2	2	3	3	3	2	2	5	3	2	4	4	5	4		2	4	5	2	5	5	3	3	4	4	4	3	4	4
Versatility		2	2	2	2	2	2	2	3	2	2	3	3	3	2	2		2	2	5	4	4	4	2	5	3	3	4	2	4	5
Main tenance reqs		4	4	4	2	2	2	3	2	2	2	4	2	3	3	3		4	4	5	4	3	3	3	3	4	4	4	5	4	5
Repeatability		4	4	4	4	4	4	4	3	4	4	3	3	3	4	4		4	4	3	3	3	3	3	4	4	4	4	4	5	5
# of Plusses	5 is good																														
# of Minuses	0 is bad																														

Figure 13: Yanchen Liu Pugh chart

When it came to early stage designs, Byron Sullivan elected to pursue a slightly different path than that of the rest of the group. Fortunately, many of the designs below represent the relative idea that we as a group have decided to pursue. Byron chose a fairly simplistic approach, which in this case should work quite well for our purposes. Most of the designs roughly depicted below more or less represent the same principal. There are very minor differences, however, these minor differences determine whether an idea is valid or not. For example, although the designs would certainly work as needed, the issue comes from cost. Designs 1-24 and 26 all utilize more than one sensor, which as discussed, is not needed. Our required function only requires one sensor to operate; any more sensors could be considered a luxury. This being said, the design below that schemes to be ideal for our purposes is design 25. Design 25 utilizes a one-dimensional laser mounted to the milling machine. Design 25 is the simplest as well as most likely the base and which this project shall be built upon. There is quite a bit of room to grow with this design. For example, the sensor that at the end of the day is chosen could end up being a two-dimensional laser.

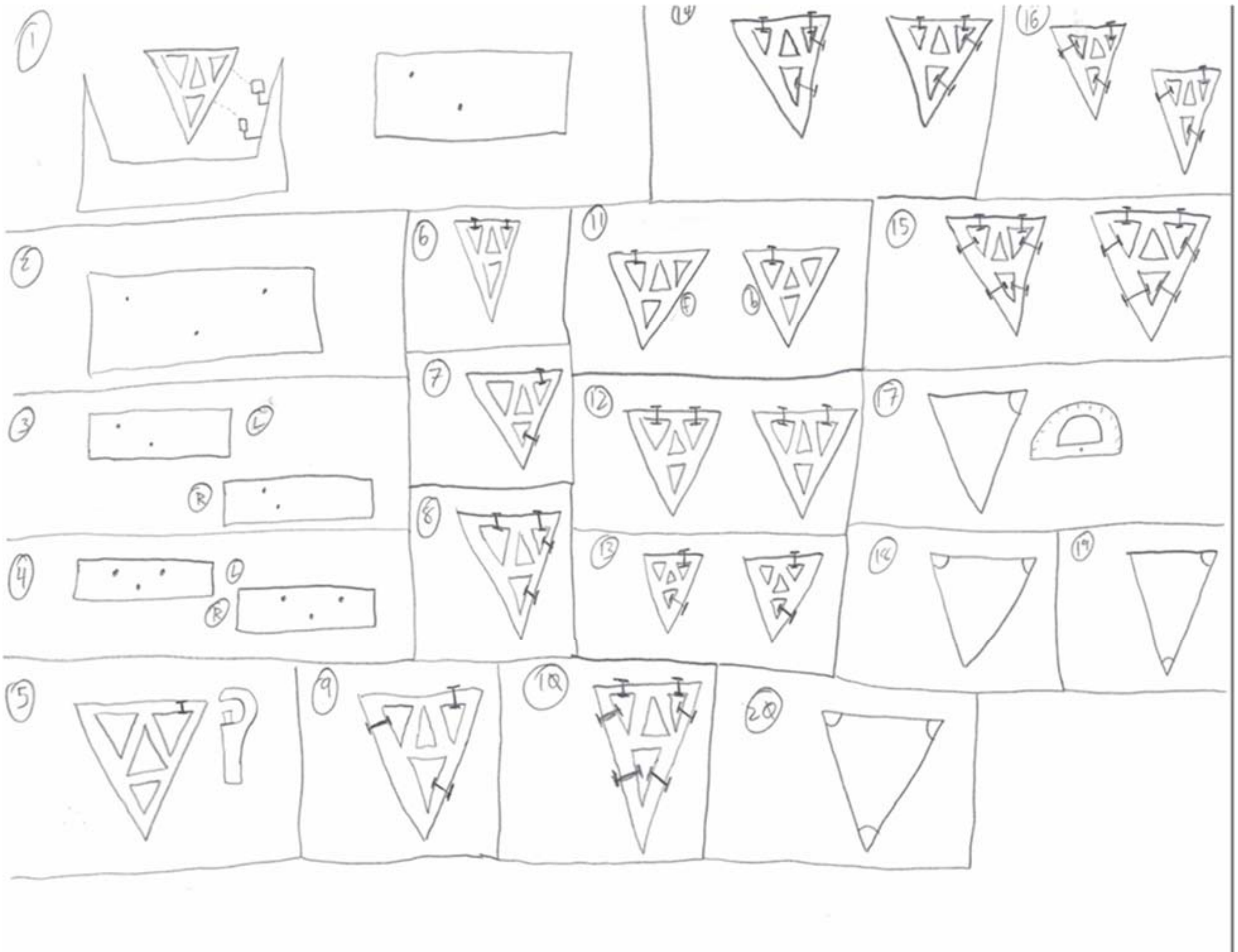

Figure 14: Byron Sullivan designs I

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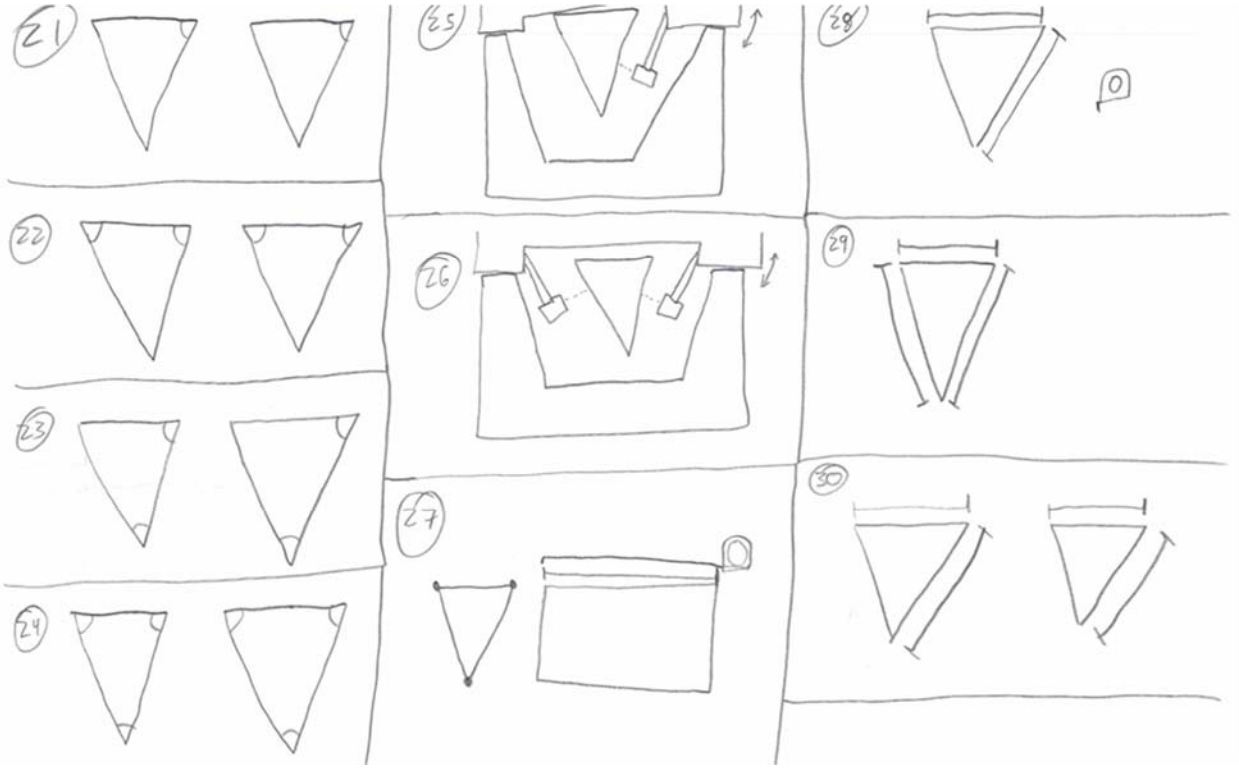

Figure 15: Byron Sullivan designs II

As well as observing the 30 images above, one can gather a further understanding of the comparative analysis of these designs by observing the Pugh Chart below. This chart represents a comparison of these 30 designs by Byron against the listed engineering criteria. Designs 25 as well as the datums discussed above are used as a reference.

		Concepts																												
Engineering Criteria	Ref	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	26	27	28	29	30
Mass	DATUM	-	-	-	-													+	+	+	+	+	+	+	+	-				
Time to Operate						-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-
Cost		-	-	-	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	+	+	+	+
Power Consumption		-	-	-	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	+	+	+	+
Noise																														
Mess																														
Versatility		+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
Maintenance Reqs		-	-	-	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	+	+	+	+
Repeatability		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
# of Plusses		1	1	1	1	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	1	3	3	3	3
# of Minuses		5	5	5	5	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	5	3	3	3	3

Figure 16: Byron Sullivan Pugh chart

6 QFD

We as a group performed a QFD analysis comparing the five designs that we considered to be best. We compared various areas of importance such as mess created, time to operate, power consumption, noise, mass, versatility, maintenance requirements, and most importantly, repeatability. These quality characteristics were compared against the engineering constraints given by Hexagon as well as by discussion with Mr. Singh. Following the analysis that can be observed via the QFD chart below, it was determined that the single horizontal sensor as well as the Conopoint 3 Glider proved to be superior to the rest. Following progression through research and discussion with Mr. Singh, it was established that the Conopoint 3 Glider was not suitable for this project for various reasons discussed in previous sections. This leaves the single horizontal sensor as the lone superior design. However, this design compared to our current progress was a very primitive design, that with quite a bit of work evolved into our current design. A design with which should theoretically improve Hexagon's overall production process regarding this product for the Global S.

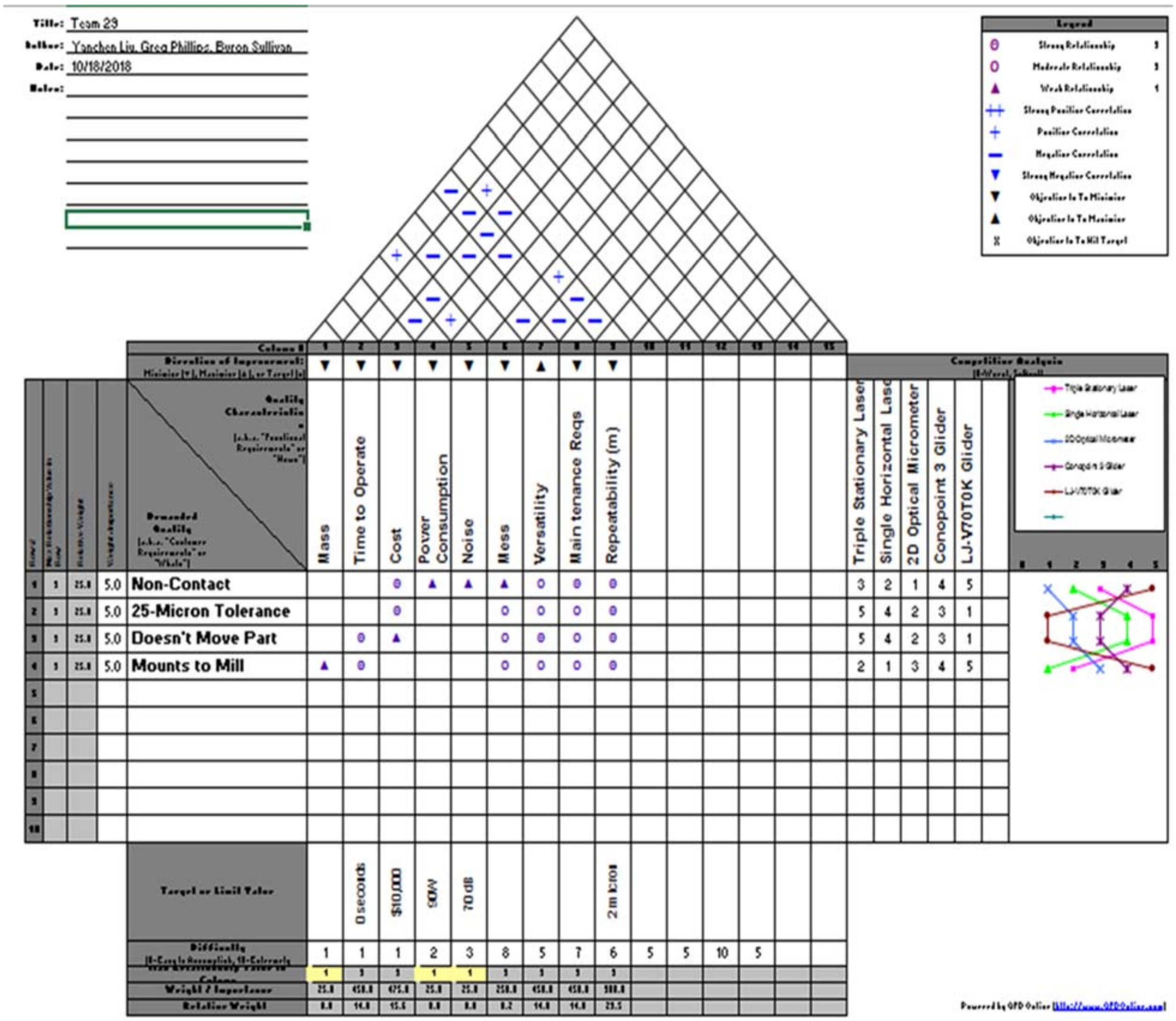

Figure 17: Project QFD analysis

7 Design for X

When it came to design of this product, functionality was at the forefront. Functionality outweighed everything including cost. Since this product's sole purpose is ensuring the validity of the triangular aluminum beam down to a micron level tolerance, accuracy and repeatability were extremely important to us. It was very important that before anything else, these key functions were met and done correctly. Due to the limited need for production of our product, this allows Hexagon to value the quality of this product more so than if this product was going to be mass produced. There is only a limited amount of production simply since our product performs a function very specific to the manufacturing of this triangular beam. Another key quality that we focused on with this design was versatility. Because we did not want to install this mount into Hexagon's mill permanently, at least as of right now, we chose a mounting solution that did not require any permanent changes to their current set up; as well as the fact that this mount can be adjusted to accommodate triangular beams of various sizes. This is possible because we as a group elected to utilize rare earth magnets. These magnets are installed into the upper portion of the mount and is attached to a steel beam inside the mill. This triangular beam runs perpendicularly between the guide rails in which the mill slides upon an air bearing track. These guide rails are a known parallel to us. Therefore, we can assume that if our mount is firmly attached to this perpendicular steel beam, then it is evident that sensor will glide perfectly along this known parallel. Once the sensor is known to be following perfectly path, then determinations can be made about whether the required tolerances of the beam are met as needed. With all, this project was very much designed with functionality at the forefront. Other factors such as environmental impact, manufacturability, and safety, for the most part, were not considered to be relevant for our application.

8 Product Specific Details and Analysis

Our project is quite unique because it does not simply fall under the product design category. Our product is designed with the goal of improving Hexagon's current manufacturing process of this key axial component of their Global S CMM. This as well as the fact that this product was designed with and extremely specific purpose in mind, one that may indeed be solely applicable to Hexagon's needs, analyzing current markets for this product quite difficult. In fact, there really isn't a market at all. This design was created to verify a very specific set of tolerances. It was designed with an angular arm with the purpose of getting the sensor as close to subject as possible due to the limited 5mm to 10mm range of the Omega sensor. It was designed to line the sensor up perpendicularly to the subject and is designed to glide along our known parallel. In addition, to achieve these measurements, we are utilizing the technologies of an inductive displacement sensor. This is quite different from other sensors and specializes this product for this role even more since inductive sensors are only capable of working with a metallic subject. This is so because inductive sensors output measurements of displacement by analyzing any changes in amplitude and phases created within the electric field that is subsequently created between the metal surface of the beam and the sensor itself. However, there is indeed a market for developing a product, that in this case, should theoretically improve Hexagon's production process of this part with regards to both money and time saved, as well as a reduction in terms of waste due to the theoretical removal of imperfect triangular beams from production. If a beam is found to be imperfect following the completion of its milling process, it is then scrapped. This is of course a rather inefficient process that has much room for us to improve it. The implementation of this sensor mount into production should theoretically verify the linear displacement in terms of microns or angular skew down to the required tolerances. As stated in the previous section of this report, this design is also quite versatile. This will allow aluminum triangular beams of all necessary sizes to be milled within the desired tolerances which, of course, is quite important when it comes to saving money.

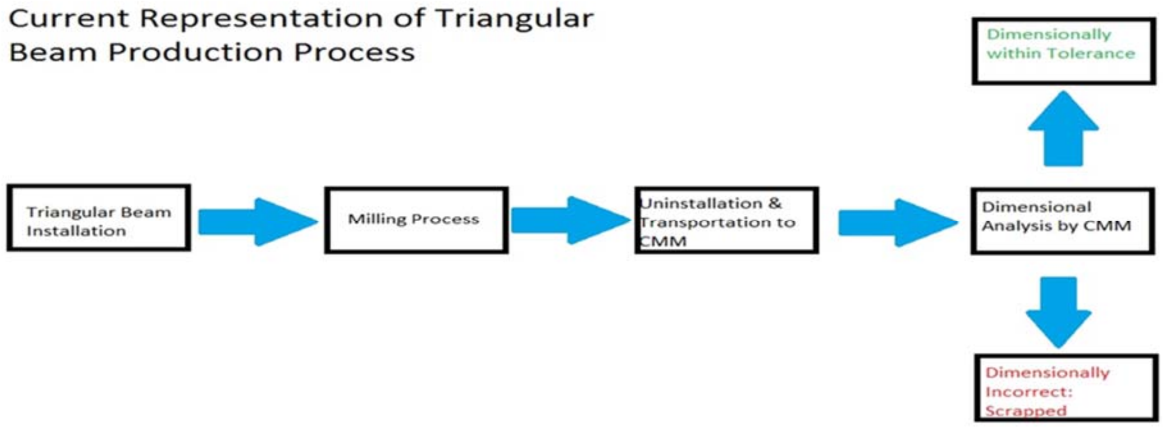

Figure 18: Current representation of triangular beam production process

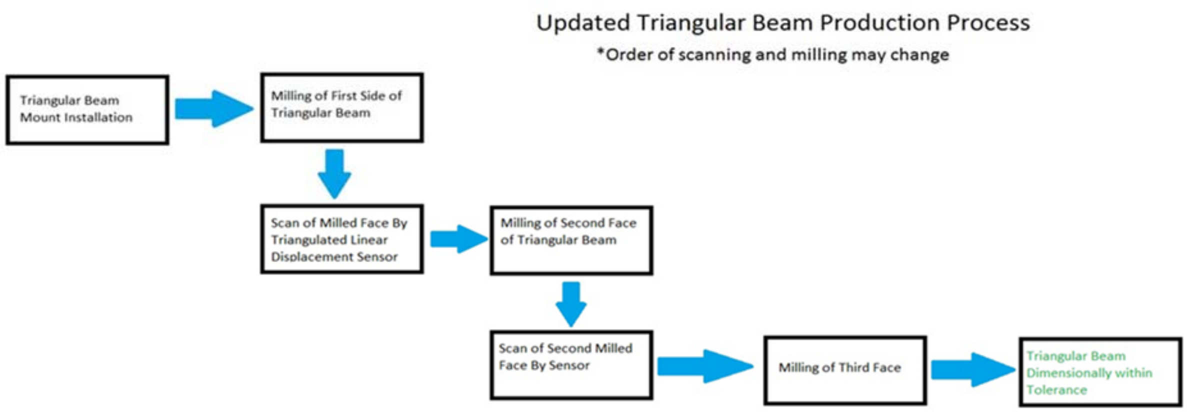

Figure 19: Updated triangular beam production process

9 Detailed Product Design and Redesign

When it came to the design of our product, there was no shortage of bumps in the road along the way. We went through countless designs and inevitably, countless redesigns to achieve our final design. Initially, we designed this mount as one piece of solid material to reduce vibration in the arm. Although the vibration due to motion is likely to be minimal because the mill glides along an air bearing track, there is still potential for there to be resulting "noise". The impact of any noise due to vibration has the potential to affect our data because we are measuring down to such a miniscule tolerance. Due to raw material constraints, we were forced to adapt our initial design to a two-piece arm which connects with the support of two steel bolts. We were unable to find a beam of raw aluminum or even Delrin for a reasonable price that suited our needs. As a result, we ordered 384 cubic inches of raw Delrin. After machining, we used about 157.78 cubic inches of this material to create our mount. This, unfortunately, is likely to result in an elevated amount of vibration. To compensate for this deficiency, in the future we hope for this product to be manufactured with enhancements in material quality, as well as we hope for it to be reverted to one solid arm rather than two. In addition to this change, our previous designs were forced to adapt from the triangulated linear displacement sensors that we researched for most of the year, to an inductive linear displacement sensor made by Omega. Not only did this alter the range of measurements in which we had to work with (it reduced it significantly), but it changed the way in which we planned to safely install this sensor to the arm itself. Finally, another way in which we upgraded our mount to achieve our final design was upgrading the rare earth magnets used to attach the mount to the milling machine. He significantly upgraded these magnets by a factor of about three in terms of attractive force. In addition to upgrading the strength of these magnets, we upgraded the number of magnets attached to the mount by one. Therefore, taking into the account of the added force per magnet, as well as the addition of an extra magnet, this mount is immensely more secure that it was in previous designs. Unfortunately, due to a variety of setbacks, we were not able to perform any true testing. Although we were able to project what our data should look like if this product works the way we project it to, we were never able to analyze the function of our product and improve upon it with a redesign. We had several redesigns along the way, unfortunately all those redesigns are adaptations that allow us to support newly given constraints, whether they be financially, or time based.

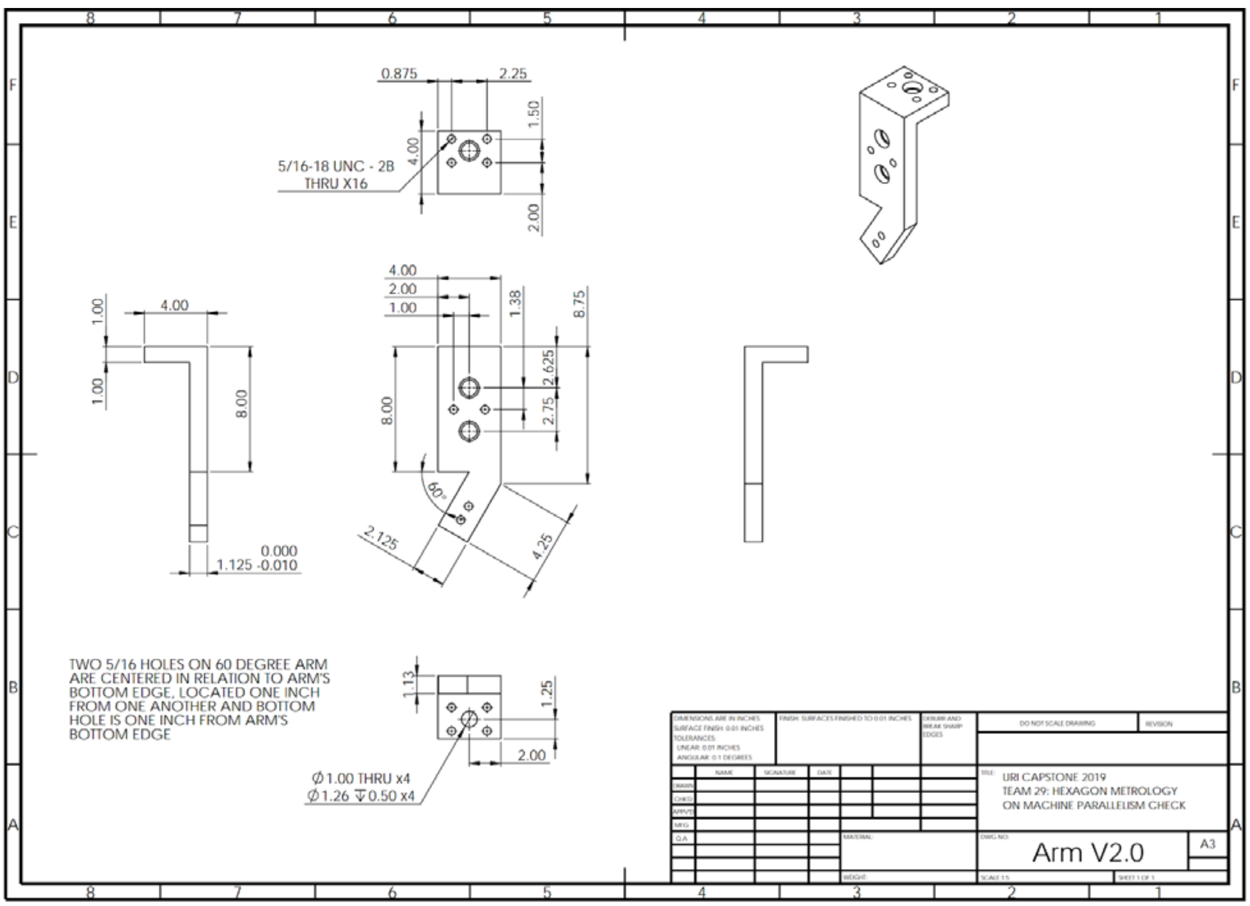

Figure 20: Final design (arm)

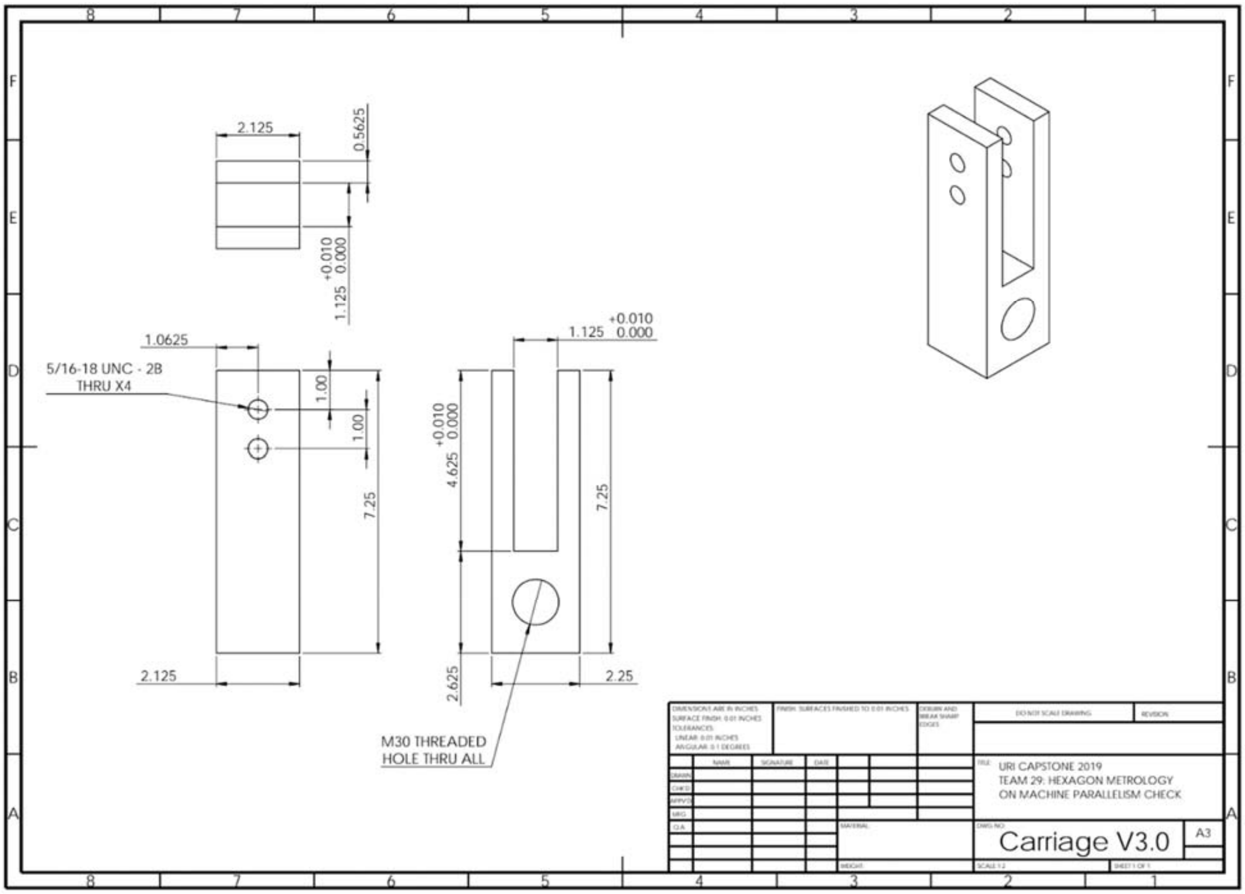

Figure 21: Final design (carriage)

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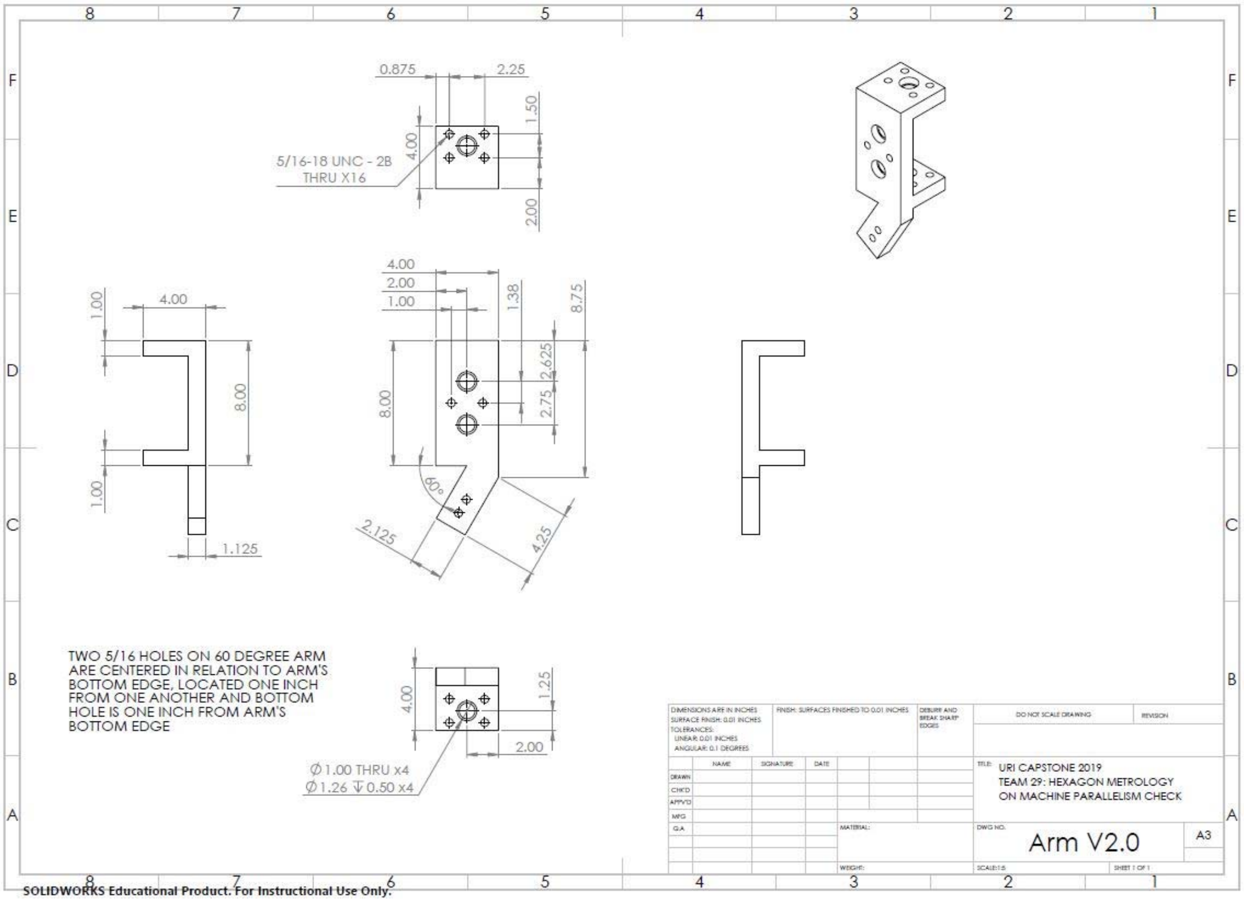

Figure 22: Mid second semester design (arm)

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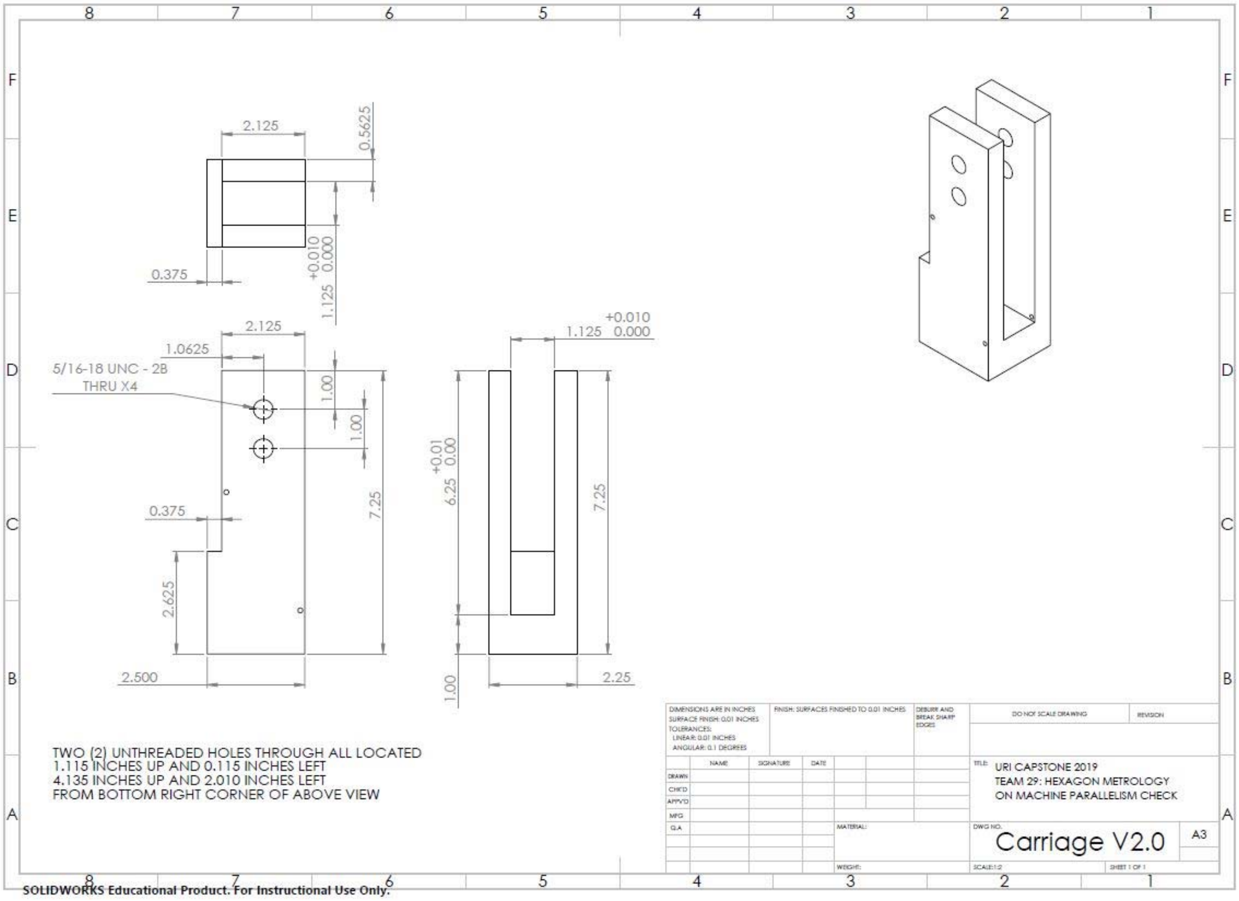

Figure 23: Mid second semester design (carriage)

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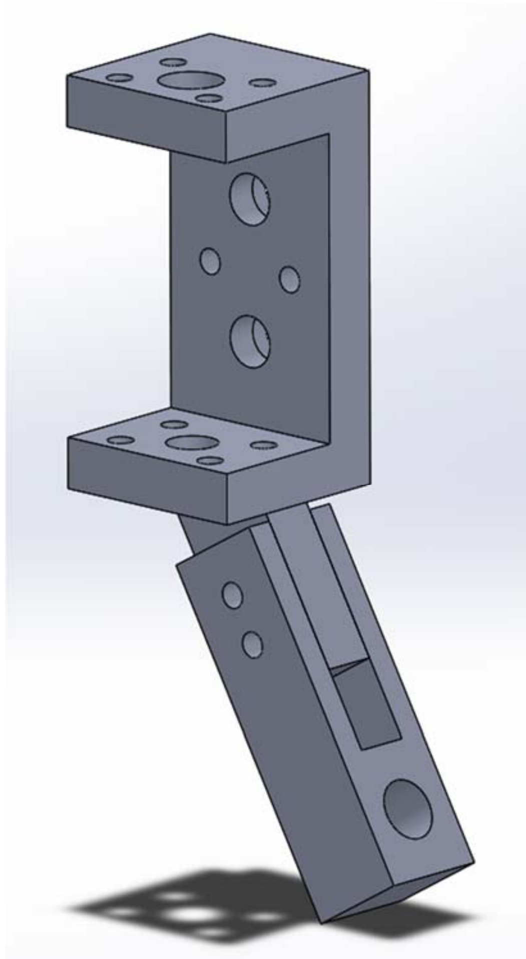

Figure 24: Final design model

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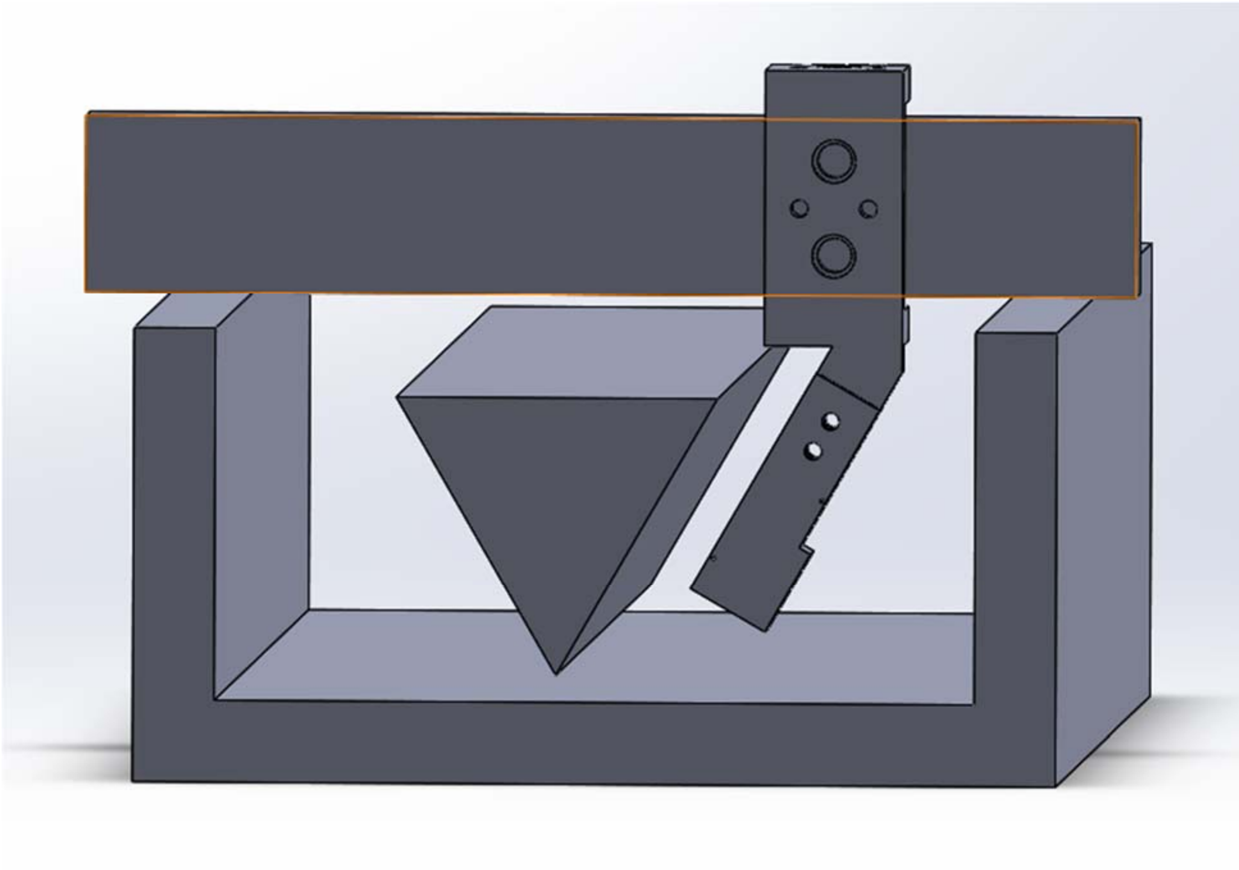

Figure 25: Sensor mount into milling machine

Figure 26: Omega LD701-5/10 Inductive Displacement Sensor

Omega Sensor Specifications	
Sensor Model	LD701-5/10
Range	5 mm to 10 mm
Repeatability	±10 µm
Linearity	±4%
Required Tolerances of Triangular Beam	
Max. Linear Deviation	25 µm
Surface Flatness	< 8 µm
Rare Earth Magnet Specifications	
Magnet Model	K&J DX48
Force (Case 1)	274.96 N
Force (Case 2)	401.23 N
Material	NdFeB Grade N42

Figure 27: Rare earth magnet triangular beam omega sensor specifications

#

Table 7: Bill of materials

BOM Level	Supplier	Product	Quantity	Unit of measure	Contact
0	Omega	LD701-5/10	1	Each	esales@omega.com
1	K&J Magnetics, Inc.	Earth rare magnets	5	Each	contactus@kjmagnetics.com
2	Dupont	Delrin	2/9	Cubic feet	www.privacy.dupont.com
3	Home depot	Bolts	2	Each	www.homedepot.com
4	Home depot	Nut	2	Each	www.homedepot.com

10 Engineering Analysis

Because of our simplistic design, there was little engineering analysis needed for our design. Our primary concern, which will be addressed in the testing phase, is the potential for vibrations in the customer's setup. However, the customer has addressed this by making sure the entire mill is already safe from vibration while it is milled.

Because of the lighter weight in using Delrin and the light weight of the sensor, bending and vibration will have little effect on the data produced. Additionally, because of the high-powered magnets used to fasten the product to the customer's mill, it is a safe bet that the product will not be moving.

11 Build/Manufacture

To manufacture our product, we needed to choose a material that was inexpensive, durable, strong and simple to machine. We chose Delrin, an acetyl resin made by Dupont. We started with a large specimen and cut away material using a band saw. We then used a Bridgeport drill press to mill away further material more precisely. We were provided these tools by URI in the Kirk building. We also had the advantage of assistance from the professional machinists who work in that building for URI.

We intended to make our Delrin-based product with a CNC machine, but none of our team members had any professional experience on the machine and the professionals in Kirk's workshop didn't have time available for us.

We made the product using the drawings (shown in our design binder) which we designed in SolidWorks. We hope that in another version, a professional may be able to make this product in a CNC setup using aluminum so the device will match our designs more exactly. Ideally, this is how our product might be mass-produced, if it came to that.

12 Testing

We were unable to complete testing on our product. We did not receive the supplemental hardware we needed to make the product operational for the customer. When this comes in, we would like to accomplish the testing we have planned, which will be outlined below.

The inductive sensor included in our product will produce data on linear displacement. This data will be collected at regular time intervals (1 sample every 0.1 seconds) as the product conducts verifies the placement of the customer's specimen in their mill. This data will be put out through the Omega meter and into a computer for collection. The data will resemble a normal distribution like the one below.

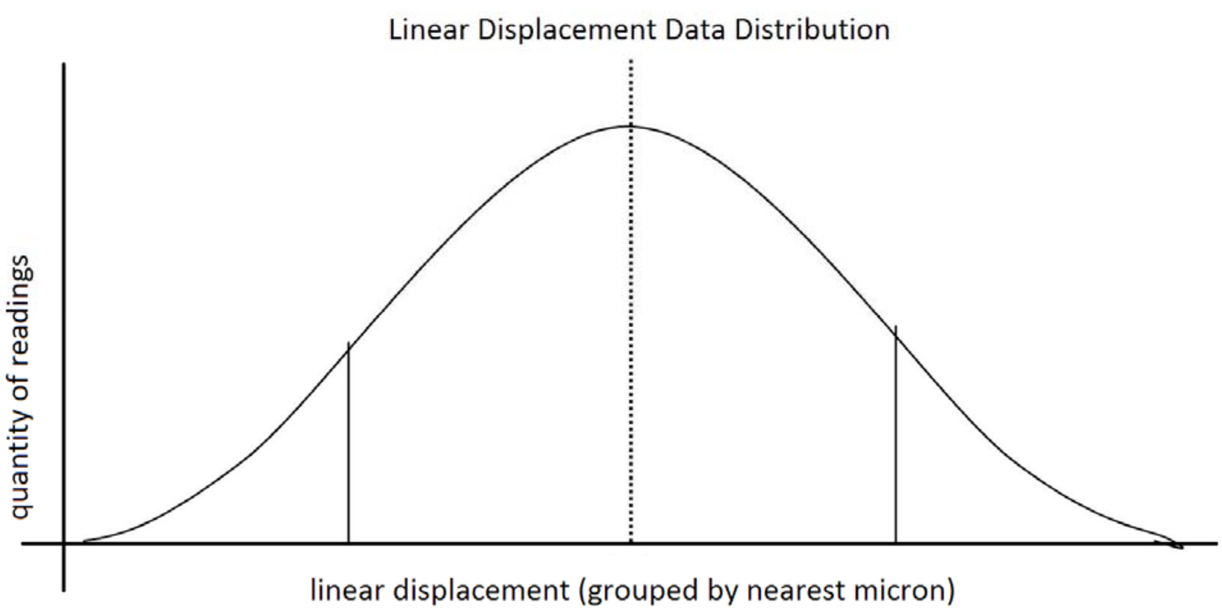

Figure 28: Sample linear displacement distribution

Normal distributions like the one above have associated values for Standard Deviation which quantify the spread of the data that define them. The higher the value of standard deviation, the more variant the data. In this case, we hypothesize our data should have a standard deviation of about 4 micrometers. This means 95.4% of all data collected in each trial will be within 16 micrometers of the average. This would be within the customer's specifications.

	A	B	C	D	E
1		What to Test?	Test Parameters	Results	Planned Resolutions (if needed)
2	Sensor bolts	Are they secure after a measurement?	Must remain tight		Thread lock
3	Mount	Does it stay in location?	Magnets must be strong enough to keep product secure		Additional magnets
4	Data	How close is data to true?	Must have reasonable Standard Deviation		Additional security/vibration ctrl
5	Cabling	Does the cabling stay out of the way?	Cabling must not be pinched or obstruct normal mill use		Cable guides
6	Data	Does the data come in a useful format?	Data must be shown as normal distribution with SD info		MATLAB programming, serial cable

Figure 29: Test matrix

13 Project Planning

ID	Task Name	Duration	Start	Finish
1	Watch Presentations I	1 day	Tue 9/11/18	Tue 9/11/18
2	Watch Presentations II	1 day	Thu 9/13/18	Thu 9/13/18
3	Patent Search	7 days	Mon 9/24/18	Tue 10/2/18
4	Meet with Sponsor I	1 day	Tue 9/25/18	Tue 9/25/18
5	Brainstorm Designs	17 days	Wed 9/26/18	Thu 10/18/18
6	Week 4 Progress Report	3 days	Thu 9/27/18	Mon 10/1/18
7	Decide on an Idea	23 days	Thu 10/18/18	Mon 11/19/18
8	Week 5 Progress Report	3 days	Thu 10/4/18	Mon 10/8/18
9	Literature Search	6 days	Thu 10/4/18	Thu 10/11/18
10	PDS First Draft	6 days	Thu 10/4/18	Thu 10/11/18
11	Concept Generation and Analysis	8 days	Tue 10/9/18	Thu 10/18/18
12	Meet with Sponsor II	1 day	Thu 10/11/18	Thu 10/11/18
13	Week 6 Progress Report	3 days	Sun 10/14/18	Tue 10/16/18
14	QFD Assignment	5 days	Sun 10/14/18	Thu 10/18/18
15	Week 7 Progress Report	3 days	Thu 10/18/18	Mon 10/22/18
16	Meet with Sponsor III	1 day	Thu 10/25/18	Thu 10/25/18
17	Week 8 Progress Report	3 days	Thu 10/25/18	Mon 10/29/18
18	Week 9 Progress Report	3 days	Thu 11/1/18	Mon 11/5/18
19	Meet with Acuity Reseller	1 day	Mon 11/5/18	Mon 11/5/18
20	Borrow Acuity Sensor	9 days	Mon 11/5/18	Thu 11/15/18
21	Binder and Journal Review	1 day	Tue 11/6/18	Tue 11/6/18
22	Week 10 Progress Report	3 days	Thu 11/8/18	Mon 11/12/18
23	Meet with Keyence Reseller	1 day	Thu 11/15/18	Thu 11/15/18
24	Week 11 Progress Report	3 days	Thu 11/15/18	Mon 11/19/18
25	Begin 3D Printing for PoC	9 days	Mon 11/19/18	Thu 11/29/18
26	Week 12 Progress Report	3 days	Thu 11/29/18	Mon 12/3/18
27	Borrow Acuity Sensor II	7 days	Thu 11/29/18	Fri 12/7/18
28	Proof of Concept Presentation	1 day	Tue 12/4/18	Tue 12/4/18
29	Week 13 Progress Report	3 days	Thu 12/6/18	Mon 12/10/18
30	Semester 1 Final Report	1 day	Tue 12/18/18	Tue 12/18/18
31	Meet With Sponsor IV	1 day	Fri 2/1/19	Fri 2/1/19
32	Develop final product (rev 1)	11 days	Sat 2/2/19	Fri 2/15/19
33	Week 14 Progress Report	1 day	Mon 2/4/19	Mon 2/4/19
34	Week 15 Progress Report	1 day	Mon 2/11/19	Mon 2/11/19
35	Meet With Sponsor V	1 day	Fri 2/15/19	Fri 2/15/19
36	Sponsor buys sensor	6 days	Fri 2/15/19	Fri 2/22/19
37	Group orders material	6 days	Fri 2/15/19	Fri 2/22/19
38	Week 16 Progress Report	1 day	Mon 2/18/19	Mon 2/18/19
39	Material arrives	1 day	Mon 2/25/19	Mon 2/25/19
40	Week 17 Progress Report	1 day	Mon 2/25/19	Mon 2/25/19
41	Rough Cuts	2 days	Wed 2/27/19	Thu 2/28/19
42	Meet With Sponsor VI	1 day	Fri 3/1/19	Fri 3/1/19
43	Week 18 Progress Report	1 day	Mon 3/4/19	Mon 3/4/19
44	Redesign for use with inductive sensor	1 day	Wed 3/6/19	Wed 3/6/19
45	CNC Machining	7 days	Thu 3/7/19	Fri 3/15/19
46	Week 19 Progress Report	1 day	Mon 3/18/19	Mon 3/18/19
47	Begin manual machining	12 days	Tue 3/19/19	Wed 4/3/19
48	Week 20 Progress Report	1 day	Mon 3/25/19	Mon 3/25/19
49	Build Test Review	1 day	Fri 3/29/19	Fri 3/29/19
50	Week 21 Progress Report	1 day	Mon 4/1/19	Mon 4/1/19
51	Meet With Sponsor VII	1 day	Wed 4/3/19	Wed 4/3/19
52	Poster and brochure design	13 days	Wed 4/3/19	Fri 4/19/19
53	Design testing process	10 days	Mon 4/8/19	Fri 4/19/19
54	Finish final machining steps	1 day	Fri 4/12/19	Fri 4/12/19
55	Paint	1 day	Wed 4/17/19	Wed 4/17/19
56	Final Presentation	1 day	Fri 4/19/19	Fri 4/19/19
57	Showcase	1 day	Fri 4/26/19	Fri 4/26/19
58	Final Report	1 day	Mon 5/6/19	Mon 5/6/19

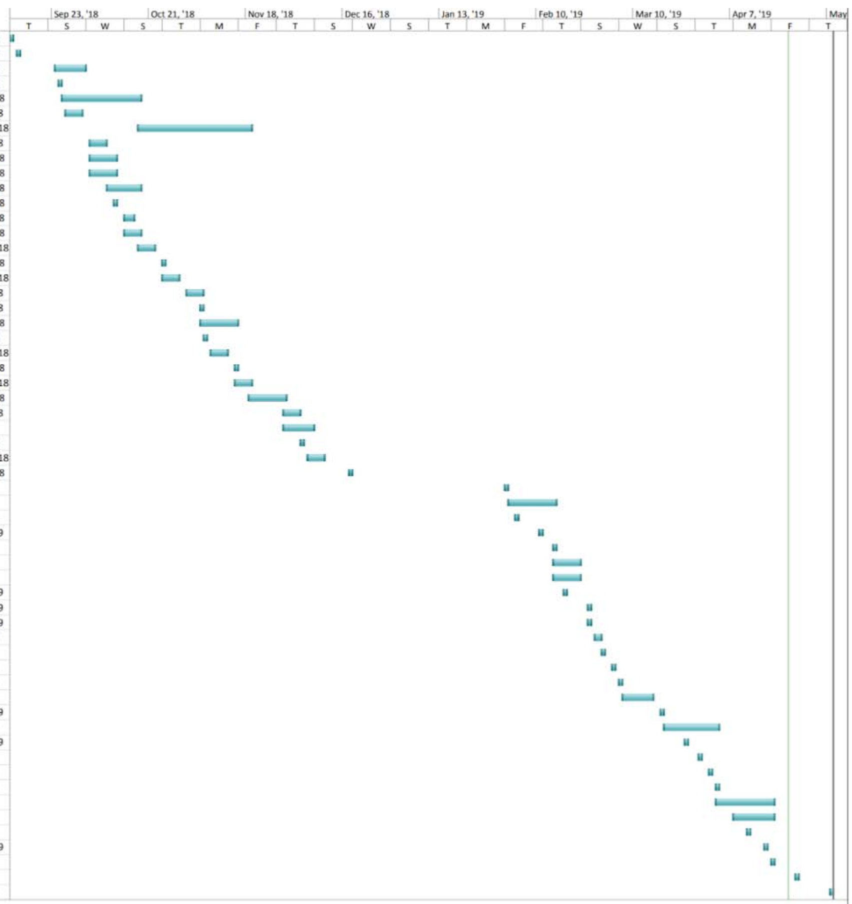

Figure 30: Project timeline

The Gantt chart shows entire project plan from September 2018 to May 2019. From chart, it is almost once of every two weeks to meet with Hexagon sponsor Gurpreet Singh. Gurpreet Singh gave us a lot of help during the project. At the beginning of February 2019, the support arm is be consider designing and displacement sensors need to be purchased to do the test. Since the type of sensor is not determined because of some complicated reasons, our team spent plenty of time to design the holder of sensor. Each of team members designed 3 models to prepare most type of sensor. After 3D model of support was be determined, the material of the support is be considering to be purchased. Our team got troubles to determine and order the materials. After discussing with Gurpreet Singh and Prof. B. Nassersharif, the Delrin and earth rare magnet can be our products to be machined. The most important and interesting time is working on material machining. The workers from workshop in Kirk Hall help us a lot for material machining. There are some problems to machine the holes on the top surface with the drilling machine, but it can be processed by CNC. The bigger issue for the project is the displacement sensor. Since Omega don't have ready-made inductive sensor, we only got sensor and cable without a meter. We cannot do the test on time. But the project is completed about 70%.

14 Financial Analysis

The below table and pie chart show the cost of the project. The total cost of the project is 8995$ and the most expensive item is labor fee. The Omega sensor and the materials of Delrin and earth rare magnets are cheaper than we expected. The sensor is 655$, Delrin is 330$, Magnets is 20$. Therefore, if the labor fee is removed, the total cost of sensor and material for sensor' support is around 1000$. So, in terms of cost, our project is very cheap.

Table 8: Financial analysis

	Hours	Cost
3 undergraduate students ($20 per hour)	100 hrs.	6000$
Sponsor ($60 per hour)	15 hrs.	900$
Schneider machine shop (40$ per hour)	15 hrs.	600$
Raise3D Printer (4$ per hour)	60 hrs.	240$
Computer and Software (SolidWorks, Abaqus, $5 per hour)	30 hrs.	150$
Omega inductive sensor	-	655$
Delrin	-	330$
Magnets	-	20$
Others	-	100$
Total		8995$

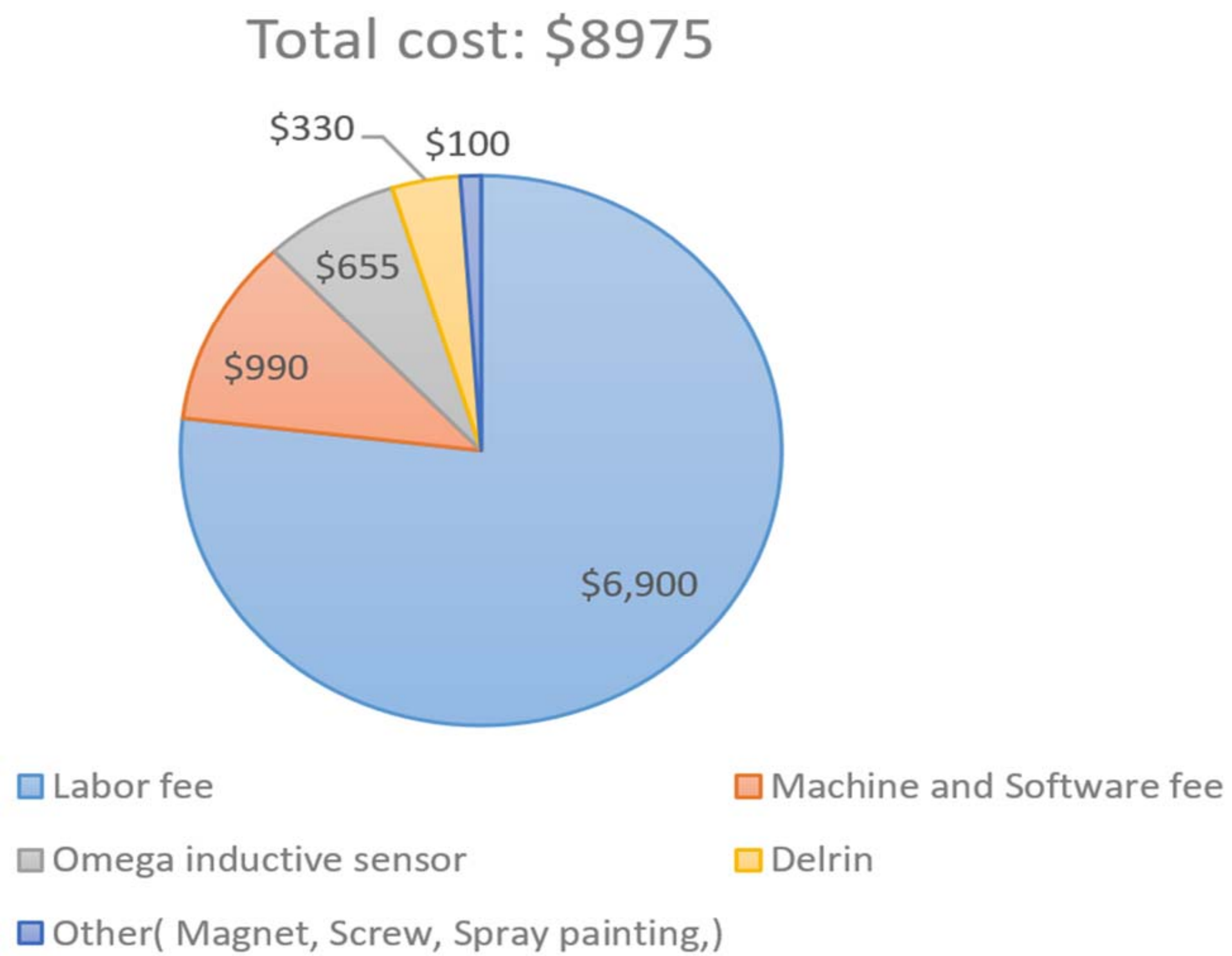

Figure 31: Financial analysis

15 Operation

The setup and operation of displacement sensor is simple and efficient. First is to mill first surface, it will be served as the reference after milling. Assume that first surface is horizontally and flatness. Then rotating the triangular beam and do the measurement. Turning on the sensor and just the distance between the sensor than the surface of beam within 5mm-10mm and the sensor must be perpendicular to beam surface. Then sliding the glider with sensor to measure the displacement of first surface. The data shows on meter. If the maximum and minimum difference displayed by the sensor is within 25 microns, then the position of rotated beam is correct, and the triangular beam can continue to be processed. If it is bigger than 25 microns, it means the position of rotated beam need to be adjusted. It is same principle for second and third face. During the milling process, the sensor should be turned off and be protected by cover or be moved from the machine. It is also very easy to take the sensor down from milling machine if it is necessary. The operator only needs give the right force to take it down.

16 Maintenance

The main product of our project is Omega LD701-5/10 inductive sensor. The Omega company already have maintenance for the senor. Therefore, we need to consider the rest parts, for example the magnets and the support of sensor. Both could may out or break. Consider the magnets at a cheap price, 5 magnets for 20$, our team will support “free change” for magnets in 2 years. But for the support of sensor, we will carry out a free return repair in 1 year. Our assessment of the life of our product is 5 years.

17 Additional Considerations

Our product will have a positive economic impact for our customer in that it will save man-hours, machine-hours, electricity and time on production deadlines.

Our product will have no societal or political impact.

Our product will have no ethical considerations.

Our product will improve safety because there will be less activity by personnel carrying the customer’s specimen.

Our product will have a positive impact on the environment because it will save electricity as it is used over the old process Hexagon used.

18 Conclusions

Over the course of the past of the two semesters, on behalf of the three of us in Group 29, it has been a pleasure and a great experience overall working on this project. This has sufficiently introduced and acquainted us with all facets of the design process whether it be for the design of a product, or the design of a process. We had the unique opportunity of working on a project that aimed to develop a product with the goal of optimizing a specific portion of a production process. We had the rare opportunity of working on a project that has the potential to noticeably impact the overall efficiency of the production of this critical axial component of Hexagon’s Global S CMM. After countless hours of design, and inevitably redesign, with no shortage of obstacles along the way, we believe our resulting product to be a success. We believe that with a few tweaks along with a subsequently enhanced budget, this product has the potential to be seamlessly implemented into Hexagon’s current production process. Theoretically this design should improve this process in terms of money and time saved along with a severe reduction in waste or scrap aluminum. We, as a group, are very happy with what we have achieved and only wish we had the opportunity to see our product in action. We would also like to thank Dr. Bahram Nassersharif as well as Hexagon’s Senior Engineer Mr. Gurpreet Singh for their much-needed advice, mentorship, and support along the way. With all, we believe our project to be a success and hope to someday see a form of our project implemented into production and utilized to its maximum potential!

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