Mechanized Ball Bar Fixture

Hexagon Manufacturing Intelligence

Team 19 - Team Heptagon

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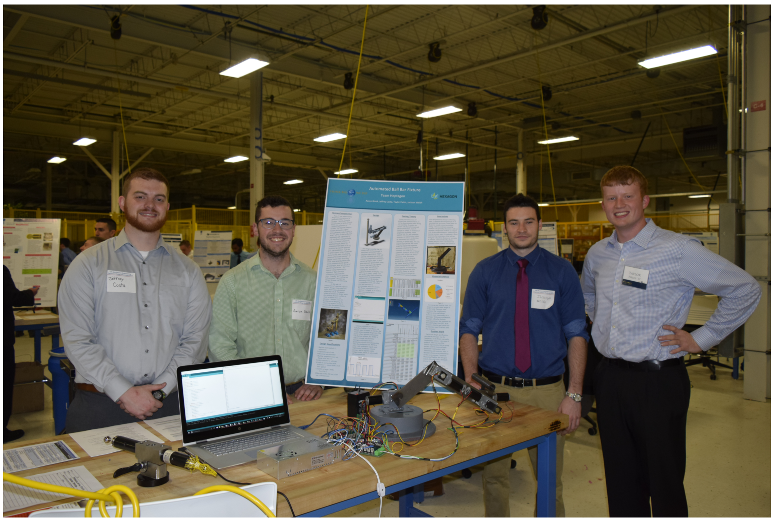

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Abstract

Team nineteen was partnered with Hexagon Manufacturing Intelligence and tasked with the assignment of automating a ball bar fixture used in error mapping of coordinate measurement machines. This design report outlines the processes employed during the design by the team, with the long term goal of creating a functional prototype of the product. This semester work was done in conceptual design and analysis to meet the design specifications developed by Hexagon and Team 19. The culmination of this semesters work is presented in a Proof of concept, with the intent of fabrication and manufacture, along with redesign and optimization being completed in the coming semester.

Error mapping is a process employed in the calibration of CMMs. This process is done by placing a Bar Ball in 12 different positions within the measurable volume of the CMM and taking a measurements on the surface of each Ball. The center of each ball is calculated along with the length distance between centers. Analysis is done of the change in measured length of the Bar Ball in each position and an error map is created to offset the known errors. By utilizing this process CMMs can be accurate to less one micron.

The problem faced by Hexagon is that currently this error mapping process must be done by hand which leads to a very labor intensive process. The Bar Ball must be moved into placed, then measurements taken manually with the CMM. Hexagon has charged Team 19 with creating a solution to this problem by automating the process. The goal of this project is to create a machine that can placed within the CMM, and after initial set up, can carry out the entire error mapping process without any human interaction.

The design solution proposed by Team 19 is a four degree of freedom robotic manipulator. Three linkages with rotation at both the base of the machine and the center of the affixed Bar Ball provide access to all 12 of the required positions. The machine will utilize worm gear driven, DC motors in order to actuate each DOF of the manipulator, and will be controlled with an Arduino Mega AVR development microcontroller. The control software will be integrated into the system and work in tandem with the CMM control software PC-DMIS in order to completely automate the placement and measurement of the Bar Ball in the error mapping process.

Table of Contents

Abbreviations

CMM	Coordinate Measuring Machine
DOF	Degree of Freedom
RPM	Revolutions Per Minute
USPTO	United States Patent and Trademark Office

List of Tables

List of Figures

1 Introduction

A coordinate measuring machine, or CMM for short, is a device that is utilized to measure geometric contours of a physical object in three dimensional space. This is possible by a sensitive probe tip contacting the desired specimen and recording it in reference to a predefined coordinate system. This predefined coordinate system is imperative for accurate readings; that is why the calibration for these systems is a significant component to this process. At the final step of the manufacturing process of the CMM, the accuracy of the machines is improved by mapping the geometric errors in the machines and apply software error compensation. To collect this process data on the machines a so-called ball bar device is used.

This ball bar device consists of two precision spheres separated by a bar. By measuring both spheres using the machine's probing system the CMM software can calculate the sphere centers as well as the distance between the spheres. Measuring the ball bar in different orientations and locations in the CMM's measuring volume will generally yield different results for the calculated lengths. Differences obtained from measuring very specific combinations of the ball bar orientations are used to check and adjust the skew/squareness of the machine that the CMM's firmware uses to correct the measuring results.

This error mapping process requires the ball bar device to be oriented into twelve well defined positions. Currently this is a very labor intensive process where the operator is required to manually maneuver the device from one orientation to the next. Typically, the process is repeated multiple times in order to validate the results of any corrections made based on the initial data set. To save labor costs a highly automated measurement setup would prove to be beneficial.

1.1 Problem Definition

Team 19 was tasked with 'automating' the existing process. As one could imagine, manipulating this fixture into 12 different orientations and probing each ball multiple times, is a tedious task. A mechanized feature to execute this process would save a great amount of time, money, and effort. Currently there is little to none research done on this subject to the extent of Team 19's knowledge; however, we were asked to continue prior work completed by a previous Capstone group.

In the 2010 - 2011 school year this same project was presented to another team. Unfortunately this team was unable to complete the project due to machining issues. The team created a very complex design in Solid Works without considering what will have to be done to machine this part. The biggest issue with the previous team's design was heat. The motors used to maneuver the arm were quite large and generated a lot of heat. This heat generation was causing thermal expansion of the aluminum members of the arm, which caused significant error.

1.2 Standards/Requirements

Hexagon Metrology established the following requirements that must be achieved in order for success.

1. The Mechanical manipulator shall be able to orient itself into 12 predefined positions accurately and reliably.
2. It shall be motorized.
3. It shall not cause the ball bar temperature to change significantly.
4. It shall lock into position automatically.
5. It shall be stable in each position.
6. It shall be controlled by application software.
7. It shall be easily scalable as to accommodate different machines

Figure 1.1: Global A Coordinate Measuring Machine

2 Project Plan

A detailed project plan is a necessity for this project. As required by this course, a Microsoft project plan (figure 2.1) is used to illustrate a Gantt chart, to keep track of milestones, as well as, highlight past and future endeavors. This micro-soft project plan was specifically oriented as to accommodate each of our schedules, allowing us to plan our meetings which occurred every Tuesday and Thursday. Team 19 found that Microsoft project planner was a useful asset in completion to this project and sought to utilize and update the plan weekly. Even through every break and vacation there were tasks that could be completed remotely; and a detailed plan assisted with meeting our deadlines.

2.1 Research

To begin, Team 19 needed to reconcile with Hexagon Metrology in order to further understand the Problem Definition and their time-line. As previously stated, project Heptagon is a continuation of a past capstone program; so Hexagon urged us to review their research and advance from there. In order to make the project more manage-able, certain tasks were separated and assigned to different group members. Each team member chose a certain aspect of the project where they would be most advantageous. Taylor Fields was in charge of test machining and coding; Aaron Binek was tasked with computer aided design and calculations; Jeff Costa was assigned with purchasing, project planning and communicating with Hexagon; and Jackson Welsh was assigned engineering analysis and Finite element simulation. After further research and first round testing, team 19 decided the motors would not conform to our requirements. This lead us to new worm-gear motors with less RPM however, with more precision and accuracy. This also lead us to update the CAD drawings, which would alter dramatically due to this minor change. The new motors would not fit properly in the former orientation. The second arm would have to accommodate two motors instead of one, where both motors would be mounted or bolted to the arm itself, however only one motor would be driving the arm.

2.2 Concept Generation

We decided to first tackle the greatest issue that the previous team discovered; thermal expansion. This eventually lead us to discuss the type of material for the ball-bar, the brand of motor to purchase, and the general contour of the fixture; which enabled us to finally construct a basis for our critical design concepts. The first major deadline was developing a detailed quality function deployment; which allowed us to narrow our focus as to accommodate Hexagon requirements and standards. From there we would generate our 30 concepts, and compare and contrast as to narrow our critical designs. The next deadline was the Critical design report; where the top 3 concepts were presented to the URI class of 2017 Mechanical Engineering student body, and thoroughly critiqued. Our three designs included; an XYZ planar table, a flamingo fixture, and an altered design from project pentagon. This was the final step in determining our ultimate Design.

2.3 Development

The preliminary design was in development. Main design software included Visual Basic, Arduino, Solidworks, Matlab, and Abaqus cae. Solidworks was the primary CAD software utilized on constructing a scale model for the preliminary design. To resolve thermal expansion and moment simulations, abaqus cae was integrated. To solve tedious calculations, matlab was implemented. While arduino, and Visual Basic were applied for the physical manipulation of the prototype. Our main design of focus was an adaptation of the previous groups preliminary model; with a substantial advancement in technology since the previous team in 2010, we are able to succeed where the previous team failed. From engineering analysis, we were able to determine that Invar was the superior material for the ball-bar; and from there we were capable to decide which motors would manipulate our fixture; while depositing a negligible amount of generated heat.

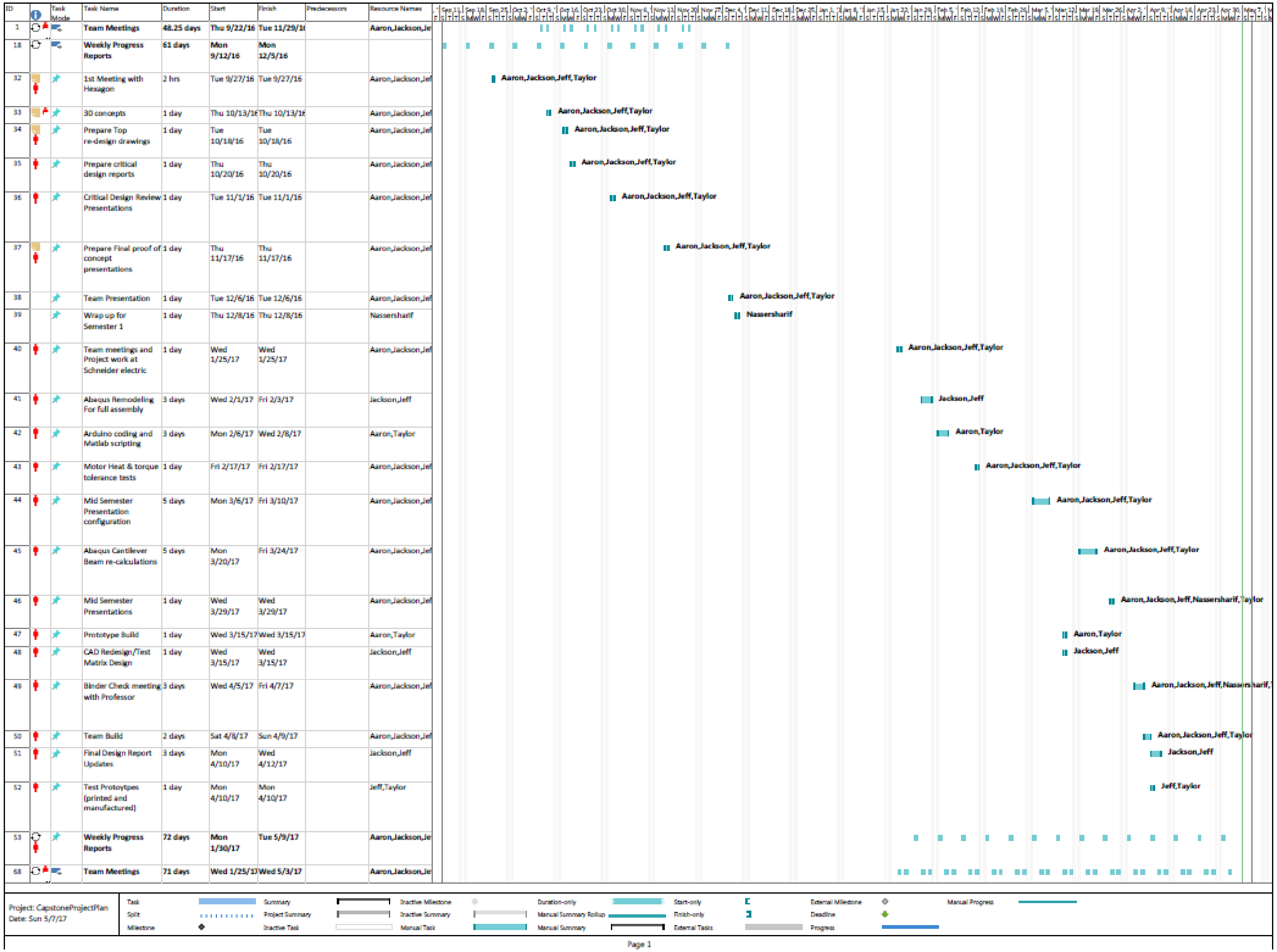
2.4 Testing

A three dimensional scale model of our fixture was manufactured and integrated with motors and Arduino/Visual Basic software. Since extreme precision is a requirement, absolute rotary encoders were implemented in order to determine exact positioning of our test arm. Direct current, wormgear, self-locking motors were utilized to stabilize the arm; fixing it in space when no current is applied. A 3-D printed PLA scale model was demonstrated, for lack of time and resources to machine metal; however, the affect was unchanged. Further Engineering analysis and finite element simulation will be performed in order to ensure that steel or aluminum will suffice as arms for the fixture.

2.5 Further Work

Overall the project resulted in a success. We managed to meet most of the design specifications that Hexagon desired. The priority goals that could be improved upon included, Scalability, and mass production. Hexagon Metrology requested that the ball-bar should be able to operate upon a full-range of their products that they export. This includes different sizes as well as, different orientations that the fixture has to meet. Team 19 chose to focus upon the most common product which was the smallest version coordinate measuring machine they produce. One way to integrate these two goals together is to focus upon mass producing the fixture, and then machining the parts according to the size and orientation they will be applied to. Overall, our Sponsor was satisfied with the results of the fixture

2.6 Microsoft Project



ID		Task Mode	Task Name	Duration	Start	Finish	Predecessors	Resource Names
1			**Team Meetings**	**48.25 days**	**Thu 9/22/16**	**Tue 11/29/1**		**Aaron,Jackson,Je**
18			**Weekly Progress Reports**	**61 days**	**Mon 9/12/16**	**Mon 12/5/16**		
32			1st Meeting with Hexagon	2 hrs	Tue 9/27/16	Tue 9/27/16		Aaron,Jackson,Jef
33			30 concepts	1 day	Thu 10/13/16	Thu 10/13/16		Aaron,Jackson,Jef
34			Prepare Top re-design drawings	1 day	Tue 10/18/16	Tue 10/18/16		Aaron,Jackson,Jef
35			Prepare critical design reports	1 day	Thu 10/20/16	Thu 10/20/16		Aaron,Jackson,Jef
36			Critical Design Review Presentations	1 day	Tue 11/1/16	Tue 11/1/16		Aaron,Jackson,Jef
37			Prepare Final proof of concept presentations	1 day	Thu 11/17/16	Thu 11/17/16		Aaron,Jackson,Jef
38			Team Presentation	1 day	Tue 12/6/16	Tue 12/6/16		Aaron,Jackson,Jef
39			Wrap up for Semester 1	1 day	Thu 12/8/16	Thu 12/8/16		Nassersharif
40			Team meetings and Project work at Schneider electric	1 day	Wed 1/25/17	Wed 1/25/17		Aaron,Jackson,Jef
41			Abaqus Remodeling For full assembly	3 days	Wed 2/1/17	Fri 2/3/17		Jackson,Jeff
42			Arduino coding and Matlab scripting	3 days	Mon 2/6/17	Wed 2/8/17		Aaron,Taylor
43			Motor Heat & torque tolerance tests	1 day	Fri 2/17/17	Fri 2/17/17		Aaron,Jackson,Jef
44			Mid Semester Presentation configuration	5 days	Mon 3/6/17	Fri 3/10/17		Aaron,Jackson,Jef
45			Abaqus Cantilever Beam re-calculations	5 days	Mon 3/20/17	Fri 3/24/17		Aaron,Jackson,Jef
46			Mid Semester Presentations	1 day	Wed 3/29/17	Wed 3/29/17		Aaron,Jackson,Jef
47			Prototype Build	1 day	Wed 3/15/17	Wed 3/15/17		Aaron,Taylor
48			CAD Redesign/Test Matrix Design	1 day	Wed 3/15/17	Wed 3/15/17		Jackson,Jeff
49			Binder Check meeting with Professor	3 days	Wed 4/5/17	Fri 4/7/17		Aaron,Jackson,Jef
50			Team Build	2 days	Sat 4/8/17	Sun 4/9/17		Aaron,Jackson,Jef
51			Final Design Report Updates	3 days	Mon 4/10/17	Wed 4/12/17		Jackson,Jeff
52			Test Prototypes (printed and manufactured)	1 day	Mon 4/10/17	Mon 4/10/17		Jeff,Taylor
53			**Weekly Progress Reports**	**72 days**	**Mon 1/30/17**	**Tue 5/9/17**		**Aaron,Jackson,Je**
68			**Team Meetings**	**71 days**	**Wed 1/25/17**	**Wed 5/3/17**		**Aaron,Jackson,Je**

Project: CapstoneProjectPlan
Date: Sun 5/7/17

Figure 2.1: Microsoft Project Plan

3 Financial Analysis

3.1 Cost Analysis

3.1.1 Time Analysis

As stated in section 1, the overall goal of this project is to reduce the human interaction and time required for this process. A study was performed to evaluate the projected efficiency of the new robotic ball bar.

The team spoke with the head of the calibration lab, Andrew Steeves, at Hexagon to discuss the current process of the Skew Square calibration. With the existing manual process the time required to perform the skew square calibration is an average of 45 minutes from set up to take down. Doing some further research into the calibration process is was determined that an average of 20 CMMs are calibrated per month.

Figure 3.1 is a graphical representation of table B.1 in Appendix B, plotting the current time to complete skew square calibration. The goal of this analysis was to determine the time that will be saved through the new automated ball bar that the team was tasked with designing. Figure 3.1 portrays the current time to perform the skew square calibration over a 12 month period. As one can see currently the process is taking on average 180 hours from a technician's day in order to complete this task.

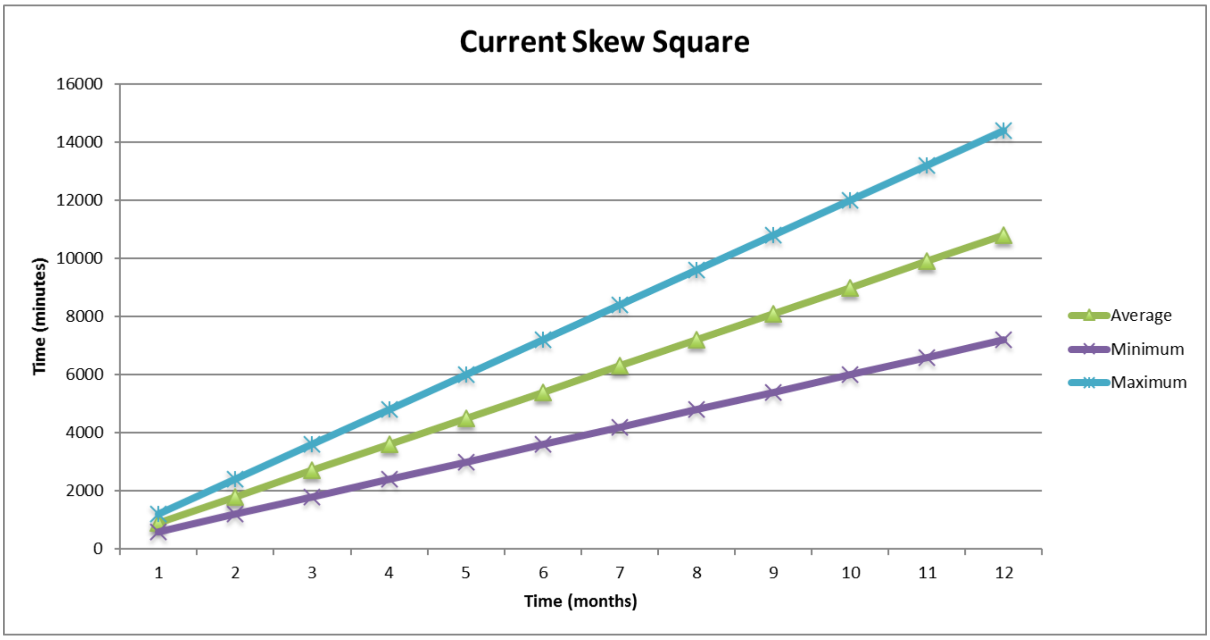


Figure 3.1: Time to perform current Skew Square Calibration process

Figure 3.2 is another graphical representation of table B.1 in Appendix B, however, this graph represents the automated section of table B.1. As we can see the automated process will save the company time and money over a 12 month period. It has been estimated that the new automated skew square process will save approximately

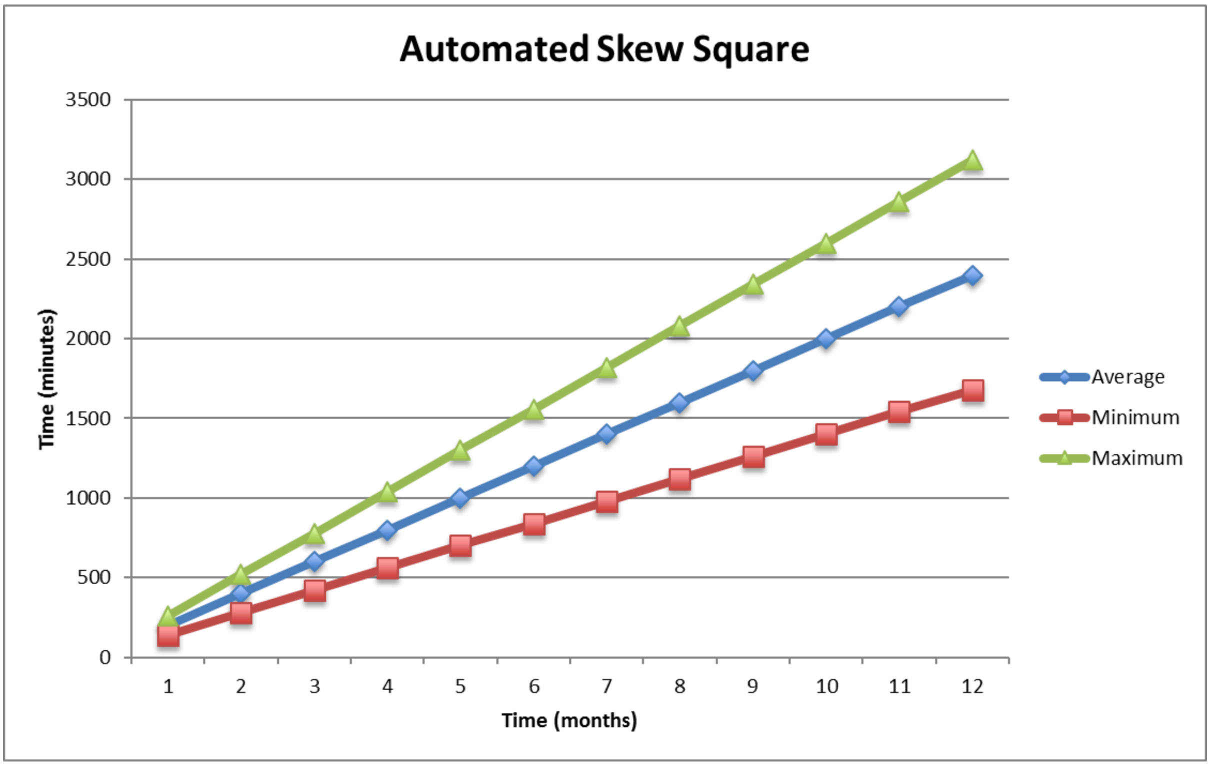
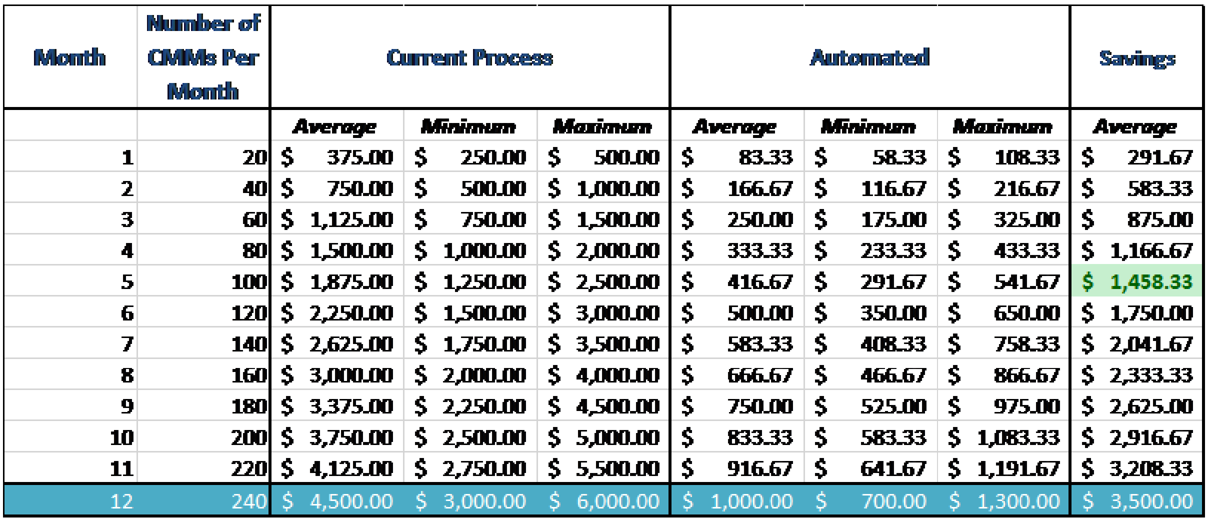


Figure 3.2: Time to perform automated Skew Square Calibration process

In order to complete our prototype the team spent $750.00. As shown from figures 11.2 through 11.18 and the redesign considerations from section 16, the cost of the robotic arm will be approximately $1,540. With the need for more advanced motors and better quality steel to decrease some of the deflection from the 1 newton probing force the device will be idea and relatively inexpensive, saving the company time and money.

Re-analyzing the cost predictions incorporating the initial cost of the new product, a new column for the Savings can be generated as shown below in Table 3.1. From the table generated it is evident that after 5 months (approximately 105 CMMs) the new product will have paid for itself and begin saving Hexagon money as well as time. After one year the new automated Ball Bar process will save the company $3,500.

Table 3.1: Automated Cost to Perform Ball Bar Calibration over One Year Span



Month	Number of CMMs Per Month	Current Process			Automated			Savings
		Average	*Minimum*	*Maximum*	*Average*	*Minimum*	*Maximum*	*Average*
1	20	$ 375.00	$ 250.00	$ 500.00	$ 83.33	$ 58.33	$ 108.33	$ 291.67
2	40	$ 750.00	$ 500.00	$ 1,000.00	$ 166.67	$ 116.67	$ 216.67	$ 583.33
3	60	$ 1,125.00	$ 750.00	$ 1,500.00	$ 250.00	$ 175.00	$ 325.00	$ 875.00
4	80	$ 1,500.00	$ 1,000.00	$ 2,000.00	$ 333.33	$ 233.33	$ 433.33	$ 1,166.67
5	100	$ 1,875.00	$ 1,250.00	$ 2,500.00	$ 416.67	$ 291.67	$ 541.67	$ 1,458.33
6	120	$ 2,250.00	$ 1,500.00	$ 3,000.00	$ 500.00	$ 350.00	$ 650.00	$ 1,750.00
7	140	$ 2,625.00	$ 1,750.00	$ 3,500.00	$ 583.33	$ 408.33	$ 758.33	$ 2,041.67
8	160	$ 3,000.00	$ 2,000.00	$ 4,000.00	$ 666.67	$ 466.67	$ 866.67	$ 2,333.33
9	180	$ 3,375.00	$ 2,250.00	$ 4,500.00	$ 750.00	$ 525.00	$ 975.00	$ 2,625.00
10	200	$ 3,750.00	$ 2,500.00	$ 5,000.00	$ 833.33	$ 583.33	$ 1,083.33	$ 2,916.67
11	220	$ 4,125.00	$ 2,750.00	$ 5,500.00	$ 916.67	$ 641.67	$ 1,191.67	$ 3,208.33
12	240	$ 4,500.00	$ 3,000.00	$ 6,000.00	$ 1,000.00	$ 700.00	$ 1,300.00	$ 3,500.00

3.2 Sources of Funding

This project is funded from two sources. The University of Rhode Island has allotted the team $1,500 towards the project. The sponsor, Zack Cobb, and the rest of the Hexagon team has also agreed to assist in funding the project and provided the option to assist in the manufacturing of parts needed to complete the project.

3.3 Human Resource Allocations

With this new process being automated, the need for technician interaction will drop drastically. With the technician only needing to initially fixture the arm onto the CMM, press start on a computer to begin the program and finally to remove the arm from the CMM. As we saw in section 3.1, the time to complete the overall skew square calibration decreases by 35 minutes per CMM or 140 hours per year of saved time (Table B.1). What this analysis does not take into account is that once the technician presses start on the program to begin the calibration they can move on to work on other machines or other projects, further improving the company's productivity.

From the discussion with the employees at Hexagon the team was able to come to an estimate that employees are paid an average of $25 per hour. The following two figures are graphical representations of the cost to perform this process over 12 months in order to show the savings for the company over a one year time span. This process is determined using the data from section 3.1. The time on the table in Appendix B is converted from hours to minutes and then used to create the following graphs.

3.4 Mass Production

Since so little machines are calibrated per month and there are currently many different sizes of the product needed to accommodate for all different machine sizes; there is no need for a mass production of this product. The company will only need 3-4 robotic arms to use at any time. Therefore, after the initial arms are made the only time more will be needed to be manufactured will be if there is an update in the design or damage to one.

3.5 Market Demand

This product, once implemented into Hexagon's standard processes, will be used solely with Hexagon. Unless the company decides to sell off the new robotic arm to other companies who which to perform the skew square calibration on their own. Any company that designs and sells CMMs will want this product for their calibration processes to improve on the current system.

3.6 Forecast of Technology

This new robotic arm is the next generation in the Skew Square calibration. Of course the goal of any project is the save the company time or to improve their profit. Knowing from the previous sections the time and financial benefits of the design, it is predicted that Hexagon will allocate some time and funding into improving on the team's design to allow the arm to work ideally for their needs.

3.7 Future Revisions

With the current prototype as an excellent foundation towards the final product, the next biggest revision would be to modify the current prototype in order to accommodate all size machines. The team designed the arm for only the smallest CMM (A machine) that is for a 500mm X 500mm cube. With CMMs varying greatly in size it will become needed to improve on the ability to make the arm adjustable to any size. A trend could be seen that the larger the CMM to be calibrated, the larger the savings in time with an automated ball bar process.

4 Patent Search

Through the patent search it has been concluded that currently there are no patents for a mechanized ball bar fixture. With no patent for a mechanized ball bar fixture it does not mean that there are not patents relative to this project. Searching through the USPTO four patents were found to be relevant to the project the team was tasked with. Below are the four patents with a brief description of each.

4.1 Validating the Error Map of CMM Using Calibrated Probe [4]

Patent 7,712,224 is for the process of error mapping a newly manufactured CMM. This patent was created by an employee from Hexagon, Peter Hicks, on October 3, 2007. As described in section 1, once a CMM undergoes various tests to ensure the machine meets all standards and requirements to provide accurate and repeatable measurements. This patent describes how the process of error mapping is performed. Three spheres are placed within the CMM at various heights. The three spheres are then probed and a new map is then generated. The new map and the theoretical maps are compared to each other and the differences between the two are programmed into the machine to compensate.

This process is different than the process involving the ball bar because the process involving the ball bar tests the skew and "squarness" of the moveable space within the CMM. However, this patent has proved beneficial for the tasked assigned to the team because the probing data to measure each sphere is recorded in this patent. Knowing the probing values (speed, force, prehit and retract) and angle of attacks at which the probe will make contact with the spheres has proved beneficial in the designing process. Come the testing stages of the prototype tests can be performed at all angles and probe values.

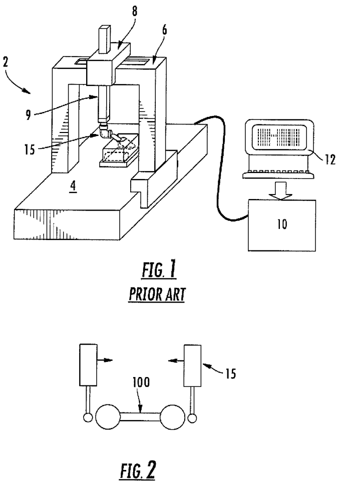


Figure 4.1: Design for Error Mapping Process

4.2 Method for Calibrating a Coordinate Measuring Machine and the like and System Therefor [?]

Patent number 4,819,195 created and filed by Frederick K. Bell ,Gary E. Brazier and Stephen N. Brown on January 20, 1987 is an overview of the methods for automatically calibrating a CMM. The system guides an operator through instrument set-up and data collection procedures. The system automatically converts the collected data into error compensation or axis correction data which represents 21 different geometry errors (pitch, yaw, roll etc.) of the CMM. The error compensation data is then transferred to a CMM measurement processor for subsequent use by the CMM during operation thereof to thereby compensate the CMM for its entire measuring volume.

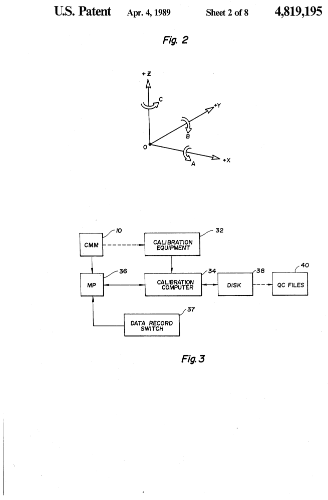

U.S. Patent Apr. 4, 1989 Sheet 2 of 8 4,819,195

Figure 4.2: Design for Error Mapping Process

4.3 Ball Cube [3]

The apparatus is a low cost and low weight ball cube with balls that can be probed with three probe styli each (with probing points distributed over more than a hemisphere in each case), the probe styli directed normal to five different cube sides. These properties are obtained by giving the balls an offset from the cube. The increased susceptibility to structural instabilities by the low weight design (e.g. plate structure) in connection with the offset balls is compensated by the use of corner connectors for the cube-edges to mount the balls on. The measurements on the ball cube yield–after evaluation–the linear approximations of the parametric errors of Cartesian axes machines: three errors of position, three errors of squareness, three roll errors, three yaw errors, and three pitch errors. The cube is as well a suited object to measure the errors of rotary tables of coordinate measuring machines and machine tools in situ. The calibration of the cube is performed by a length comparison between a calibrated reference ball bar and the ball distances along the 12 edges and the 12 diagonals of the 6 cube sides. This comparison is carried out with a self centering device.

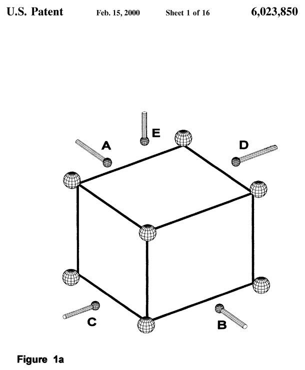


Figure 4.3: Ball Cube Patent

4.4 Method of constructing a 3-dimensional map of a measurable quantity using three-dimensional coordinate measuring apparatus [6]

A novel, portable coordinate measuring machine comprises a multi-jointed (preferably six joints) manually positionable measuring arm for accurately and easily measuring a volume, which in a preferred embodiment, comprises a sphere ranging from six to eight feet in diameter and a measuring accuracy of 2 Σ ± 0.005 inch. (It will be appreciated that "Sigma" means "one standard deviation".) In addition to the measuring arm, the present invention employs a controller (or serial box) which acts as the electronic interface between the arm and a host computer. The coordinate measuring machine of this invention is particularly useful in a novel method for constructing a 3-dimensional map of a measurable quantity (such as temperature, coating, thickness, density or the like) using an independent transducer located at the end of the measuring arm.

U.S. Patent May 9, 1995 Sheet 15 of 18 **5,412,880**

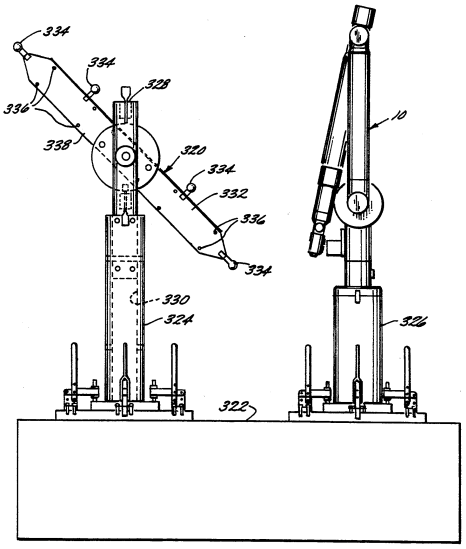


FIG. 19

Figure 4.4: Ball Cube Patent

5 Evaluating Competition

One of the first tasks faced in the development and design of the Bar Ball manipulator was market analysis. The market identified for this product as a whole, specifically in the scope of this project, is strictly Internal to Hexagon. At this time, the objective of this project is not to create a product for a production scale, or to market the product to other companies. Therefore, consideration of the market is based mainly on products currently utilized by Hexagon, these being deemed as the best available options. The team was tasked with creating an automated version of a Ball Bar. Through patent search and market research is was found that no such product currently exists. This product could therefore be a subsection of both the precision measurement instrumentation market, or the robotics and automation market. Analysis was completed with comparisons to the design chosen by the team, this being the worm gear driven manipulator explained in Section 10.

5.1 Traditional Ball Bar Fixture

As this product has no direct competition it will enter the precision measurement tools market as a subsection, however it will still compete with the current commercially available version of the Ball Bar. Precision measurement devices for the purpose of calibration are currently on the market and available from companies such as Bal-tec. These companies produce the actual ball ends, the bar, and in many cases, will also have available the stand to affix the ball bar into space. Our product will not complete with the precision measurement aspects of these products as, in the scope of this project, we are not concerned with developing the actual Ball Bar, and only with its fixture method. Our product will compete with the current fixturing methods available.

Stands are pictured with Ball Bars, priced separately

Figure 5.1: Examples of Ball Tec Bar Ball Fixtures

Table 5.1: Available Ball Tec Bar Ball Kits and Pricing

Part #	Description	Price	Purchase
FS-10M	STAND TIE DOWN	$56.88	🛒
FS-14	BALL BAR STAND 355.6 MM, 14 INCHES, INCLUDES A SINGLE CLAMP, COLLAR	$570.63	🛒
FS-14-0	BALL BAR STAND ONLY, 355.6 MM, 14 INCHES	$346.75	🛒
FS-14-3-6	BALL BAR KIT, INCLUDES 300 MM AND 600 MM BALL BARS, STAND, A COLLAR AND DUAL CLAMP	$1242.63	🛒
FS-1BB	SINGLE BALL BAR CLAMP	$137.00	🛒
FS-1BB-S	SMALL BALL BAR CLAMP	$137.00	🛒
FS-24	BALL BAR STAND 609.6 MM, 24 INCHES, INCLUDES A SINGLE CLAMP, A COLLAR AND A TIE DOWN	$591.25	🛒
FS-24-0	BALL BAR STAND ONLY, 609.6 MM, 24 INCHES	$364.38	🛒
FS-2BB	DUAL BALL BAR CLAMP	$164.00	🛒
FS-3	TRI-MOUNT COLLAR, 2 INCH DIAMETER THROUGH HOLE, FOR HEAVY DUTY STAND	$248.00	🛒
FS-36	BALL BAR STAND 914.4 MM, 36 INCHES, INCLUDES A SINGLE CLAMP, A COLLAR AND A TIE DOWN	$620.63	🛒
FS-36-0	BALL BAR STAND ONLY, 914.4 MM, 36 INCHES	$443.75	🛒
FS-3BB	TRI-MOUNT COLLAR AND THREE SINGLE BALL BAR CLAMPS	$548.83	🛒
FS-WB	WASHER AND SHOULDER BOLT	$9.82	🛒

Figure 5.1 shows an example of the currently available Bar Ball systems. These products range from approximately $500 to $1200 depending on the size of the Bar Ball and are currently utilized by Hexagon for their error mapping process. The draw back to these devices is exactly the problem we are tasked with fixing, they must be moved by hand. This is time consuming and a waste of labor. These products are solid, metal, heavy and purely mechanical, meaning that they can be fixed very solidly into place and withstand significant dynamic forces without any movement. Bar Ball fixture stands have two main trade-offs, both based in overall cost, initial price vs labor costs. The initial cost of the automated bar ball is higher than that of the traditional stands, however if the target price of approximately $1500 is met, this is a marginal difference. When considered against the long term labor costs associated with the use of both products it is easy to see that the automated version will recuperate its extra cost quickly and be the less expensive

option overall. The one advantage that the traditional system may possibly have is that of its simple, sturdy design. With the integration of electronics and electrical actuation, the joints will be dependent on gears which will introduce backlash into the system which could leave the system vulnerable to dynamic forces. This must therefore be accounted for in the design of the automated version of the machine in order to remain a viable competitor to the traditional methods of fixturing.

5.2 Robotics

The second market that this design enters is robotics and automation products. The automated Bar Ball is at its base design, a three-linkage manipulator, requiring similar accuracy to similar products such as pick and place robots, or manipulators commonly used in manufacturing atmospheres on assembly lines. It was found that there exist two major levels of these robotic manipulators, desktop and industrial.

5.2.1 Desktop Manipulators

Figure 5.2: Example of Desktop Manipulator

Desktop Robotic Manipulators, such as the example in Figure 5.2.1 are inexpensive, small, and versatile. Their popularity has exploded in the past several years, as advancements in electronics development tools such as Arduino or Raspberry Pi combined with easy to use software packages have made projects such as robotics possible for the average hobbyist. The example in Figure 5.2.1 is a model available for approximately $440 from SparkFun.com. Similar products can be found from other distributors such as Amazon, Ebay or other discount websites, their prices ranging from as low as $50 to as high as $500. These desktop "toys" are functional but due to their low costs, they lack high level quality. In general, they are made of plastics, acrylics, wood, or low grade aluminum, and are constructed with low quality bearings and hinges. The major advantages of our design are in quality and robustness. From the design specifications described in section 7, it is stated that our manipulator must not have more than 1 micron dynamic response to a 1 N dynamic force. The lack of robustness of these machines leave them vulnerable to fail this specification. Also, the load which the manipulator must carry and place in space is of concern to these systems. The Bar Balls used, depending on material selection, can be several pounds, and as these products are actuated by hobby grade servo motors, the lack of power, fine positioning feedback, and their plastic geared construction make them undesirable to use in this application.

5.2.2 Industrial Automation

Figure 5.3: Example of Industrial Manipulator

The second level of currently available robotic manipulators are industrial robots used in manufacturing. The examples seen in figure 5.2.2 are built buy KUKA, and there are several companies that produce a similar product such as EPSON or DENSO Robotics. These are high precision tools, optimized to work in the most demanding of manufacturing environments. On the surface, it seems likely that due to the precision nature of the Bar Ball manipulator, this style of robot would be a perfect solution, however these machines do have some major drawbacks. The first major issue with these devices is their cost, which is in the range of $10,000 plus. This exceeds the target cost of the automated Bar Ball by a wide margin and although the return from labor cost savings is a factor, these machines are designed on a much higher scale for workload, with the goal of producing thousands of parts per day rather than the limited number of uses our machine will see. The other major advantage our design has over these products is their geometry. These machines are generally designed for pick and place applications, or other processes done in manufacturing. This means that due to their geometry, design, and construction, even high degree of freedom machines can only reach a select volume of space. The advantage of our simpler design is that it has the ability to fold down on itself in order to reach positions three and four, described in figure 6 of section 7. A manipulator not capable of reaching all 12 positions is not an appropriate choice for this application.

6 Specifications Definition

Design specifications were provided early in development by Hexagon. Due to precision nature of the machine, design specifications were decided on with two methodologies in mind, precision and repeat-ability, along with feasibility. After initial meetings with Hexagon, the team was able to expand upon initial specifications in order refine the problem and move forward with design. Because this machine,Äôs intended use and scope of its design are solely for internal applications, market analysis was not a factor in preliminary design specifications.

The purpose of this machine is to place a Bar Ball into 12 positions in a CMM, so as to be measured for the generation of an error map. The 12 positions are presented in figure 6 and are defined as follows in table 6.1. Based on these 12 positions it was determined that a 5 degree of freedom machine was required to reach every position.

Table 6.1: Description of 12 positions

Position #	Measurement made at position	Geometric Description
1 - 2	XZ Square	Bar oriented in both diagonals in XZ plane, at center of Y
3 - 6	XY Skew and Square	Bar oriented in diagonals of XY plane at both Z min and Z max
7 - 10	X Skew and YZ Square	Bar oriented in diagonals of YZ plane, at both X min and X max
11 - 12	Z Skew	Bar oriented in a skew through XYZ dimensions

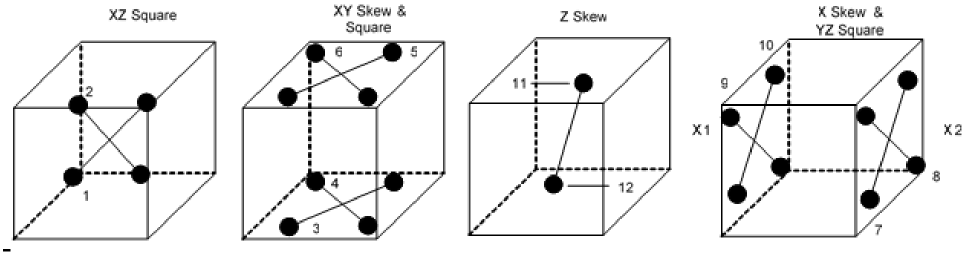


Figure 6.1: Location of 12 positions in 3D Cartesian space

The current process used at Hexagon already utilizes a Ball Bar placed in each of the 12 positions described previously. This is done by moving the bar into place, taking the measurement and moving the bar once again by hand. The goal was set to automate this process to that after an initial placement and set up by hand, the operator would be able to start a program in PC-DMIS while simultaneously starting a program on the machine. The machine will then actuate itself into the first positon, the CMM then will measure the Bar and once completed the machine will actuate to the next position to be measured. This is repeated until all positions have been reached and all measurements have been taken. This will eliminate the down time in which am operator must wait for each measurement to be taken, along with the time and effort to physically move the bar into position. Currently the process by hand can take between 45 minutes to an hour to complete. This time is to be reduced to 20 to 25 minutes, however, the goal of complete automation of the machine will eliminate the need for the operator interacting with the machine and therefore is free to complete other tasks.

Precision in general is a large aspect of this project and a large concern in the design and development of the machine. However, it is specified that the actual placement of the Bar Ball in 3D Cartesian space is not critical, only the measurement taken. That said, the level of precision of the placement of the bar in 3D space does affect the interaction between the Bar Ball Manipulator and the CMM measuring it. These two machines will be working in tandem and yet will be running independently from each other, using different programs and different processors. This means that they will not be aware of each other and will have the ability to crash, resulting in damage to both machines. Therefore, two things must be considered, the dynamic movement set by the tool path of each machine, and the steady state error of the bar when the CMM makes measurements of the ball end. PC-DMIS has the ability to troubleshoot inaccuracies between expected and actual placement by slowly searching a designated volume of space in order to account for any inaccuracy. To avoid dynamic crashes during movement the tool-path of each machine will be calculated carefully, to ensure that the machines never pass closer than the combined uncertainty range of both machines. Although these measures can be taken for avoidance of crashes, they are limited by the time in which the CMM can search a volume, and geometrically by the amount of space available for movement of each machine. In both cases, smaller error results in faster and more optimal function. Therefore, it was decided that the manipulator must place the ends of the Bar Ball within 1 cubic cm of Cartesian space, and produce feedback to the same accuracy during dynamic movement.

Along with the precise placement of the bar not being directly critical to the error mapping process, the total length of the Bar Ball itself is also not critical. The error mapping process is based on all changes in the measured length of the bar during the process, this means that good transient stability is required to accurately complete error mapping. In the time from when the first measurement is taken to the last measurement is taken, the maximum allowable change in length of the bar is 1 micron. It was foreseen that the two major factors that could contribute to a large change in bar length is a change temperature of the bar resulting in thermal expansion, or droop of the bar due to gravity, when held at certain angles. A temperature change of 1 degree was found to produce the maximum admissible expansion of the bar and was chosen by the team as a benchmark to work with. This value is larger for different, less thermally sensitive materials and is therefore a specification dependent on the overall spec. Bar droop will be addressed in the fallowing description of Repeatability.

Closely related to Transient Stability is Repeatability. As stated previously, the actual length of the Bar Ball is not critical, therefore deformation of the bar is acceptable as long as the deformation is repeatable, and constant for every measurement. This is also true for dynamic response, and other factors which could produce error in the measurement taken. If the error is the same in every direction and at every position measured, then it can factored out and the error mapping process will not be affected. In initial design it was determined by the team that at 5 degrees of freedom, any fixturing method would be non-isometric and non-linear and therefore respond differently in different directions.

Hexagon produces several different types of CMMs in a range of sizes, all requiring the same set up and error mapping process. The design of the machine should therefore be scalable, to make and utilize the machine in any CMM applicable. Using the same design elements, models, and calculations a machine of any size should be produced with the same function. It was decided by the team that this could be achieved by utilizing two methodologies in design, modulatory and optimization. By utilizing a simplistic design with standard attachments and actuation, changing the length of any part would be easily achievable. It was decided that although this helped meet the initial scalability requirement it would also be beneficial if a single Bar Ball manipulator would be able to fit in multiple CMMs and fit the size requirements for said CMM. Therefore geometric optimization of the manipulator was added as a goal.

Initially, Hexagon made no requirement about the Ball Bar Manipulator being controllable through PC-DMIS software, and required only that the machine be able to work in tandem. It was specified that a specifically timed dwell time should be applied to both pieces of software so that the Bar Ball would be moved into place and wait while the CMM made the measurement in a pre-determined amount of time. After the measurement is completed the manipulator would then move to the next position in known amount of time and the CMM would resume measurement. This was foreseen as problematic by the team and due to other requirements described previously the time required to complete the measurements would be slightly variable. It was determined by the team that most reliable way to avoid issues in separately timing the two machines was to set up serial communication between PC-DMIS and the controller of the manipulator, where movement of each machine would be triggered by signals sent at the termination of the other machines movement.

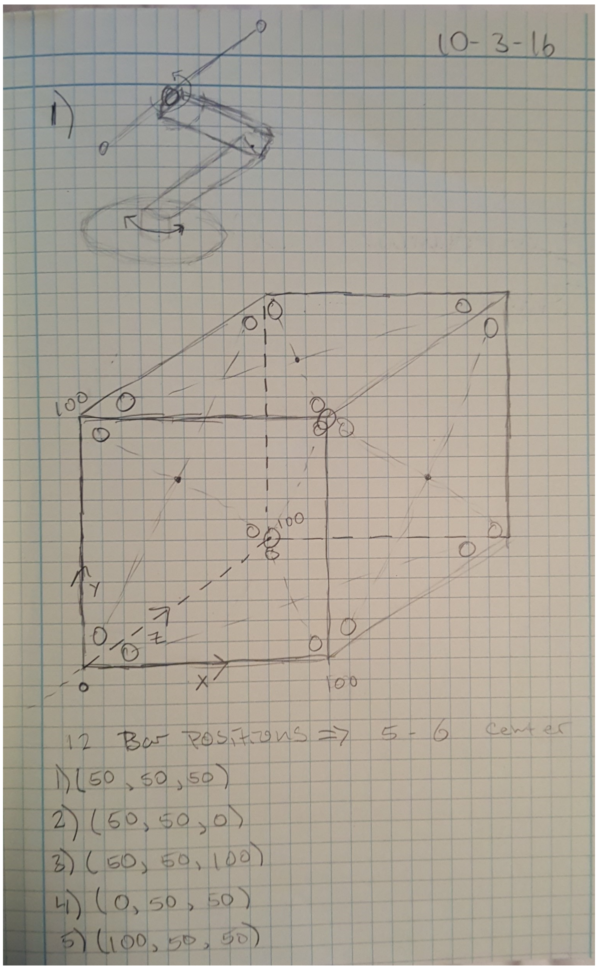
This project was given a budget of $1,500. Addition funds are available from Hexagon if necessary. Hexagon did not stress cost as a requirement.

Table 6.2: Design Specifications

1	Reach 12 Positions	Be able to place Ball Bar accurately into each of the 12 positions
2	Automation	Require no human interaction after initial set up.
		Reduce cycle time to 20-25 minutes
3	Precision	Place ends of bar within 1 cubic cm of desired position
		Measure feedback within 1 cubic cm
3	Transient Stability	Bar length cannot change more than 1 micron through duration of each measurement.
		Max change in Temp of 1 degree C
5	Repeatability	Any dynamic response to a 1 N pressure at ends of bar must be with .5 micron in every direction.
6	Scalability	Have ability to be scaled to fit large or small CMMs
		Modularity
7	Control	Be controllable with PC-DMIS software
8	Cost	Cost less than 1500 dollars

7 Conceptual Design

7.1 Aaron Binek Concepts



12 Bar Positions => 5 - 6 Center
1) (50, 50, 50)
2) (50, 50, 0)
3) (50, 50, 100)
4) (0, 50, 50)
5) (100, 50, 50)

Figure 7.1: Aaron Concept 1

This concept was based on the previous teams design of a 5 DOF manipulator. This was simply a two linkage arm with a 2 DOF bar type clamp. This design was meant to be the basis of thinking that the many subsequent designs would be based on. This design was where consideration was taken of how a machine of this nature would be able to reach all 12 positions required.

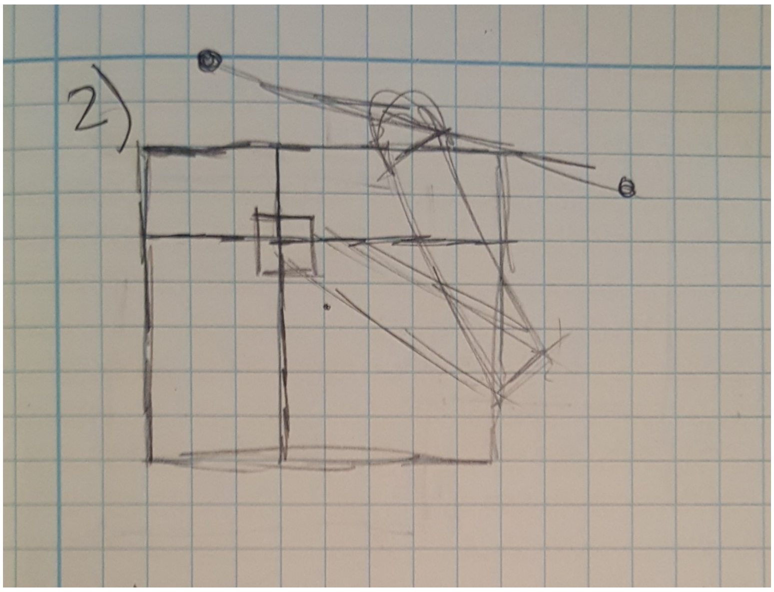


Figure 7.2: Aaron Concept 2

Moving forward from the first design, this was based on a similar two linkage actuator. The difference was the ability to move the base of the actuator on the X,Y plane with the use of the linear rails and bearings running on an X and Y carriage. The base piece would slide along one carriage while the other was actuated, pushing the base along.

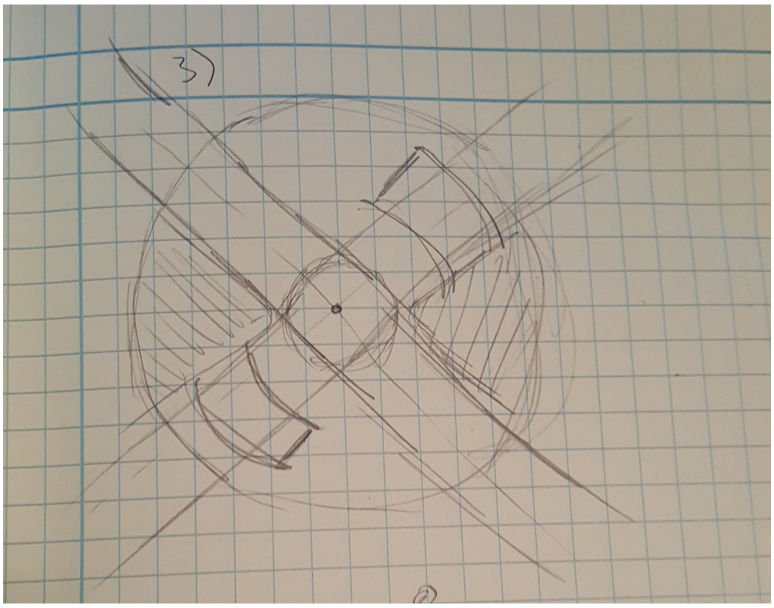


Figure 7.3: Aaron Concept 3

This is a concept for a mechanical apparatus to lock the bar into two separate positions. From concept 1 it was observed that for the 12 positions, there was only 6 positions that the center of the bar needed to reach, then a 90deg rotation of the bar would place it in the next position within that plane. This is a device to put a hard stop at each position, and a locking mechanism to keep the bar in place.

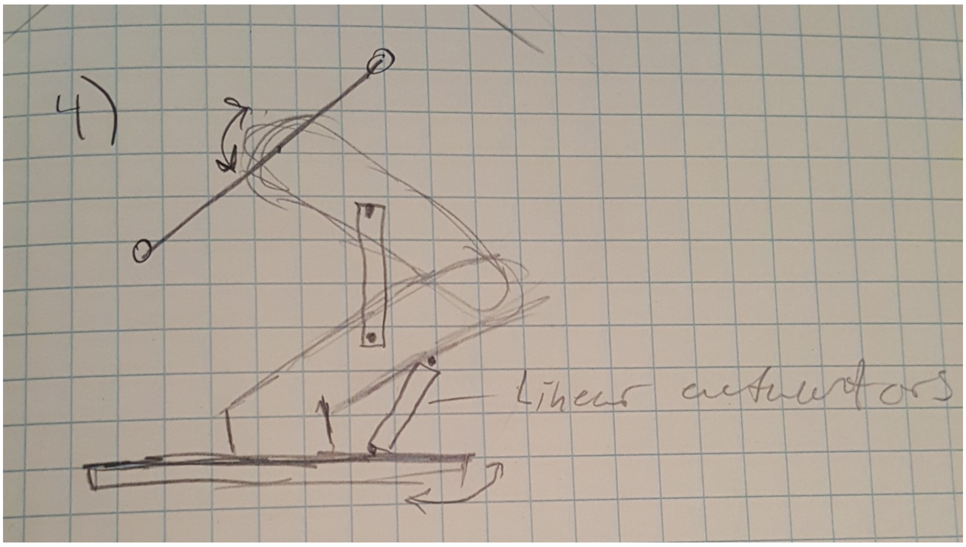


Figure 7.4: Aaron Concept 4

Based on the first concept, this concept was a design for the actuation of the two linkage manipulator utilizing linear actuators. Rather than directly driving each joint of the machine, which leads to a large torque, this design utilized the mechanical advantage gained by a tangential force. This can be optimized based upon the distance from the joints the linear actuators are placed.

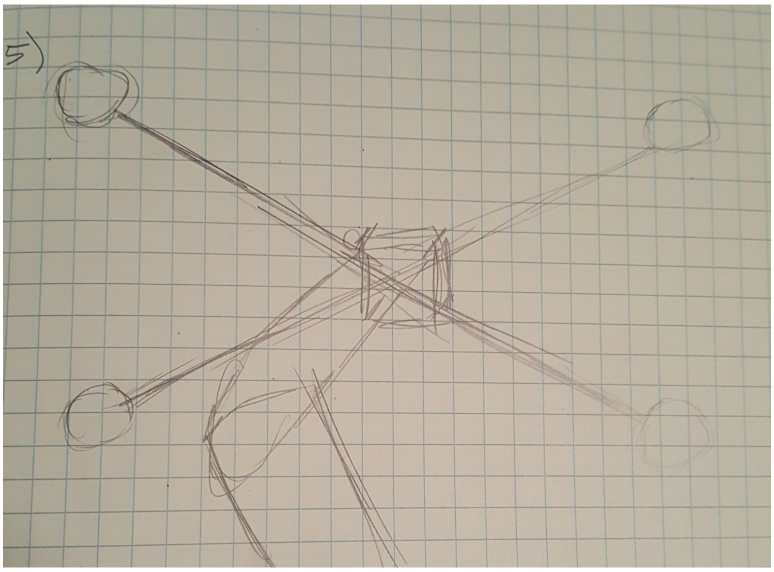


Figure 7.5: Aaron Concept 5

Similar to design 3, this design is based on the fact that within the 12 positions, the center of the bar only reaches 6 positions, with the bar being rotated 90 degrees to reach

each position. This concept makes use of two bar balls, made into a single, fixed piece. The double bar ball could be placed into position before and both bars be measured.

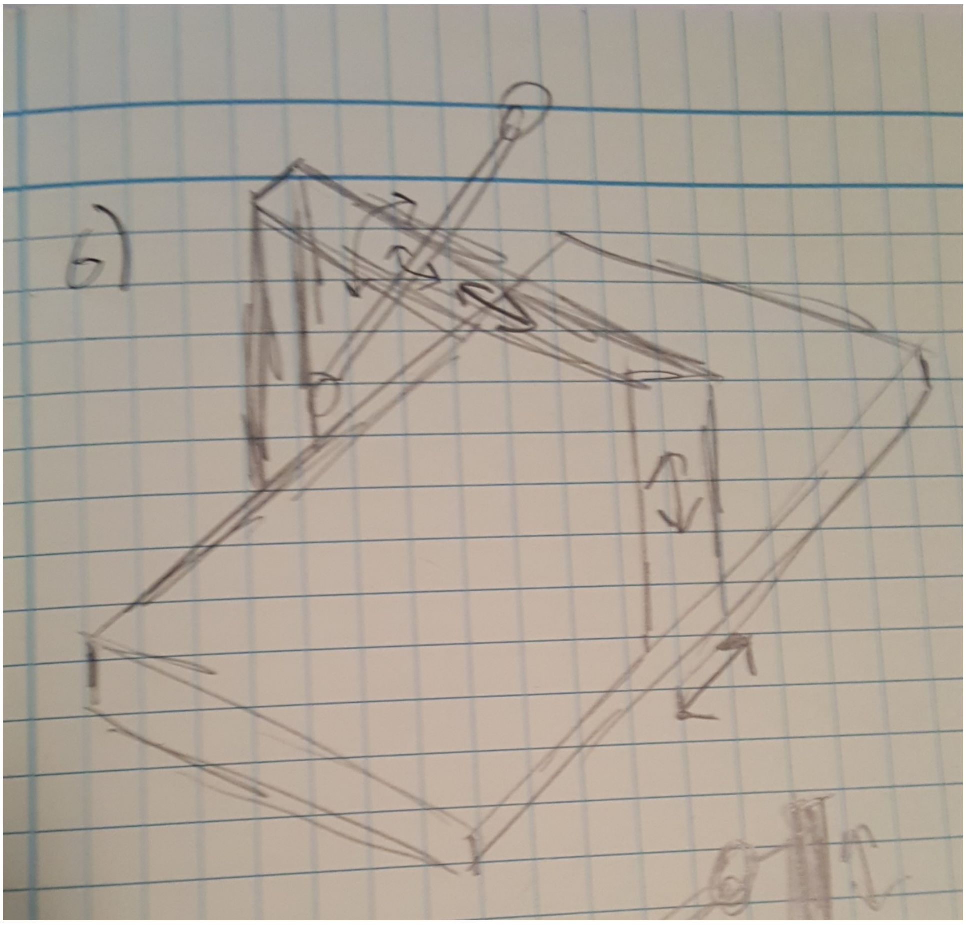


Figure 7.6: Aaron Concept 6

The X,Y,Z Cartesian slider is a design based on the design of the CMMs themselves. The first three degrees of freedom are achieved by X,Y linear carriages that create a plane where the center of the bar ball is affixed. This X,Y plane is then actuated linearly in the Z direction. The last two degrees of freedom are actuated at the center of the bar, where the bar can be rotated about its center, and around the carriage it is affixed to.

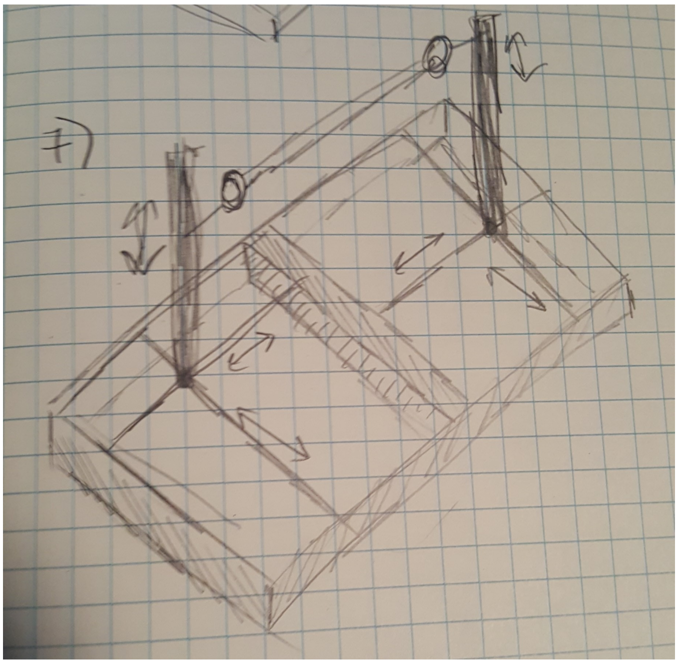


Figure 7.7: Aaron Concept 7

This concept took inspiration from the second concept. It is based on a different methodology of placing the ends separately in space. The table would be divided into two halves, as in each position the bar ends exist in separates halves of the CMM. Each end is then placed in the X,Z plane by a device similar to that in concept 2. The Z direction is then set by a single, vertical, linear slider. This design utilizes only linear positioning and therefore feedback could be very accurate and errors in placement would be minimal.

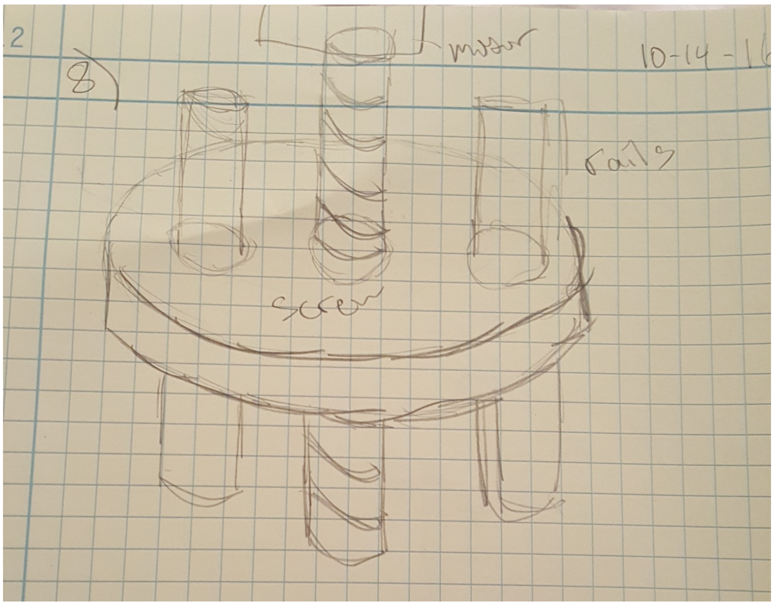


Figure 7.8: Aaron Concept 8

This concept was for use in any concept using linear positioning. This piece is based on a lead screw and flange. The flange rides on two rails with linear bearings, with a threaded, central hole. As the lead screw is turned, the flange ridding on the rails will resist turning and be actuated forward or backward, up or down, depending on the rotation of the lead screw. This provides very fine linear positioning control.

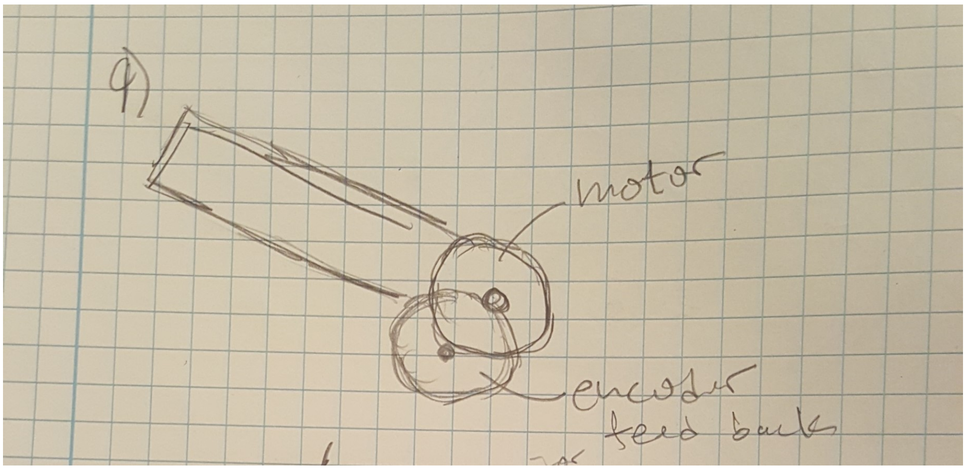


Figure 7.9: Aaron Concept 9

This concept was to compliment any non-linear positioning design. This design is based on gearing down the feedback through an encoder, at any joint between two linkages. By placing a disk or gear directly on the joint, then meshing a separate gear coupled to the encoder, the angle of the joint could be measured, with the ratio between the two gears controlling the level of accuracy of the measurement.

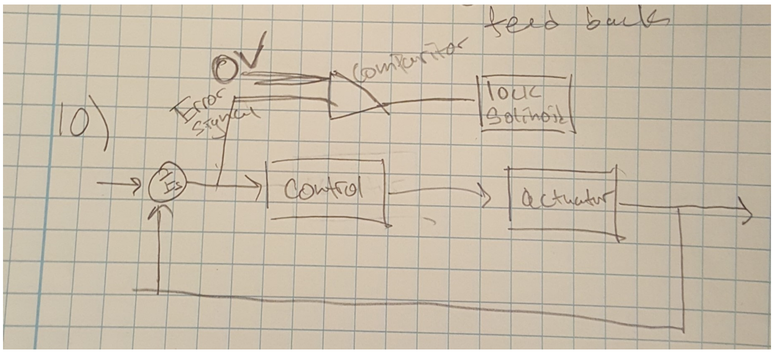


Figure 7.10: Aaron Concept 10

This concept was a methodology in which to apply an external locking mechanism. It was thought that in order to avoid heat, the motors that actuate the machine could be work cycled, only being active while moving the machine. However, due to gravity, this would not be possible for any of the designs without external locking. This circuit is designed so that when the joint is in the correct place, the measurement is equal to the desired, and the error signal attenuates to zero. At this point a comparator sees that the error is equal to zero and sets an external lock to the on position. Then when a new signal is sent, the error is no longer zero and the comparator opens the lock.

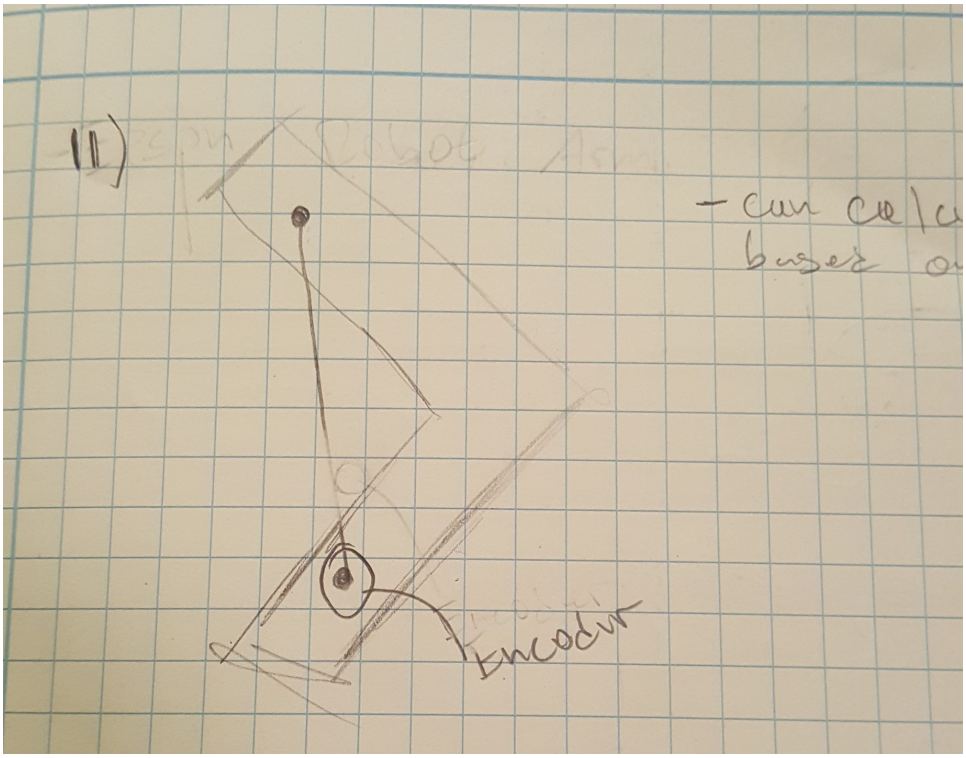
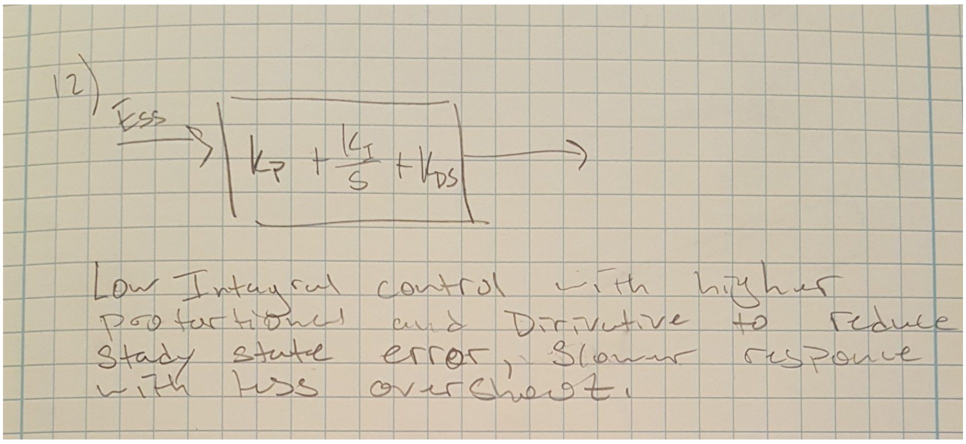


Figure 7.11: Aaron Concept 11

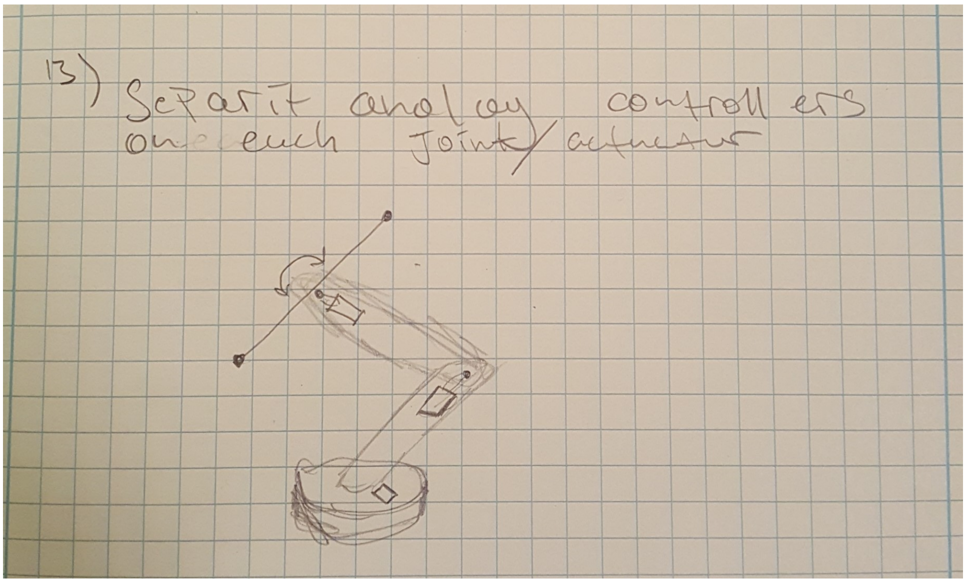
This concept was a way to measure the angle of a joint by means of geometry. The situation arose where two linkages were pressed against one another, this along with the motor attached to the outside there was difficulty in placing the encoders for measurement of the angle. This design moved the encoder away from being directly coupled to the linkage joint. By using a collapsible, linear link between two points, and measuring the angle of the end of the link, the angle can be calculated between the two arm linkages.



Low Intagral control with higher proportional and Dirivative to reduce stady state error, Slower responce with less overshoot.

Figure 7.12: Aaron Concept 12

This concept was a methodology for the control system involved in actuating the linkages of the manipulator into correct and accurate placement. Because of the accuracy desired from the placement, this concept was a controller that would minimize overshoot and oscillations by setting a low Ki value. By using longer settling time, the motion to a specific angle would be smoother.



Separit analog controllers on each Joint/actuator

Figure 7.13: Aaron Concept 13

This concept was based on the method of control for the system. By placing a separate, analog controller on each Degree of Freedom, a central processor is able to set the angle desired for each joint and send a signal. This signal is read at each joint and the standalone controller adjusts for any error at the joint. The advantage is that the central processor is only aware of the calculations needed to place the joints correctly and is blind to errors that are handled separately.

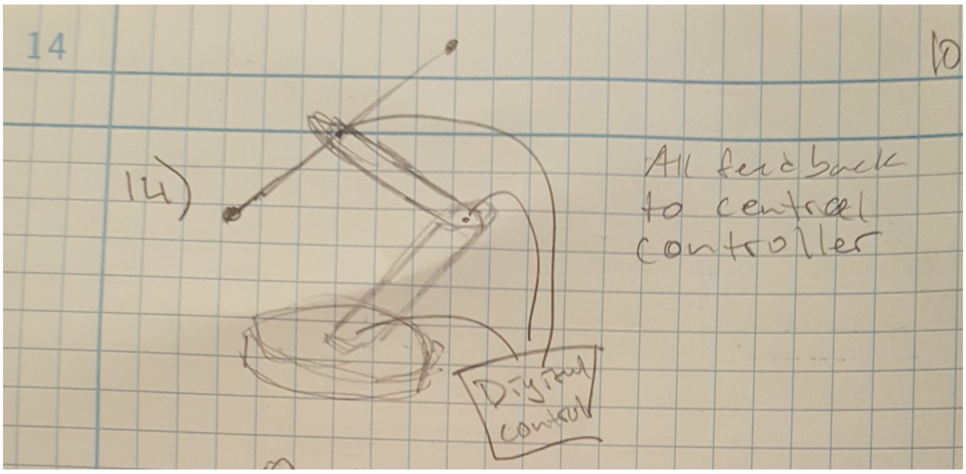


Figure 7.14: Aaron Concept 14

This concept is opposite of that presented in concept 13 and uses one single, centralized, digital processor. This processor handles all calculations for joint placement and all error and control. The advantage of this is that the processor is aware of the accumulated error in the machine and can adjust more than one joint to mitigate error experienced at the final linkage end.

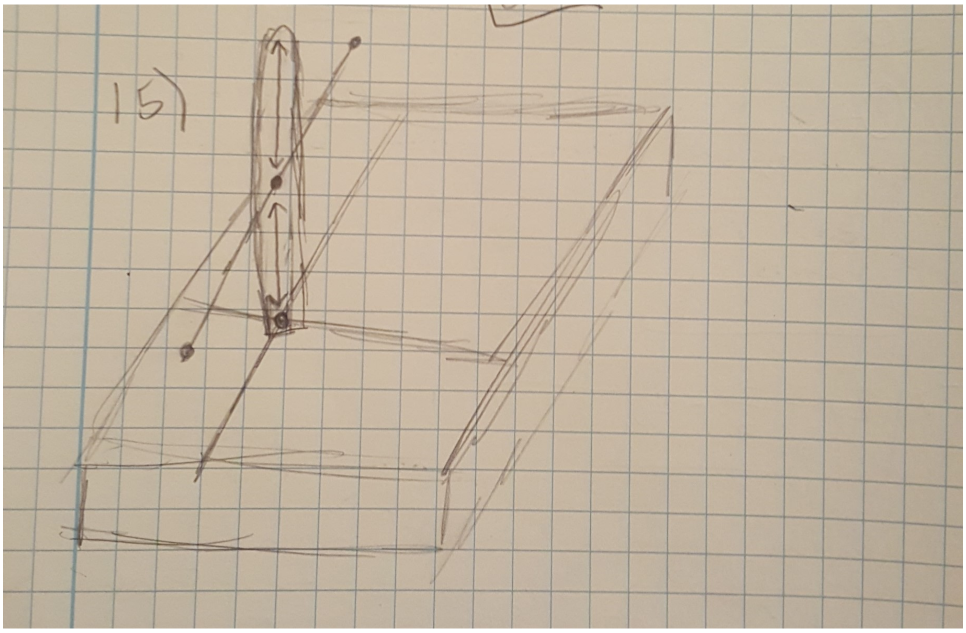


Figure 7.15: Aaron Concept 15

This design is bases on the apparatus presented in concept 7. In this case however a single X,Z carriage is used to place the base of the vertical Y carriage. The center of the Bar Ball is affixed the Y carriage and linearly actuated up and down. The bar must be affixed to a 2 DOF wrist in order to place the bar in each of the 12 positions.

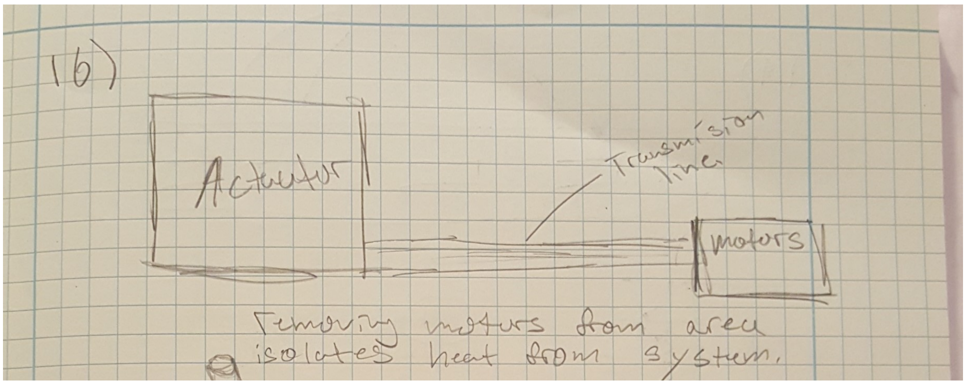


Figure 7.16: Aaron Concept 16

This concept was a solution to the problem of heat generation of the motors. The use of stepper motors in the first attempt at this project lead to heat issues. In order to remove heat from the system this design moves the motors away from the machine where the heat generated cannot transfer from the motors to the bar or the linkages. The torque required to actuate the machine is transmitted through a transition line, or shaft into the machine.

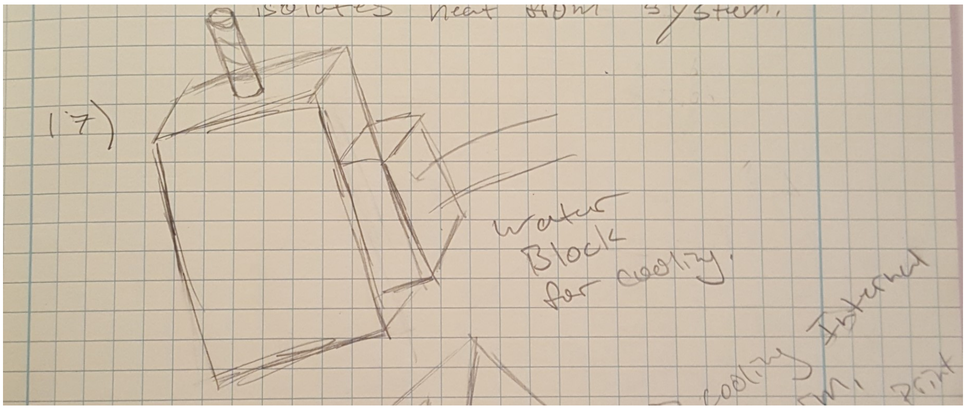


Figure 7.17: Aaron Concept 17

This concept was also a solution to the issue of heat generation of motors but this design is based on removing and dissipating the heat generated by water-cooling. Liquid cooling is widely utilized in the computing industry where CPU‚Äôs and other computer parts tend to generate a great deal of heat. A hallow copper block, with an inlet and outlet, is affixed to the stepper. Liquid with high thermal conductivity is flowed through the block and heat is pulled from the stepper out into the liquid. The warmed liquid is then flowed through radiators and the heat is removed to the outside environment.

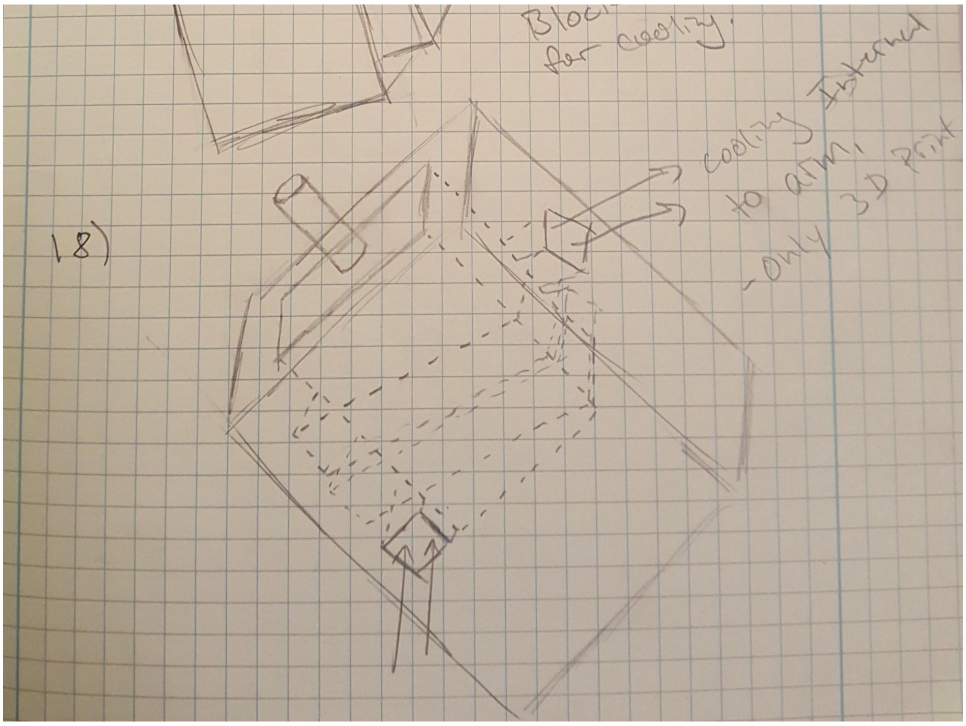
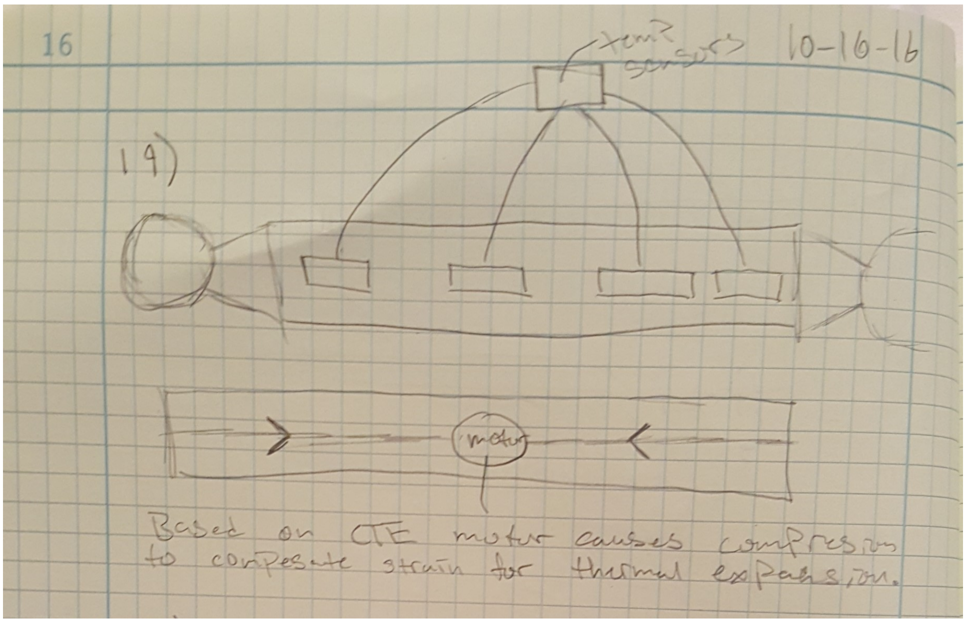


Figure 7.18: Aaron Concept 18

This concept is a continuation of concept 17, water cooling. This design is for a sleeve in which the stepper motor can be placed in order to be cooled. As stated previously liquid cooling is widely used in computers for cooling CPUs and other computer parts. In general cooling of circuits is a 2D process, where a flat plate Is cooled by a flat block. This sleeve allows the stepper, a 3-D object, to be cooled from all 5 available sides. This will lead to higher amounts of heat being removed from the system.



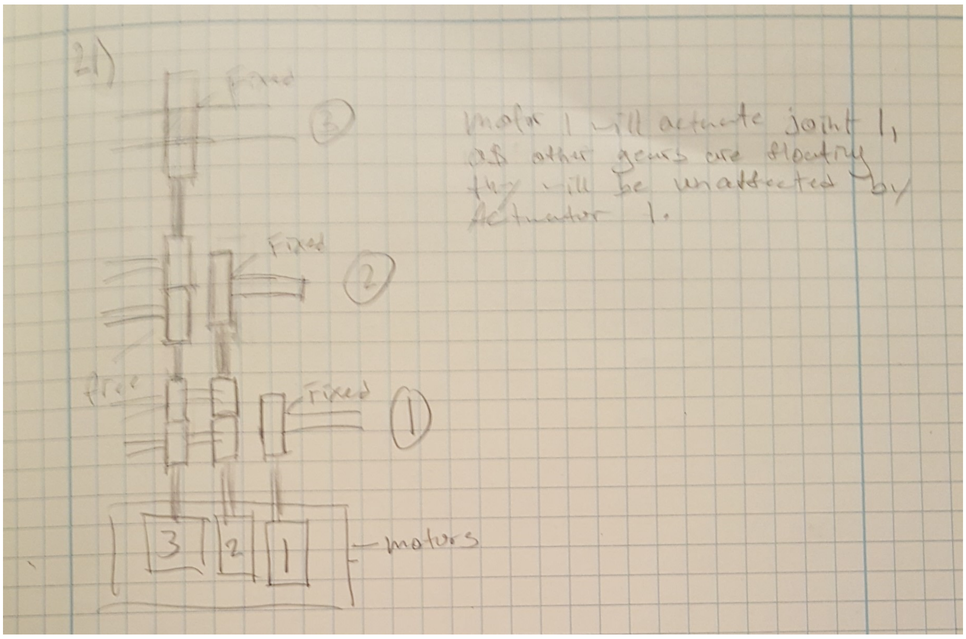
Based on CTE motor causes compresion to conpesate strain for thermal expansion.

Figure 7.19: Aaron Concept 19

This concept is for accounting for the error caused by a change in temperature of the bar ball. The bar ball cannot change length during the duration of the measurements. This can be a problem if the bar is made of a material with substantial thermal properties where a change in length is the result of a negligible change in temp. This design accounts for these changes by measuring the temperature at intervals along the bar, and based on a history of the temperatures being sensed during the measurements, will apply compression to the bar. If the strain from compression is equal to the thermal expansion the bar length will stay constant.

Figure 7.20: Aaron Concept 20

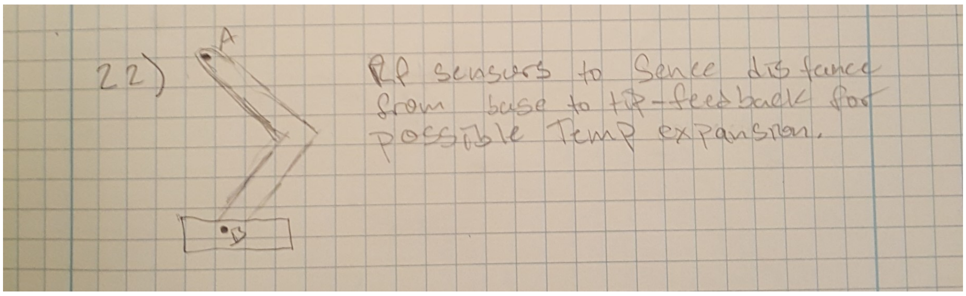
This concept is based on the solution presented by concept 16. This concept is a method of power transition from a power source placed away from the actuator. This intent for this design was to be able to pass torque through a joint without placing any of the torque on that joint. This was done by meshing two gears and a one to one ratio. It was determined that this design was geometrically impossible and was replaced with a similar design utilizing bearings which will be presented in concept 24.



Motor 1 will actuate joint 1, as other gears are floating they will be unaffected by Actuator 1.

Figure 7.21: Aaron Concept 21

This design follows in the continuation of concept 16 and presents a method of transmitting torque successively through each joint of a manipulator with n number of linkages. The first joint contains n power transmission gears, with the last gear affixed in place to the central shaft and in turn, affixed to the linkage it powers. The other n-1 transmission gears do not affect the actuation of that linkage and only pass transmit torque through the joint. In the next link a similar set up with n-1 gears, where n-2 gears are transmission gears and one is fixed. This continues to the bottom of the last link where the one gear is affixed in place.



RF sensors to Sence distance from base to tip - feedback for possible Temp expansion.

Figure 7.22: Aaron Concept 22

This concept was a method for calculating the combined error of each length of the manipulator. By measuring the distance from the base to the tip of the last link, or the center of the Bar Ball, the summed error from each joint can be calculated by comparing the value to a theoretical value. This would be measured by a proximity sensor such as RF.

The machine can then trouble shoot the angles at each joint until the error is accounted for.

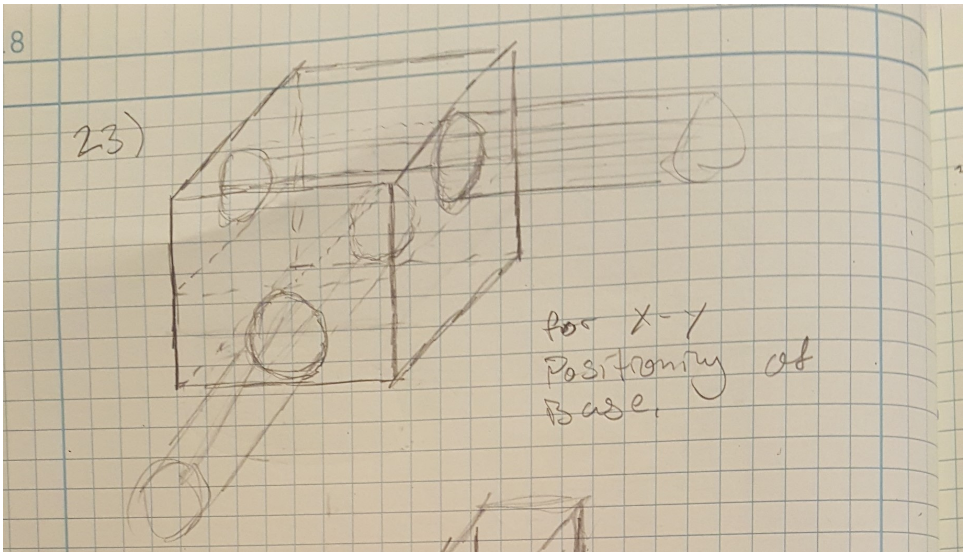


Figure 7.23: Aaron Concept 23

This concept was for a piece relating to other concepts that utilize an X,Y plane carriage positioning system. This fixture can be accurately placed in a 2D plane with the use of linear sliding rails and bearings. As the rails are perpendicular, each degree of freedom is dependent of the other. Therefore when the rail perpendicular to the X direction is being positioned, it will push the fixture and slide it across the Y rail. The fixture is the base of several other fixtures presented in concepts 15, 17, and 2.2

This concept was based on concept 20. When it was discovered that this concept had geometric problems there was a need to be able to transmit torque through a joint without affecting that joint. This design is based on a bearing. The joint has a single shaft with a single fixed gear on the end for its actuation. This piece is two belt gears affixed together that ride on a roller bearing. The bearing is placed on the shaft of the joint. Therefore, when the shaft of the joint is actuated the gears ride on the bearings and are unaffected.

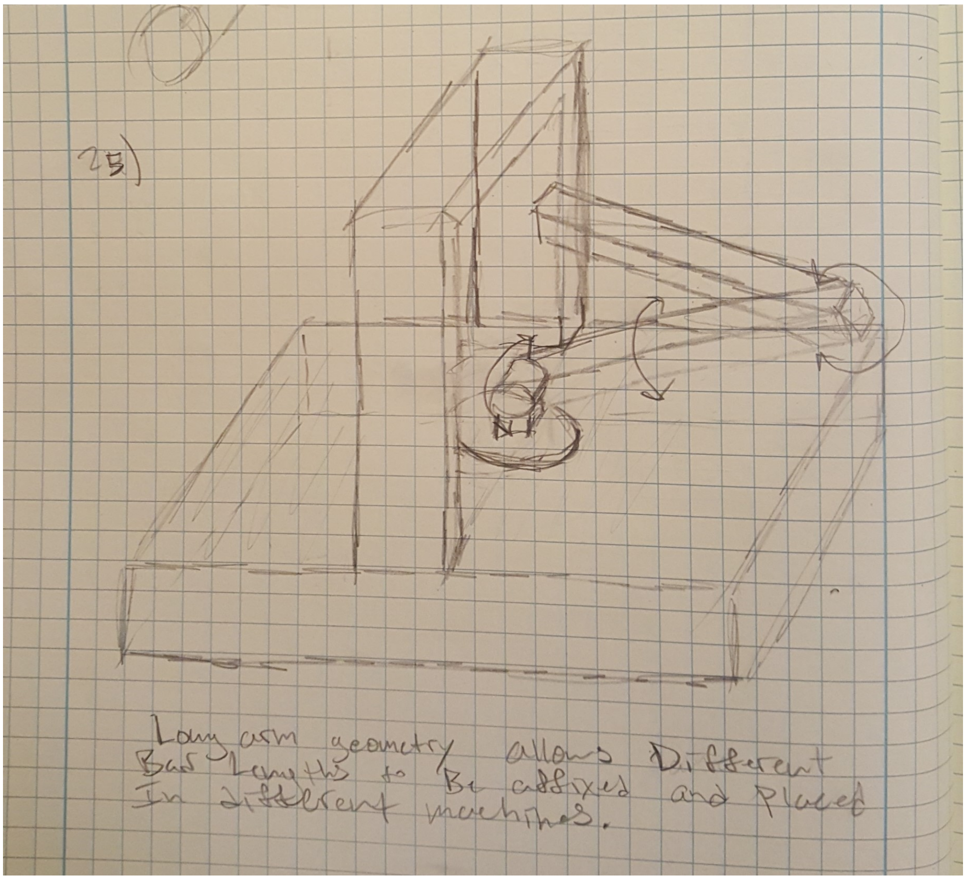


Figure 7.24: Aaron Concept 25

This design was in an attempt to optimize scalability. Based on the original two linkage design, this concept utilizes a different method or creating one of the degrees of freedom. Rather then rotating the entire manipulator, the plane in which the linkages actuate is tilted in order to reach the rest of 3D space requited. This design allows for a manipulator with much longer linkages to be used, as they can stick out the open end of the machine. The advantage gained is that a large manipulator could be used in a small machine, while also being able to reach the positions required for a much larger machine, therefore being extremely scalable.

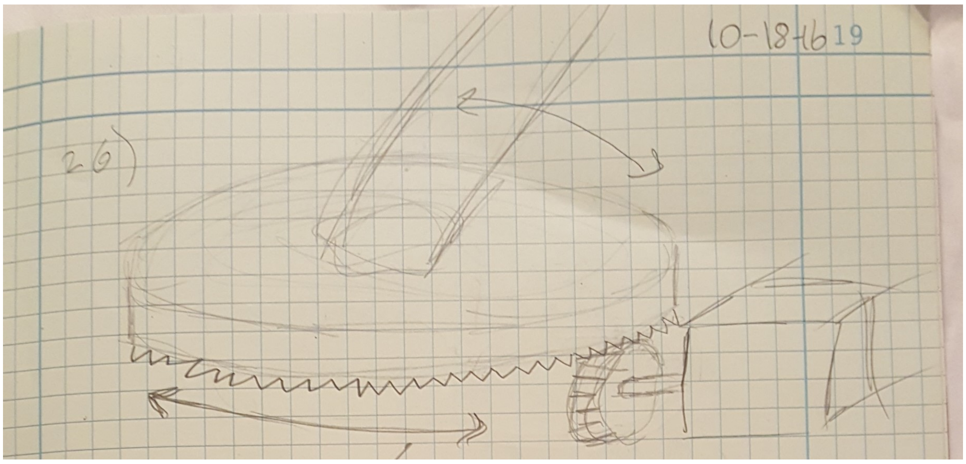


Figure 7.25: Aaron Concept 26

This concept is a method of stepping down the rotation of an arm manipulator such as in concepts 1, 14, 13, or 4. For larger manipulators, it is likely that they will have quite a large mass, and required a large torque to actuate. In order to avoid heat issues the use of a smaller motor is desired. This design actuates the rotation of the bottom plate through a high gear ratio of beveled gears. The advantage of these gears is that the ratio can be finely controlled, but also can be extremely large, creating a large mechanical advantage with only one gear mesh, which reduced backlash errors.

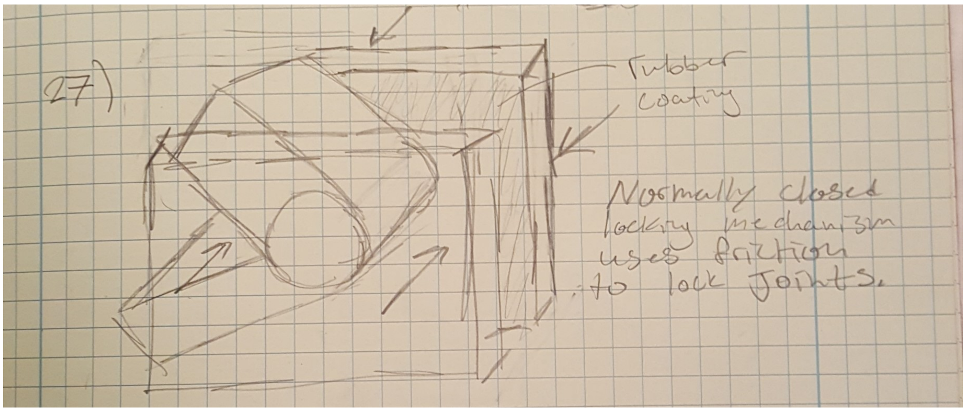


Figure 7.26: Aaron Concept 27

This concept is for an external physical locking mechanism of two linkages. In order to be used at any angle of the joint, this design uses friction rather than a hard stop. When the joint needs to be fixed in place, the normally closed lock will apply spring pressure to the two plates. These plates are coated in a rubber material with a high coefficient of static friction to the metal of the linkages. When the joint needs to be actuated a signal will be sent to the lock and will be actively opened by a solenoid or other actuator. This is advantageous for the use of power cycling, where power is only delivered to the manipulator overall when it is in motion. This lock requires to power to lock in place.

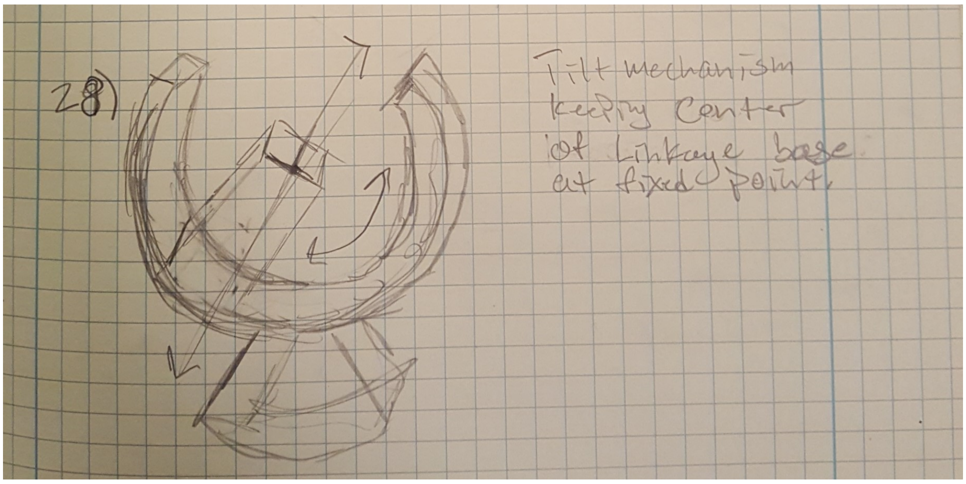


Figure 7.27: Aaron Concept 28

This concept is a tilt mechanism to for addition to concept 25. The idea behind this design is that the base point of the manipulator must stay affixed in space, where the length of the linkage rotates about this point. The circular sliding track is used as the center point will only rotate and will have no translational movement. This allows for the mechanism to tilt and calculate accurately the placement of the end of the linkages being actuated.

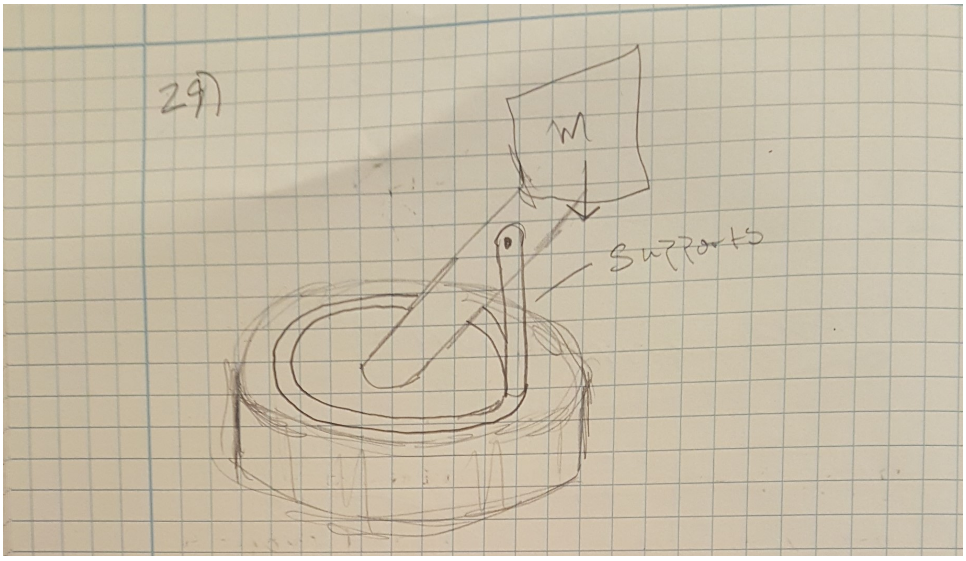


Figure 7.28: Aaron Concept 29

This design was in addition to the general design on a linkage manipulator. This concept was for a support mechanism to be added to the machine. Geometrically the strongest shape is a triangle. By adding this support, most of the torque is taken off the motor at the base of the linkage. The support is able to be slid around the circular track and along the length of the linkage, where it can be locked in place in order to give support.

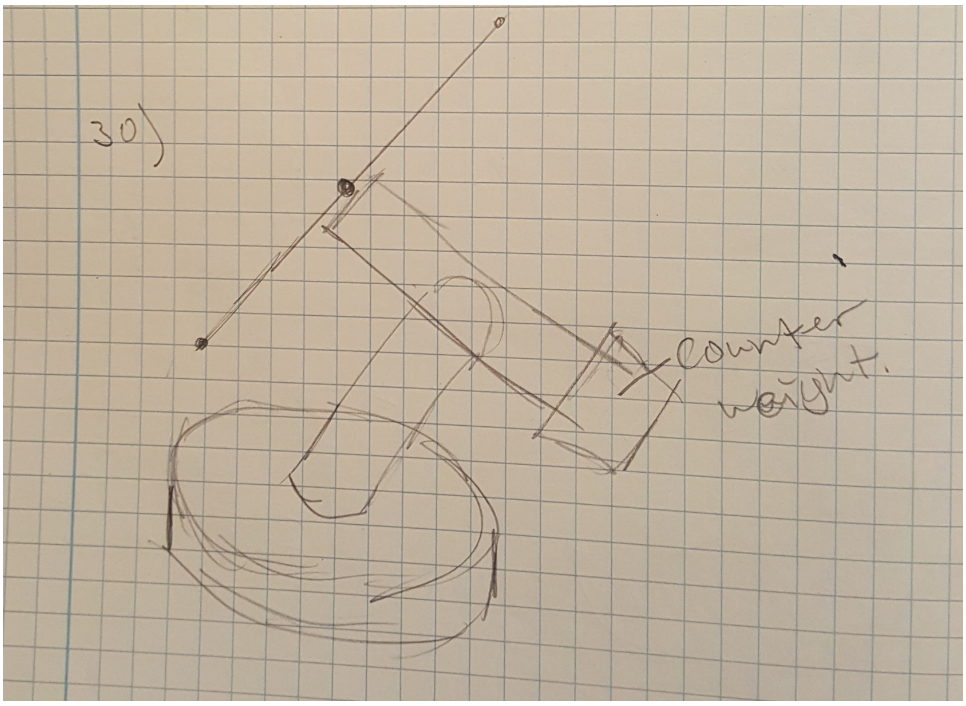


Figure 7.29: Aaron Concept 30

This design was also addition to the general linkage manipulator design. Rather than support this concept utilizes counter weights in order to achieve balance. A linkage manipulator in inherently unbalanced, therefore a large amount of torque is required at certain angles to support the linkages. By adding counter weights this is negated, and if the system is balanced well, the system then needs no power to hold its position. However, this will add a large moment of inertia which must be overcome when movement begins. Therefore this design requires ether larger motors, or more time in which to actuate its movement to the next position.

7.2 Jackson Welsh Concepts

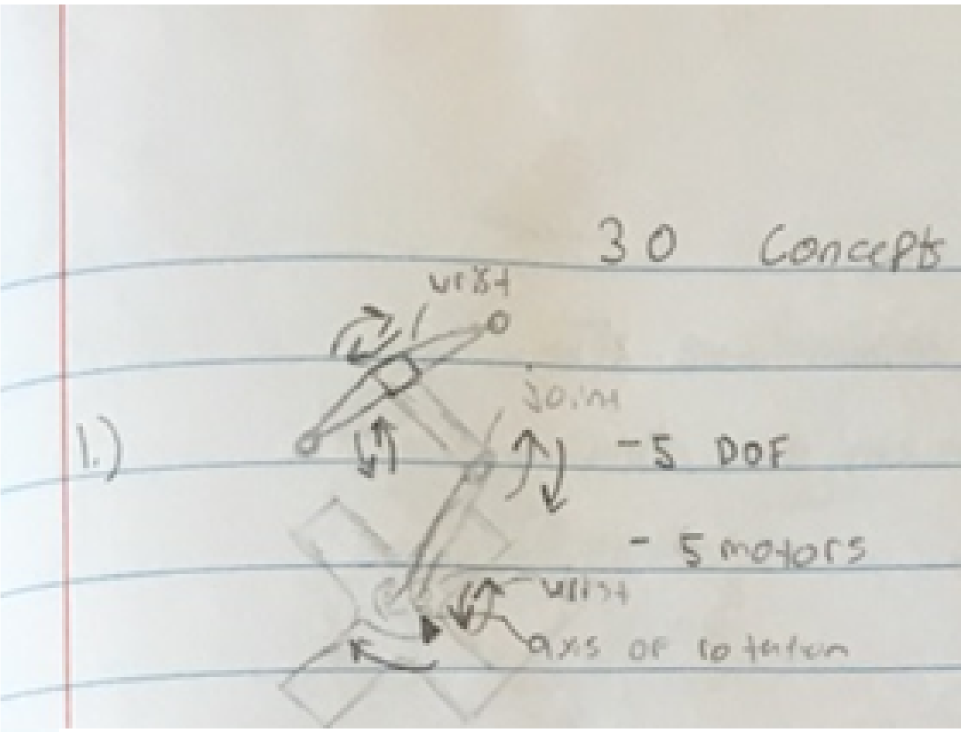


Figure 7.30: Jackson Concept 1

Classic Ball-bar Fixture that includes five degrees of freedom and five motors. Also features two wrist joints located at the base and the farthest arm from the base; and one elbow joint between the base arm and ball-bar arm. This fixture is a modification to the original design proposed by the previous 2010 Capstone team Pentagon.

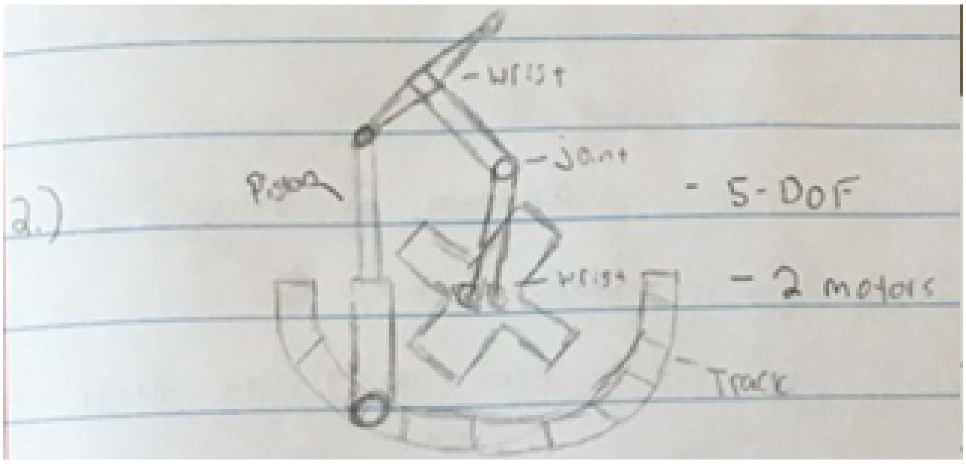


Figure 7.31: Jackson Concept 2

Ball-Bar fixture situated on a track. This simple idea includes a 180 degree track that a piston attached to one end of the ball-bar can manipulate. A positive for this concept is that it would be extremely accurate; however, high maintenance and higher cost. This fixture would require only two motors while sporting 7 degrees of freedom.

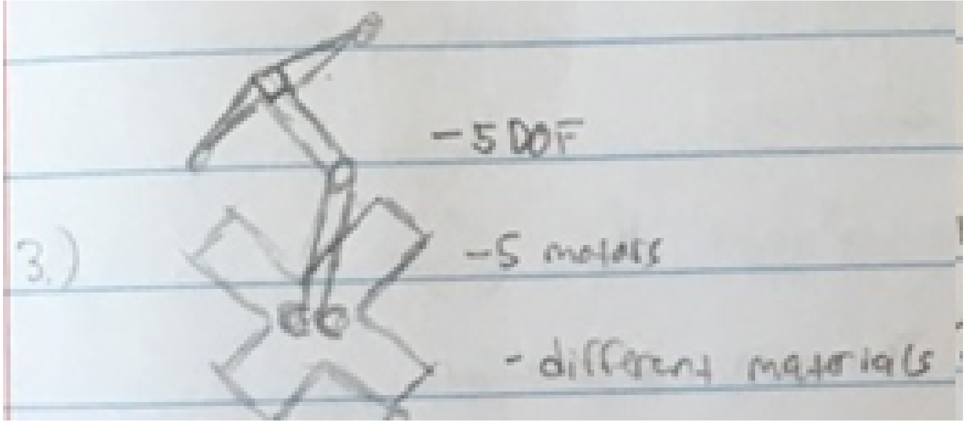


Figure 7.32: Jackson Concept 3

In order to tackle previous conflicts like thermal expansion, moments and cost, different materials could be implemented and simulated. This is a simple however critical factor to the entire fixture; primary materials for testing include, ceramic, glass, granite, quartz

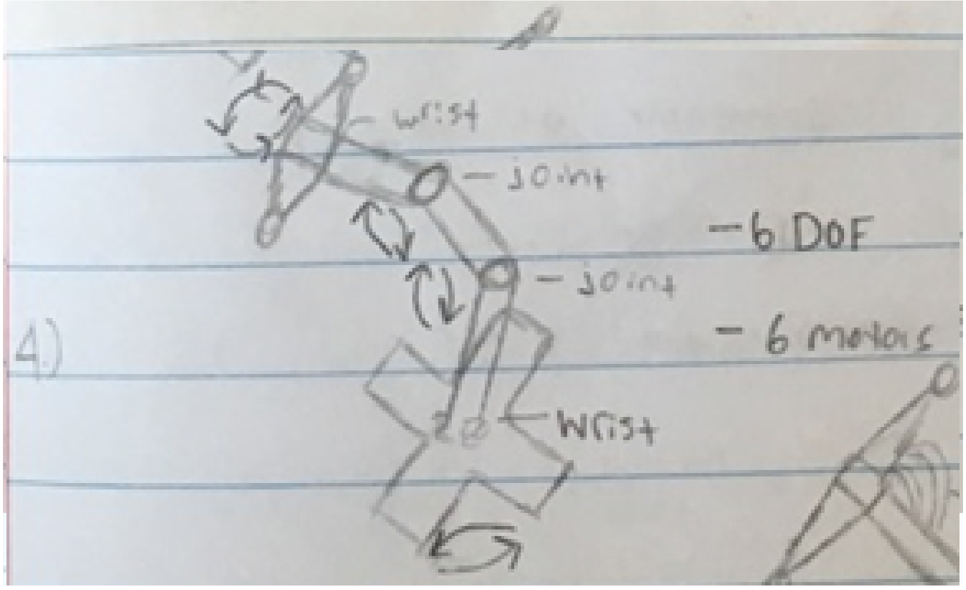


Figure 7.33: Jackson Concept 4

Concept 4 features an extra jointed ball-bar including six degrees of freedom and requiring six motors. The extra joint allows for more accuracy, but trades-off with less precision. The extra joint is unnecessary for current Hexagon standards, however for future calibration and more precise measurements, this design concept orientation might be considerable.

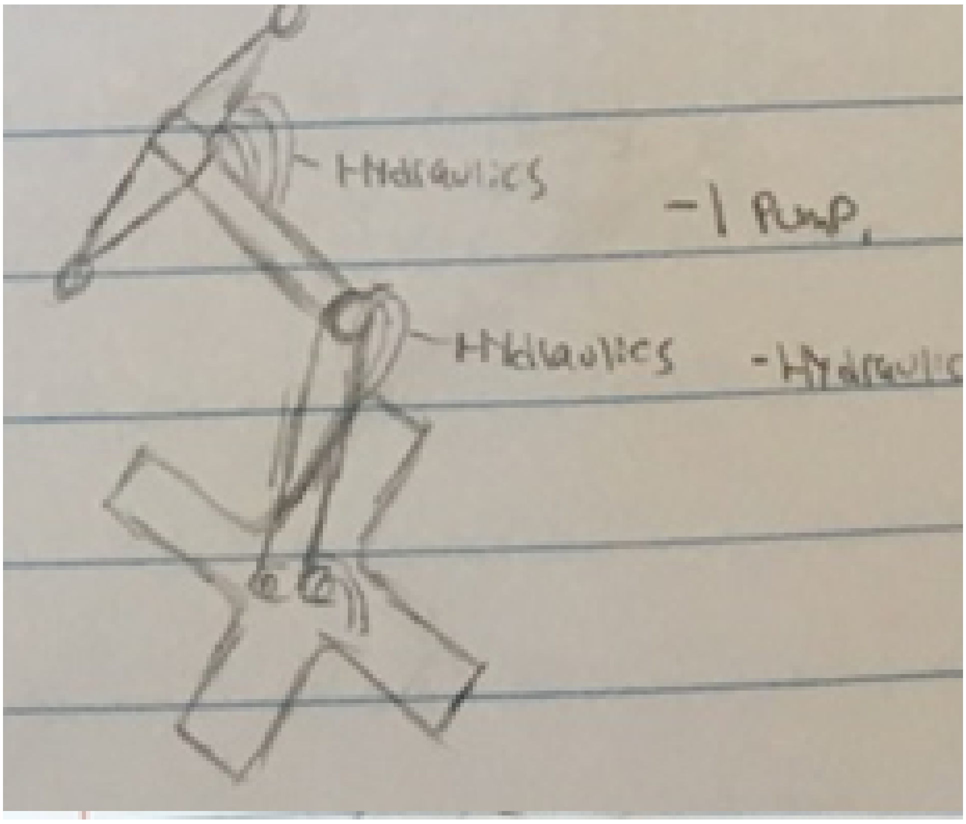


Figure 7.34: Jackson Concept 5

Original ball-bar hydraulically driven; direct pressure right to joints, elbows and wrists. A positive feature of utilizing hydraulics is the precision, and stability. Hydraulics are also ideal for propulsion, guaranteeing that the bar would always be manipulated no matter how massive it becomes. This allows for more leniency with material usage and machining. A downside to hydraulics is that they are expensive and need constant maintenance.

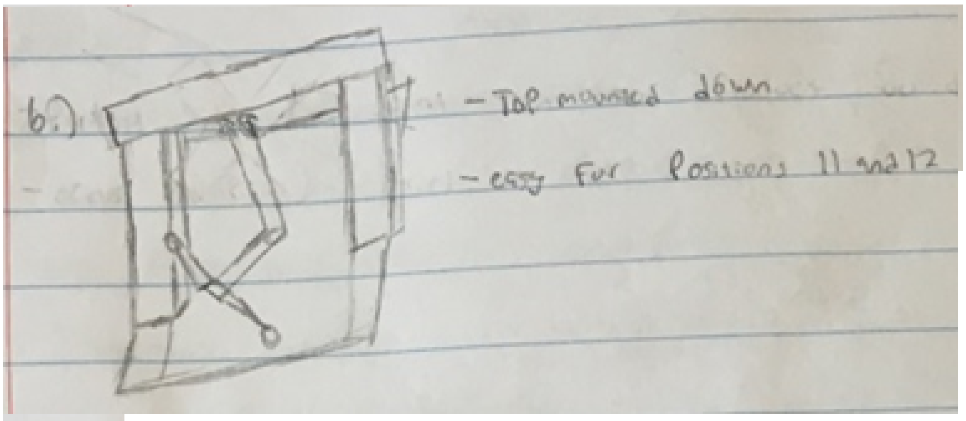


Figure 7.35: Jackson Concept 6

The next concept features a top mounted fixture essentially flipping the degrees of freedom. This fixture is interesting because it may enable the CMM to reach certain positions more accurately; although, it may obstruct the the CMM probe from contacting the ball-bar itself. This design concept is also un-realistic because the CMM does not have any top mounting capabilities.l

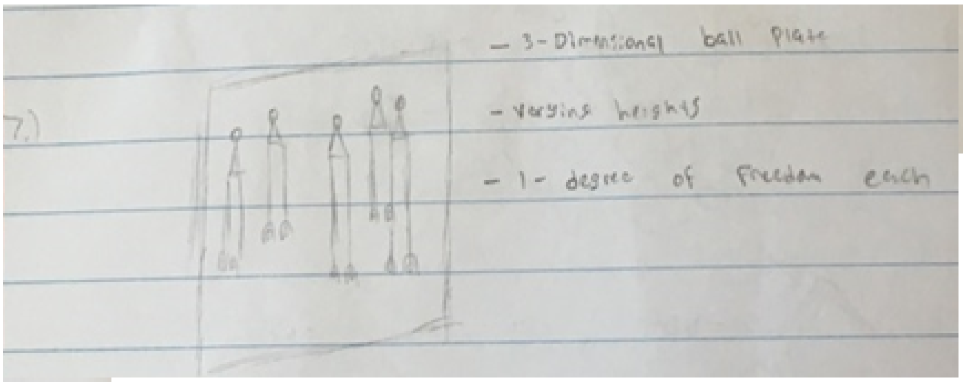


Figure 7.36: Jackson Concept 7

The next Concept includes a three-dimensional static ball plate. It features multiple ball-bars protruding upward from a plate, which may or may not be adjustable depending upon the design specifications. Each ball-bar would vary in height as to meet the design requirements; this concept may also include ball-bars on pistons as to adjust to different heights.

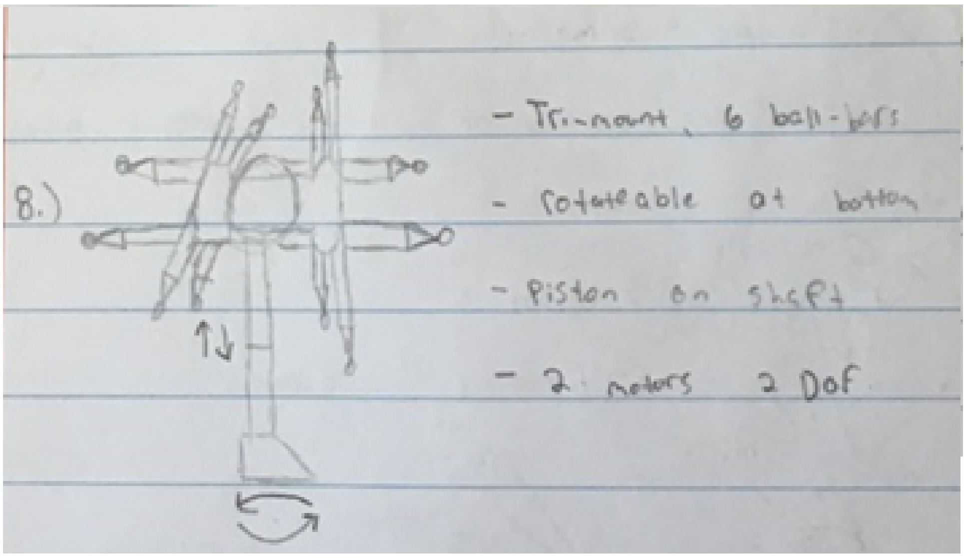


Figure 7.37: Jackson Concept 8

Design Concept 8 is an interesting idea, and a contender for the top concept. It is a realistic, tri-mount ball-bar that includes a static end wrist, but a piston driven output shaft as to adjust to various heights. This fixture is also capable to rotate at the base as to account for the skew errors. It would include two degrees of freedom and two motors.

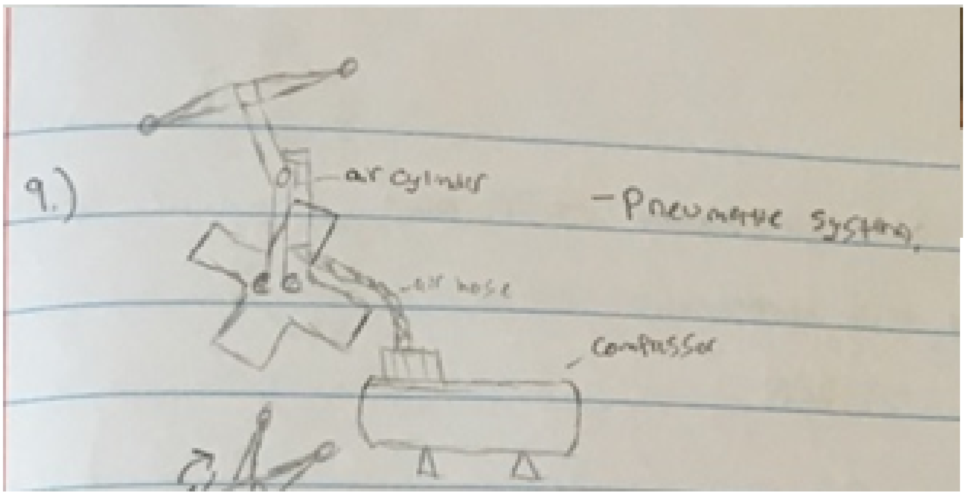


Figure 7.38: Jackson Concept 9

Concept 9 entails different pressure driving systems as well as their positive and negatives. Touches upon pneumatics, comparing to motor driven, comparing to hydraulics. Foreseeable conflicts include, precision and not enough pressure for pneumatics; thermal expansion for motor driven; and cost/efficiency for hydraulics.

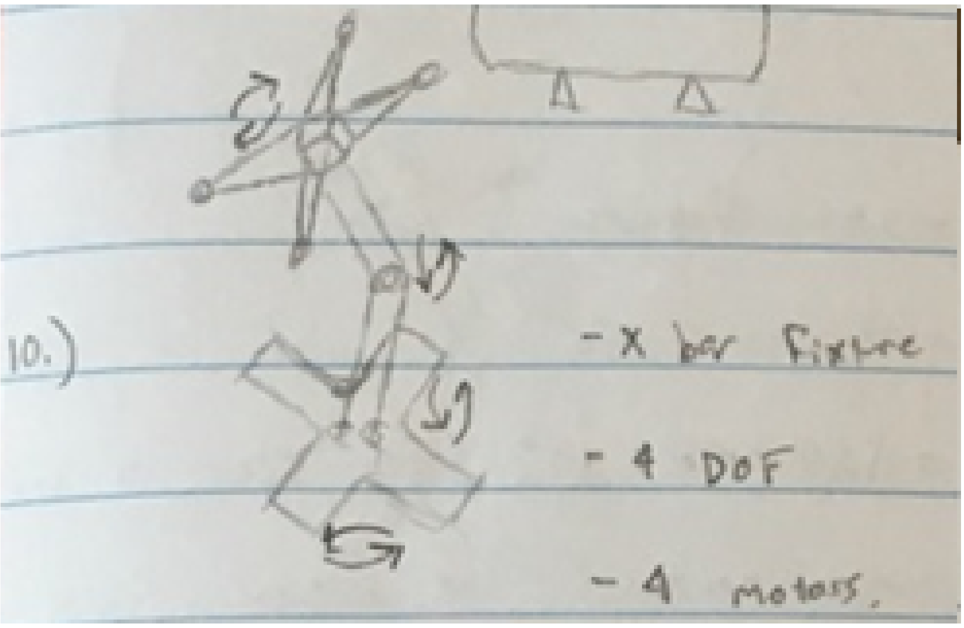


Figure 7.39: Jackson Concept 10

An X-bar fixture is the next featured concept. This manipulator would include four degrees of freedom, four motors and would act similar to the original mechanized ball-bar fixture. The two perpendicular ball-bars would intersect in their mid-section, successfully eliminating one motor. One problem with this fixture is the cost of the ball-bars, and precision as well as the fixture obstructing the CMM from achieving every orientation.

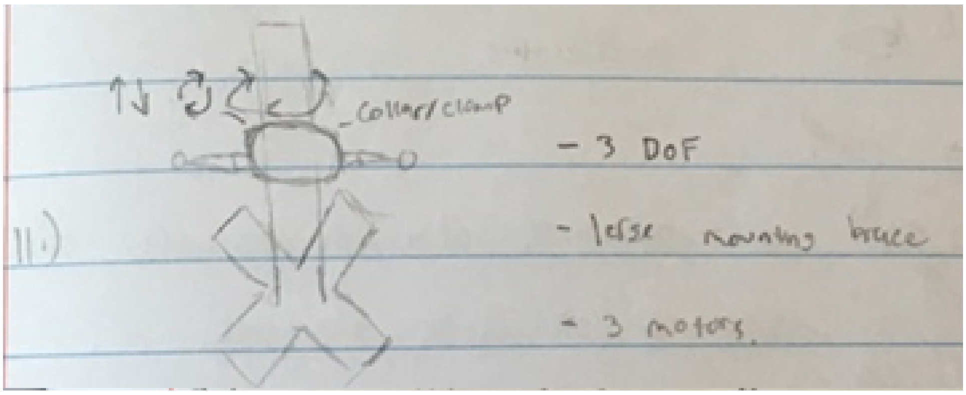


Figure 7.40: Jackson Concept 11

Concept 11 features a collared piston bar system. The ball-bar would be fastened to a collar that is rotate-able around a central column. This fixture would include three degrees of freedom and three motors. The central column would also have a large mounting base and piston as to allow verticality. Some design flaws that would surface include, scaling, repeat ability, reliability, and precision.

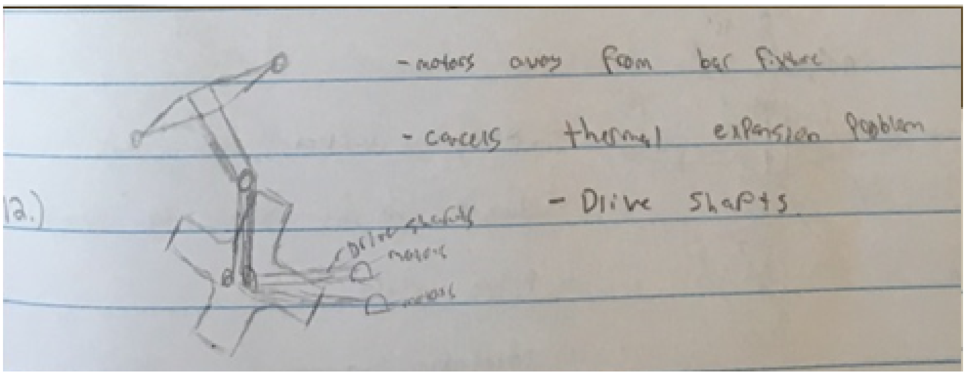


Figure 7.41: Jackson Concept 12

Concept twelve features a direct drive manipulator. This would feature off-site motors, not allowing environmental or physical disturbances. It would also need drive shafts to physically maneuver the fixture; this would severely complicate the optimization process when trying to sync the movements with micro-controllers. It would also severely reduce accuracy, and very expensive and powerful motors would be required to manipulate a hefty fixture.

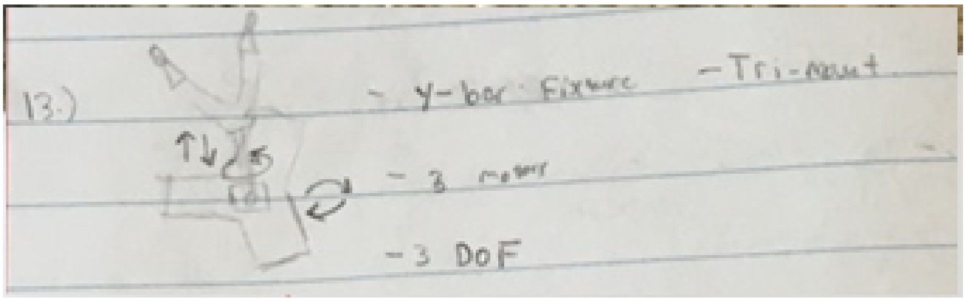


Figure 7.42: Jackson Concept 13

Y-bar fixture is the next concept. This includes a warped ball-bar that forms a "Y" shape presenting a voided space is the mid-section of the ball-bar. This would allow the CMM probe to reach different perspectives of the balls themselves. A foreseeable problem would include droop over time, and awkward moment calculations and movement restrictions. This new ball-bar would sit on top of the original mechanized ball-bar system, including five degrees of freedom and five motors.

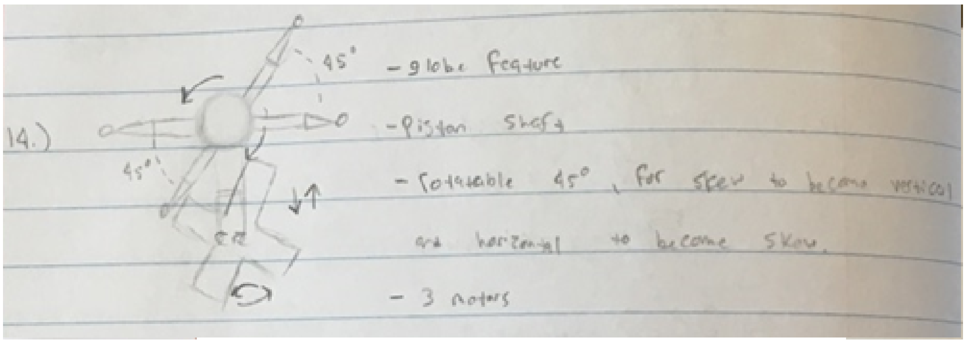


Figure 7.43: Jackson Concept 14

Globe bar fixture is featured next. This arm would have a 'globe' a the end of the base arm piston allowing for near 360 degree rotation. Would also include an x-bar implementation as to account for skew errors. It would include six degrees of freedom and six motors. Design flaws include, precision and emercency troubleshooting.

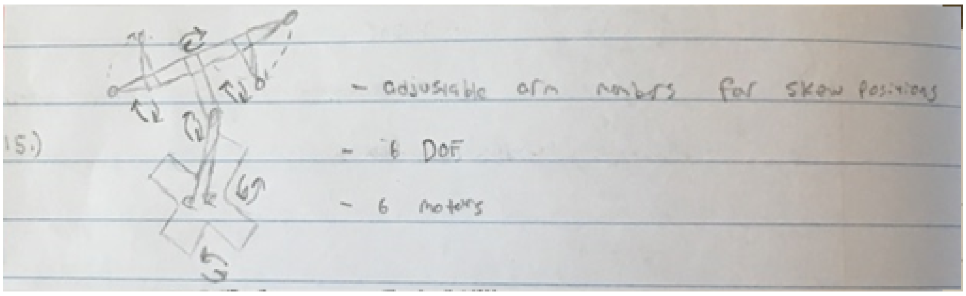


Figure 7.44: Jackson Concept 15

Concept 15 includes a self-correcting bar adjustment feature. This fixture would display two extra joints in the ball-bar itself; allowing for the measurements of skew error positioning while also successfully eliminating 1 motor. A severe design flaw for this concept would be precision; any physical alterations to the ball-bar itself would colossally affect the output measurements of the CMM itself.

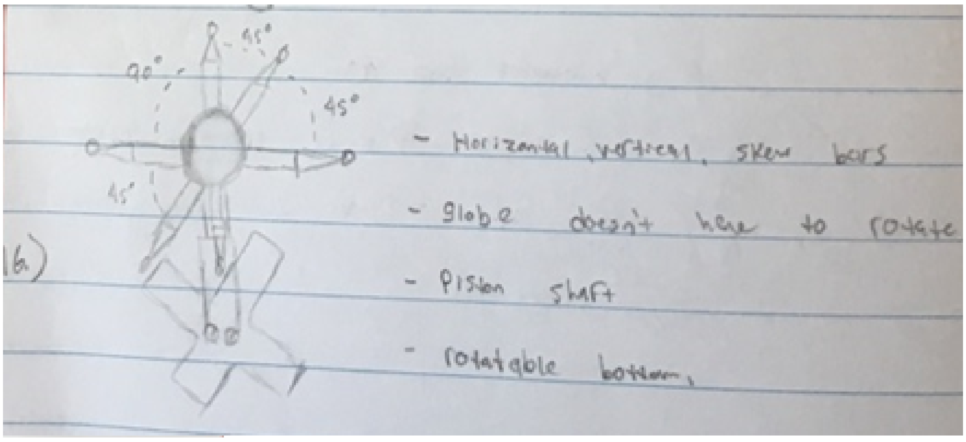


Figure 7.45: Jackson Concept 16

Concept 16 is a modification of the globe fixture. It would include three ball-bars instead of two, eliminating two motors from the original design. The globe would be capable to achieve skew error orientations and would be more compact than the original mechanized ball-bar fixture design.

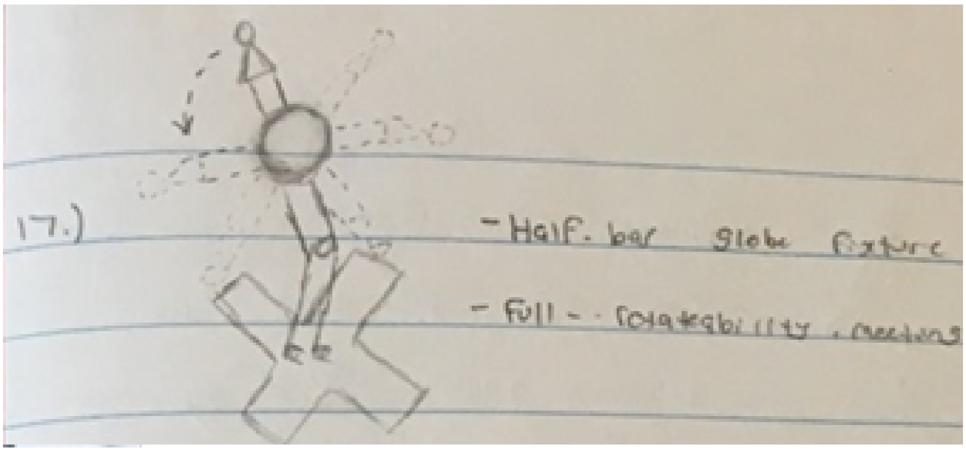
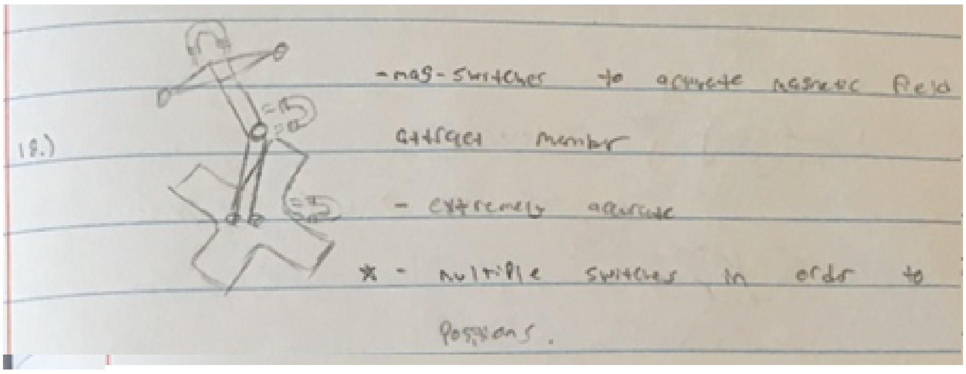


Figure 7.46: Jackson Concept 17

Design 17 is yet another alteration of the parent globe fixture. This time it would only include a half-ball bar, objectively requiring a near 360 degree rotation of the end arm. This fixture would be highly accurate and stable, as well as easy to manipulate without thermal expansion.



18.)

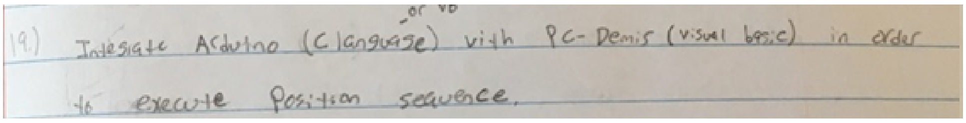
-mag-switches to activate magnetic field attract member

- extremely accurate

* - multiple switches in order to positions.

Figure 7.47: Jackson Concept 18

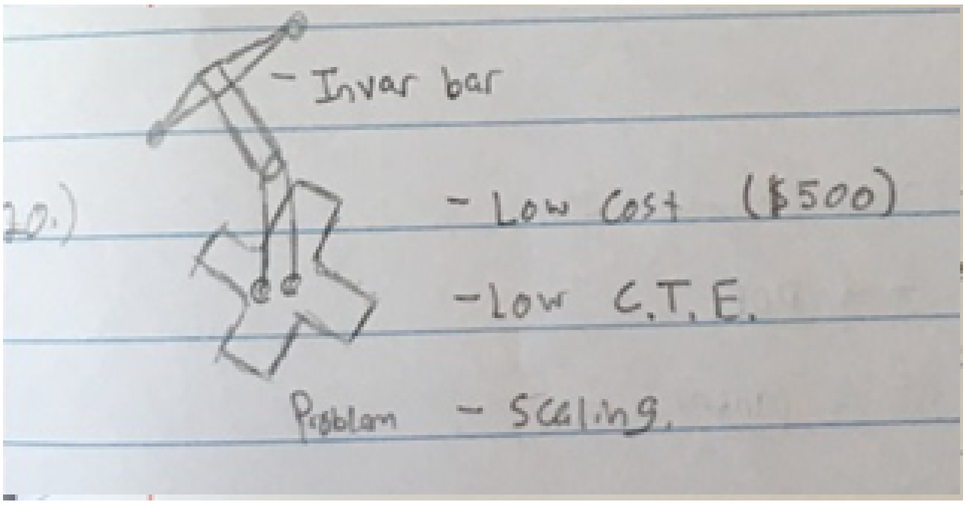
Figure 7.2 displays the usage of magnetic field switches to manipulate the overall fixture. Similar to a DC brush motor, a current running through a magnetic field creating mechanical motion would be the main driving force for this concept. Also one could argue actual magnetic attraction of a ball-bar system; this would optimize accuracy and eliminate motor usage and thermal expansion.



19.) Integrate Arduino (C language) or VB with PC-Demis (visual basic) in order to execute position sequence.

Figure 7.48: Jackson Concept 19

Concept 19 focuses on the optimization of the programming and software features. Arduino or visual basic interfacing integrated with the local parent metrology software that Hexagon utilizes is the ideal goal. Implementing timing functions, as well as troubleshooting and explicit user requests of physical manipulation.



20.)

- Invar bar

- Low Cost ($500)

-Low C.T.E.

Problem - Scaling.

Figure 7.49: Jackson Concept 20

To compensate for the thermal expansion conflict different techniques must be considered. Outside distributors of ball-bar fixtures were contacted for assistance for thermal expansion; they recommended the usage of Invar material, which has an extremely low coefficient of thermal expansion. Invar is commonly used for metrology purposes because of its extremely low thermal expansion; if this bar was implemented, thermal expansion reduction would reduce by a factor of 20.

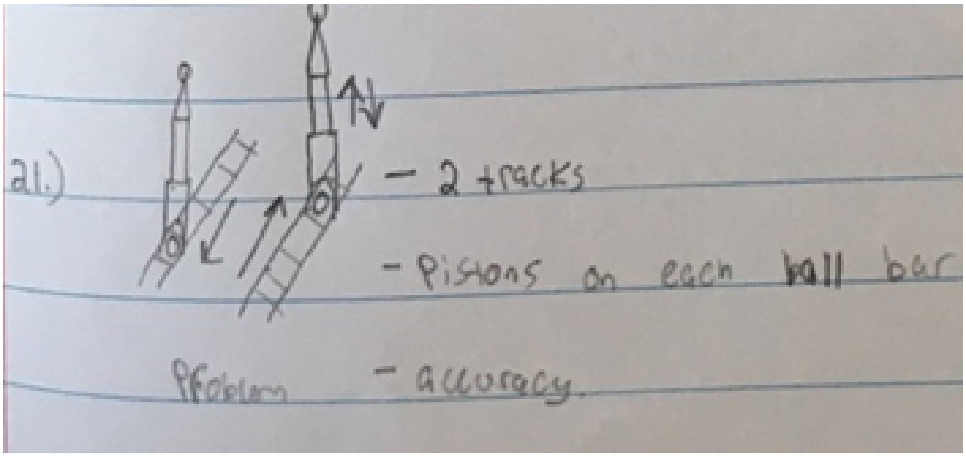


Figure 7.50: Jackson Concept 21

Concept 21 features a track-bar fixture sporting two ball-bars fastened to pistons on tracks. These ball-bars would be controlled remotely by a local computer software interface. Magnetic switch stoppers would halt the process in case of emergency. This fixture would include four motors and four degrees of freedom.

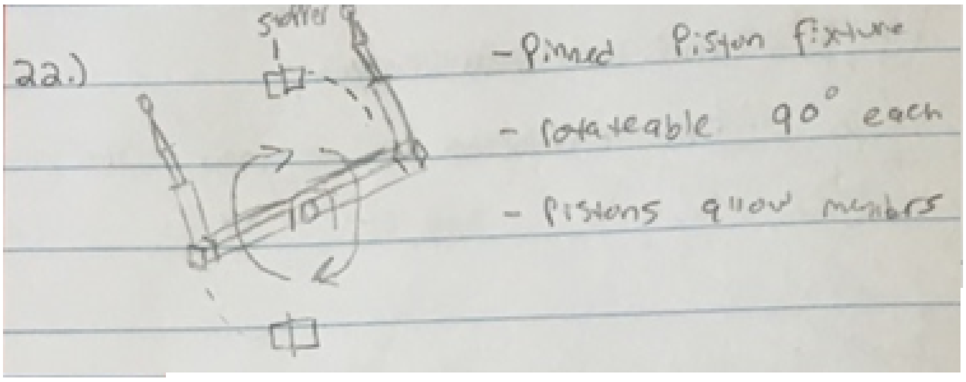


Figure 7.51: Jackson Concept 22

A pinned piston fixture is the next concept. The main attractions for this manipulator include, high accuracy and stability when fixed into position. This fixture would also feature pistons for verticality. It would also include 3 motors and 5 degrees of freedom.

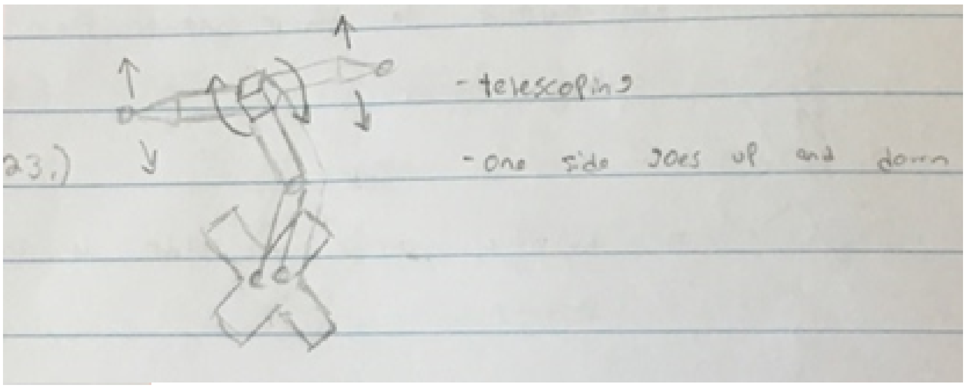
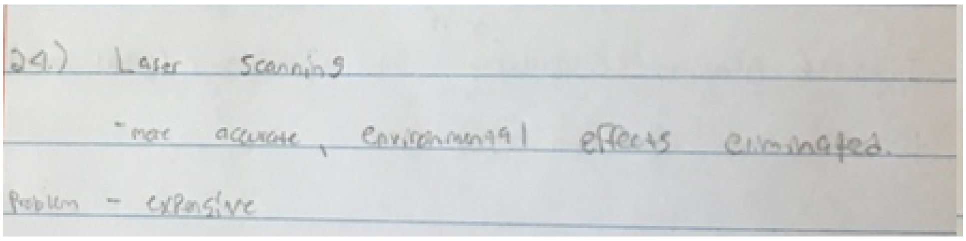


Figure 7.52: Jackson Concept 23

Concept 23 is a Telescoping ball-bar. This fixture would include two independent ball-bars that are capable of movement without one another. A foreseeable design flaw is that precision up to microns would be difficult to achieve if each ball-bar is even the slightest skewed from one another. This fixture would have 5 degrees of freedom and 5 motors.



24.) Laser Scanning

- more accurate, environmental effects eliminated.

Problem - expensive

Figure 7.53: Jackson Concept 24

The next concept includes a complete re-design of the entire fixture. It involves laser scanning, or optical metrology, which would be highly accurate but also more expensive as a trade off. Optical CMM's are extremely prolific and highly valued in industry today; they are most commonly used in quality engineering and are extremely useful for tolerancing. Although, optical metrology is extremely difficult to pro-create.

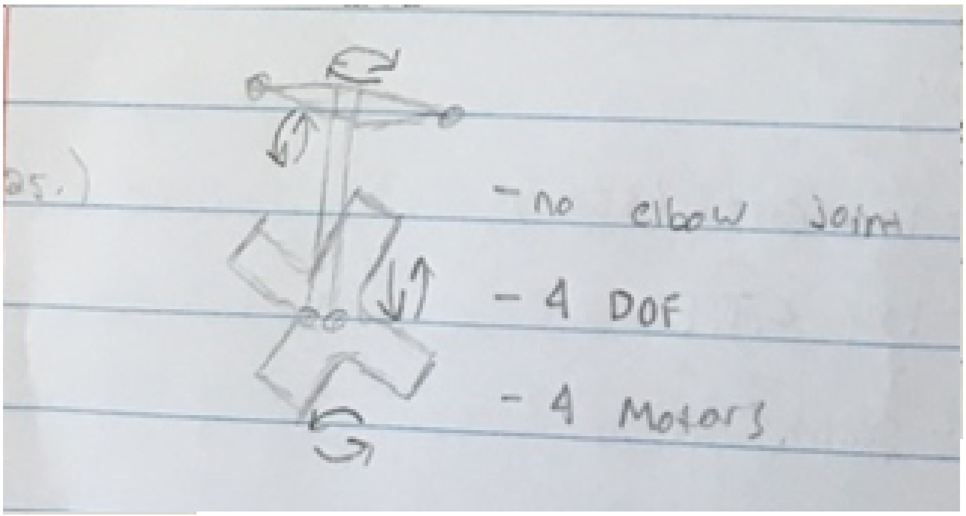


Figure 7.54: Jackson Concept 25

25 features a moderately scaled version of the previous mechanized ball-bar system team Pentagon proposed. It features a fixture with one arm separating the ball bar from the base. This would increase accuracy, however the positioning of the bar may not allow for all of the error orientations. This fixture would only have four degrees of freedom and four motors. Further research is needed to determine if a ball-bar of this orientation would satisfy all of Hexagons requirements and standards to meet error mapping.

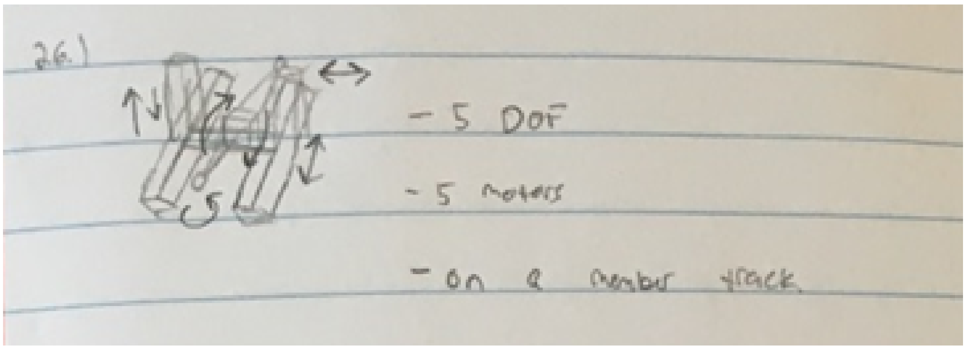


Figure 7.55: Jackson Concept 26

Design 26 features a telescoping track fixture. It is a generally bulky widget, however, it is extremely stable and precise. The fixture would include a three-dimensional arching arm that would guide the ball-bar through 3-d space. Some foreseeable problems would include; scaling difficulties, and obstruction of the CMM probe. This fixture would include 6 degrees of freedom and 5 motors.

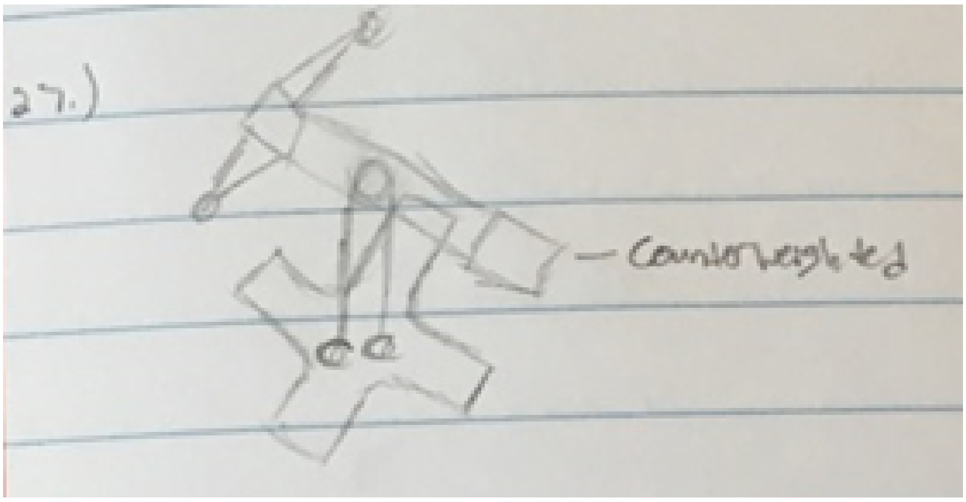


Figure 7.56: Jackson Concept 27

Design 27 features a counter-weighted fixture. This is a design that is extremely prolific throughout the robotics and robot arm industry. If standards require us to be precise up to microns of a meter, moment torques of the weight of the fixture itself might throw the entire process off balance. A counter weight would compensate for extreme stresses in certain orientations; although, with each counterweight added, there exists a new issue onto the next member of the assembly. This is one of the most prevalent flaws deterring us from utilizing this concept. Counterweights would most likely be implemented onto the original design fixture with 5 degrees of freedom and 5 motors.

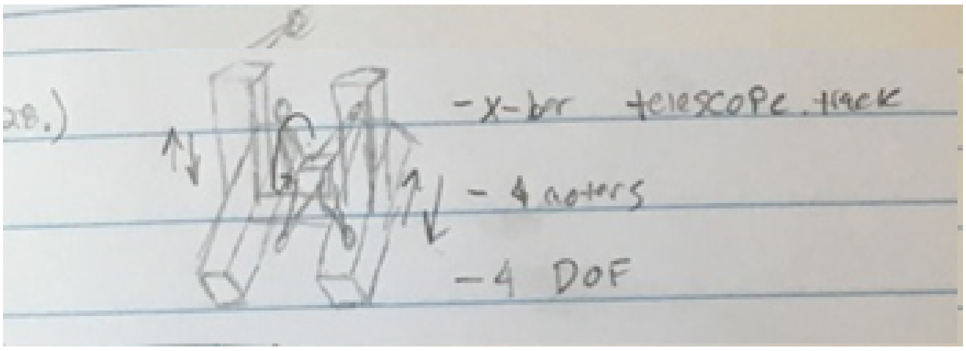


Figure 7.57: Jackson Concept 28

The next concept is a hybrid of two previous ideas. It combines the x-bar and the telescoping track concepts. This fixture would display a cube-like skeletal track allowing the fixture to move about freely within the void of its space. Stability and accuracy are two qualities of this concept. Some foreseeable design flaws would include the fixture obstructing the CMM probe from contacting the specimen; and scalability. This fixture would have four degrees of freedom and four motors

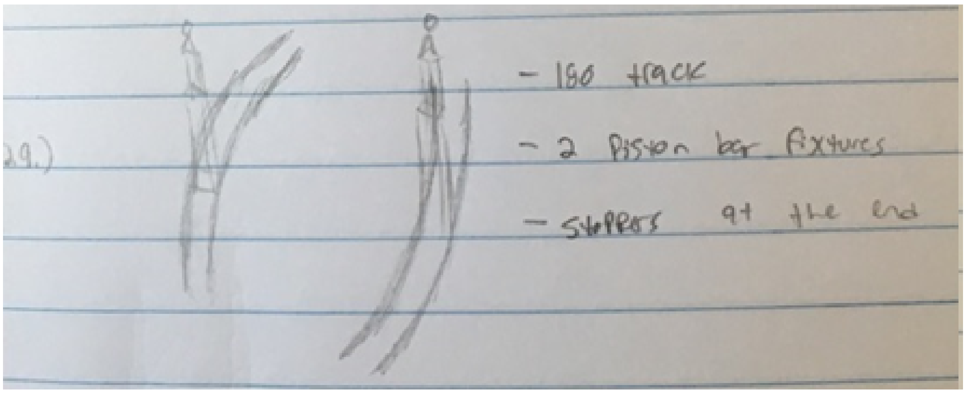


Figure 7.58: Jackson Concept 29

Design concept 29 features a 180 degree piston track, with ball-bars fastened to the ends. The two tracks and fixtures would be independent of one another; however, they would be synced with software GUI coding to maximize efficiency. This fixture would most likely not be a great contender for proof of concept due to the fact that the ball-bars are independent of one another, increasing uncertainty. This fixture would include four degrees of freedom and four motors

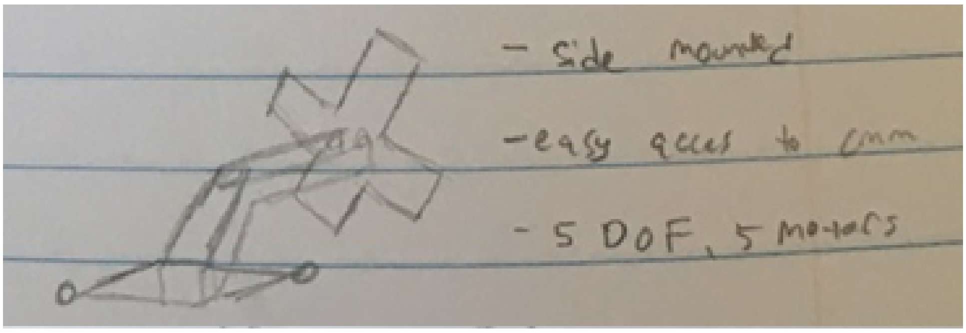


Figure 7.59: Jackson Concept 30

The last concept includes a side mounted ball-bar fixture. This manipulator would fasten to a custom made base plate and protrude from the side. This fixture is ideal because it allows for the CMM probe to contact the ball-bar with ease. It also successfully eliminates one motor. A foreseeable design flaw is a re-design to the CMM itself would have to be considered, and Hexagon stressed that was out of the question. This fixture would include four degrees of freedom and four motors

7.3 Taylor Fields Concepts

Swivel Base

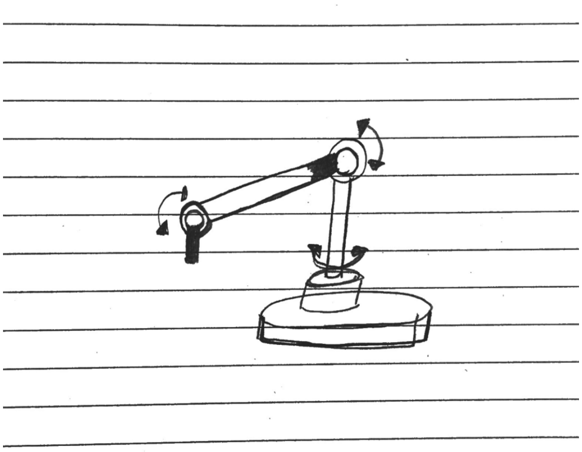


Figure 7.60: Taylor Concept 1

This concept utilizes a base that can swivel. This would allow a mirrored operation of the sequence, essentially cutting the needed code in half.

Dual Ball Bar

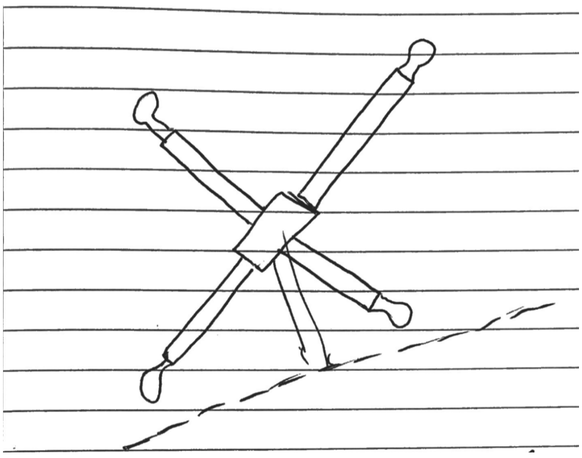


Figure 7.61: Taylor Concept 2

Adding a second ball bar to the setup would allow us to fix the last manipulator instead of having to rotate a single bar. This would reduce the wear and complexity of this device.

3 bar with fixed 4th

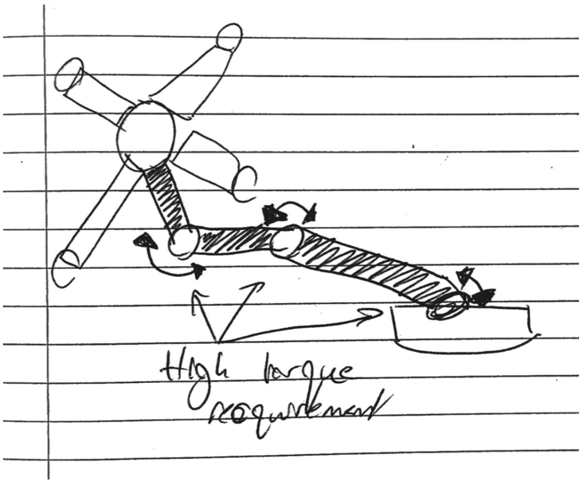


Figure 7.62: Taylor Concept 3

This setup uses the dual bar idea to increase the rigidity and remove all heat input from the final linkage, because that is the most critical component to avoid heat.

"Stewart Platform" with pistons

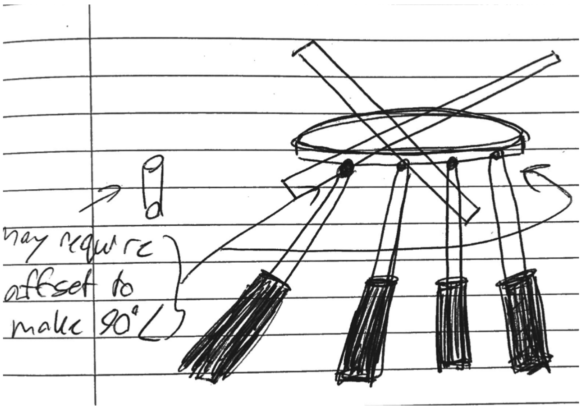


Figure 7.63: Taylor Concept 4

The setup uses air pistons to manipulate a platform for the ball bar to attach to. This series of air pistons allow for a high level of control without any heat buildup. All the air power can be forced remotely.

"Stewart Platform" with screws

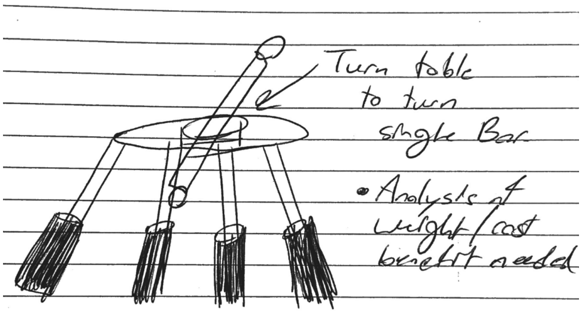


Figure 7.64: Taylor Concept 5

This version is the same exact setup as the previous one but instead of using pistons powered by air, motors are used to remotely turn screws up and down the on the corners. The advantage of using the screws instead of pistons is that the power can be shut off and the platform will stay stationary.

Right Angle Mount

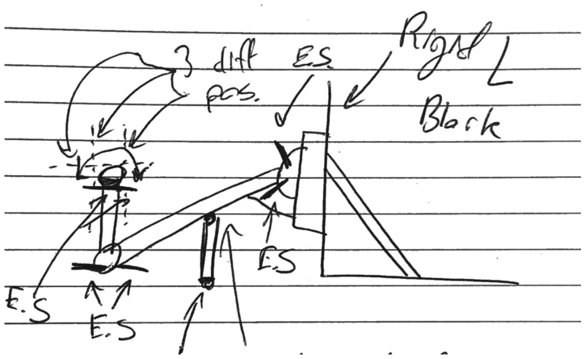
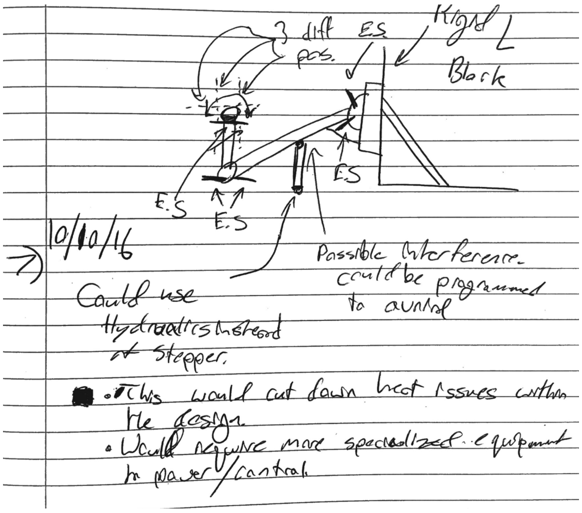


Figure 7.65: Taylor Concept 6

Taking the previous design and turning it on its side would free up a larger area of free space, allowing for more precise manipulation. Powered with steppers and screw type position holders.

Right angle hydraulic



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Possible interference. could be programmed to avoid

Could use Hydraulics instead of stepper.

- This would cut down heat issues within the design.
- Would require more specialized equipment for power/control.

Figure 7.66: Taylor Concept 7

same setup of the previous design, however replaces stepper motors with hydraulic rams to push and pull the arms into place. This would ideally allow for no heat build up.

Hydraulic Stepper

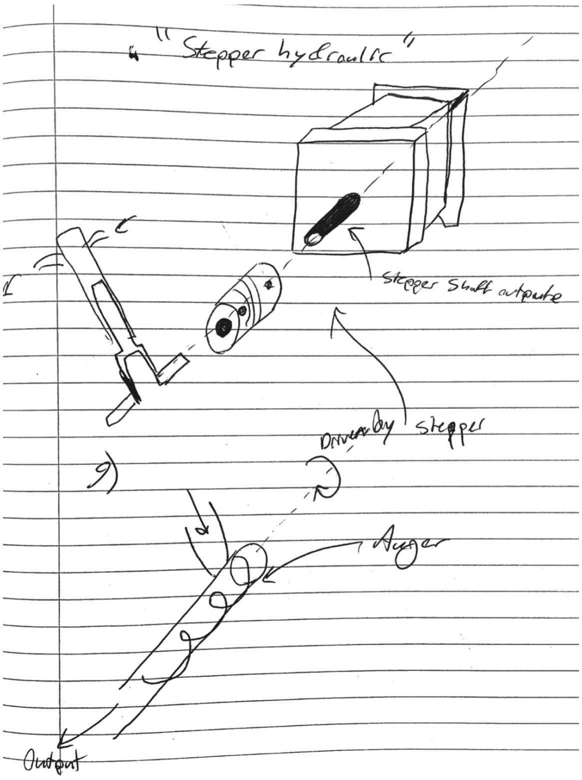


Figure 7.67: Taylor Concept 8 and 9

Instead of using a directly drive stepper motor, a hydraulic ram piston can be utilized. There is not an accurate way to control the motion of the fluid moving about in a standard hydraulic pump, so design 8 makes use of a piston volume pump attached to a stepper motor. This would essentially make for an extremely accurate fluid control process.

Design 9 uses the same design except instead of using a piston setup to control fluid volume, a screw type pressurizer is used. The advantage to this setup is efficiency.

End Stop top bar

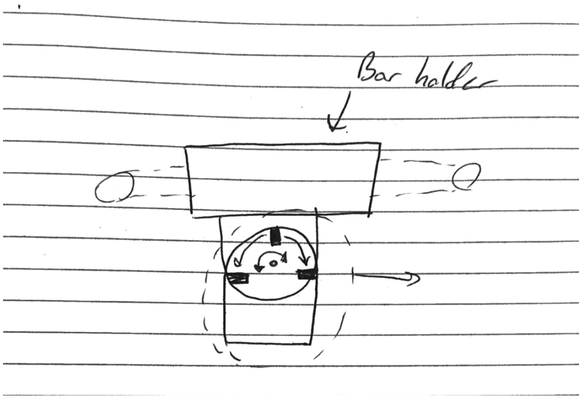


Figure 7.68: Taylor Concept 10

Using end stops allow for 100 percent accurate end positions. There would also be no wear as the end stops would be made of the same material as the arms.

Air over End Stops

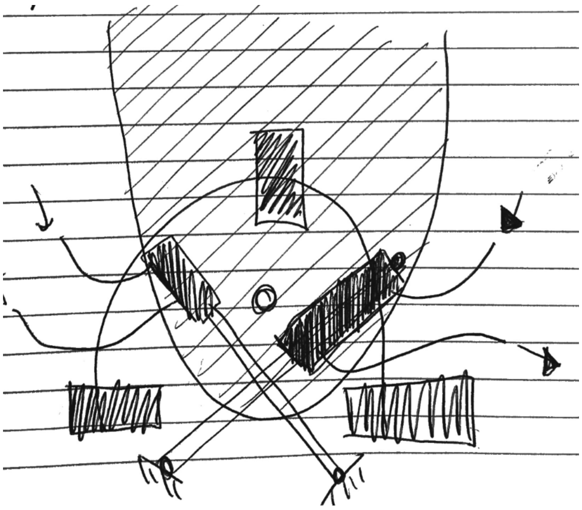


Figure 7.69: Taylor Concept 11

With positively identified end stops, the top bar can be rotated by any means, such as dual air pistons.

Thrust Bearing Joints

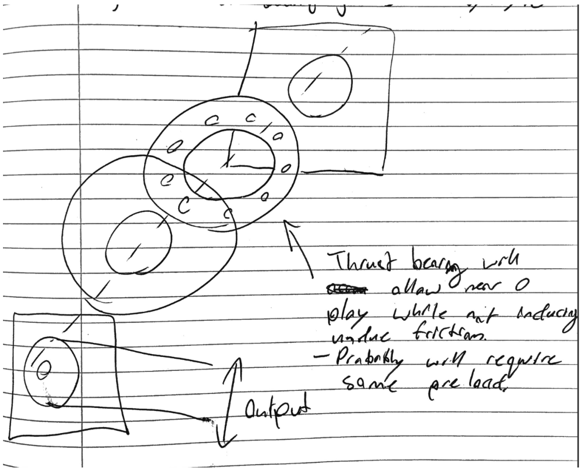


Figure 7.70: Taylor Concept 12

Placing a thrust bearing between the arm and motor interface would minimize the twisting force on all of the motor shafts. The bearings are inexpensive and easy to replace if ever worn.

Light Disk Rotation

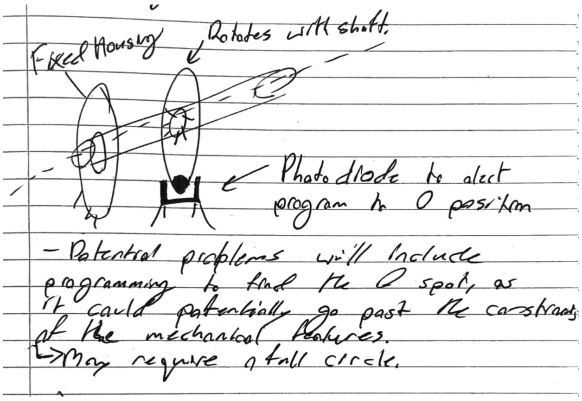


Figure 7.71: Taylor Concept 13

Placing a ring on the rotating shaft and using an LED and light sensor would allow the location of the shaft to be known in the same way as a potentiometer but with no extra space requirements.

Potentiometer on Shaft

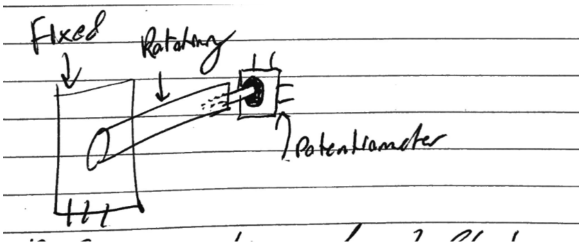


Figure 7.72: Taylor Concept 14

On the backside of the rotating output shaft, a potentiometer could be adhered. This would relay absolute position to the microprocessor, and potentially be the most accurate option.

End stop switch

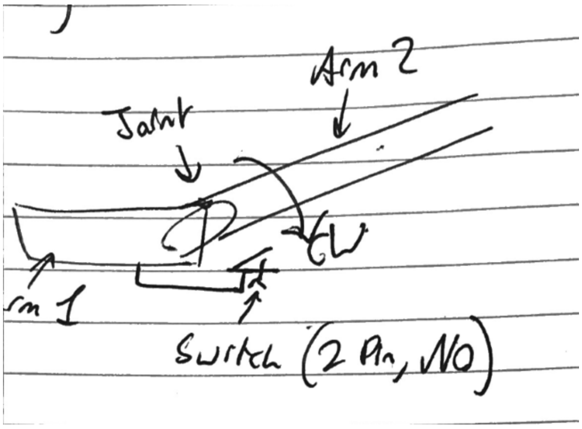


Figure 7.73: Taylor Concept 15

Running a calibration function initially could help reduce error in movements, but the variables would first need to be zeroed at the home position. Placing a switch where an arm could contact it could reset the home position.

LED indicators

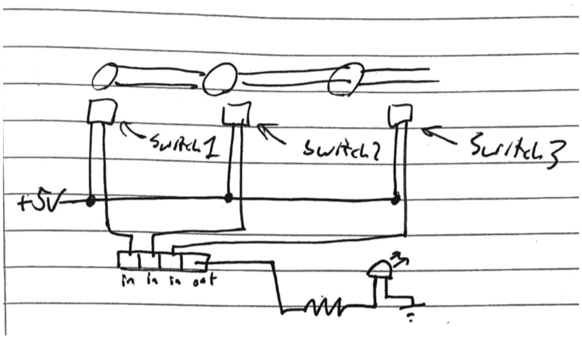


Figure 7.74: Taylor Concept 16

Building off of the previous idea that uses end stops to tell the microprocessor where the home location is, this concept uses LED lights placed on the arms to show the operator that the function has been completed. This will help to increase accuracy.

Stop Switch circuit

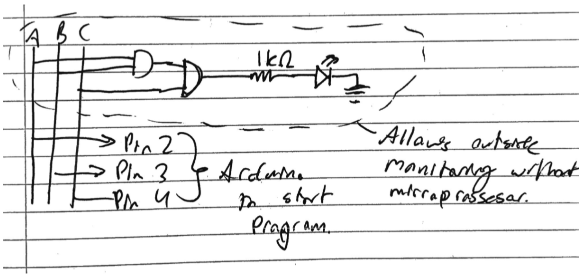
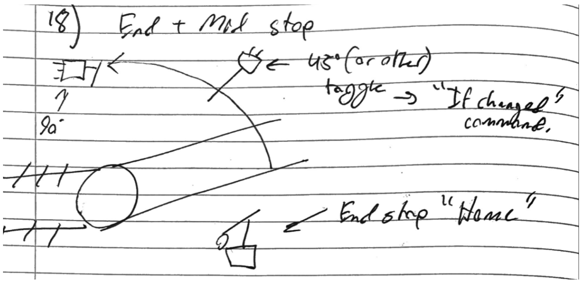


Figure 7.75: Taylor Concept 17

Here is a circuit diagram that can tell the arduino controller and operator where the arms are located.

Three Position Stop

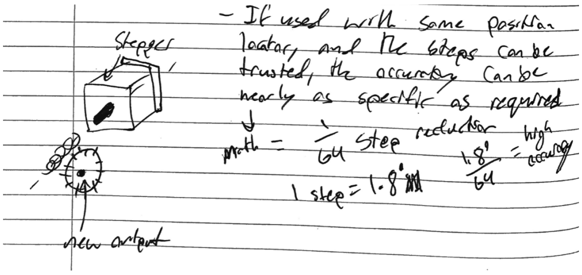


toggle → "If changed" command.

Figure 7.76: Taylor Concept 18

If end stops can be used at the home position, they could be implemented at other positions throughout the movement process. This could be used to show definitive position of the arm.

Worm Drive Stepper



- If used with some position locator, and the steps can be trusted, the accuracy can be nearly as specific as required

math = 1/64 step reduction

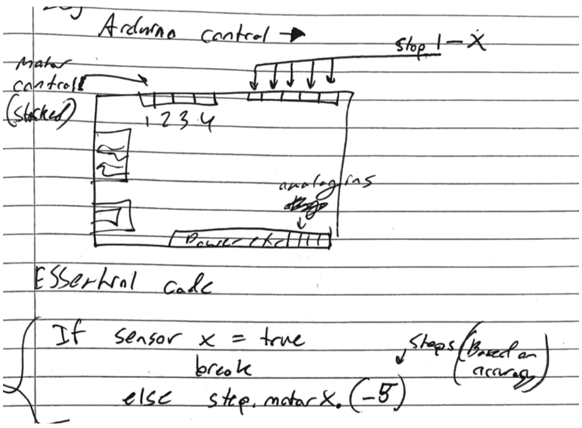
1 step = 1.8°

1.8°/64 = high accuracy

Figure 7.77: Taylor Concept 19

By implementing a worm gear reduction between the stepper and the arm would allow a very accurate movement of the arm. The screw type gearing would also allow for the motor to be self locking, so that the power to the stepper could be shut off to prevent heating of the joints.

Arduino Controller



Essential code

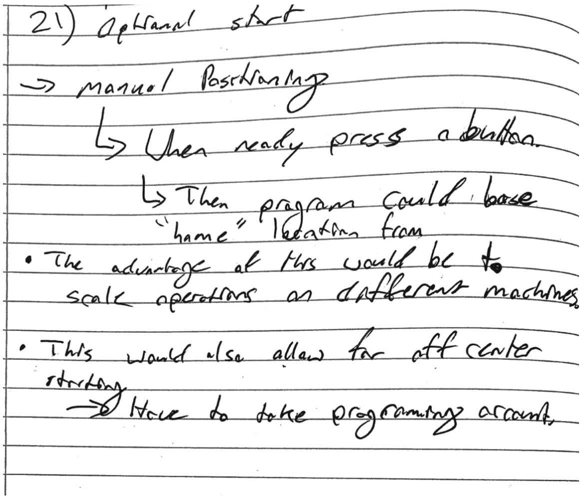
```
If sensor x = true
        break
    else step.motorX.(-5)
```

steps (Based on accuracy)

Figure 7.78: Taylor Concept 20

Using an arduino to control the movements of all the arms would allow for an easily manipulation of all the components in this system.

Optional Start



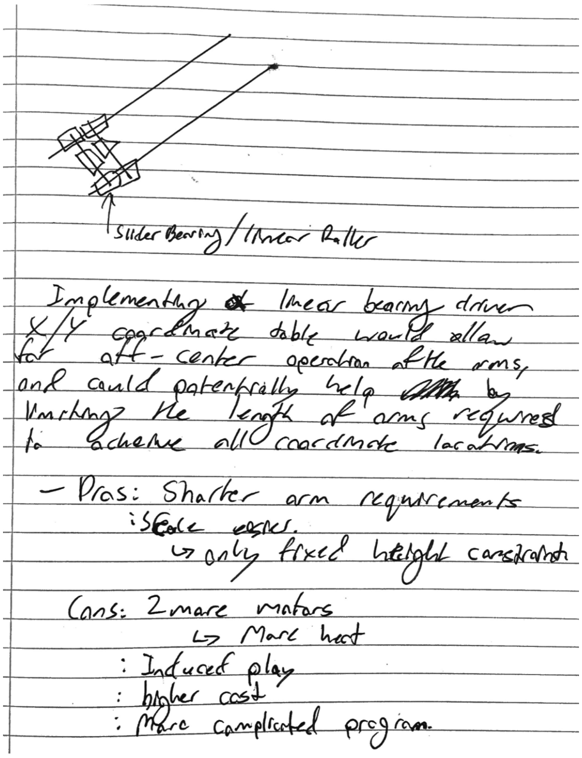
21) optional start

→ manual Positioning
  ↳ When ready press a button.
    ↳ Then program could base "home" location from
- The advantage of this would be to scale operations on different machines.
- This would also allow for off center starting
  → Have to take programming account.

Figure 7.79: Taylor Concept 21

A button could be added to on the device interface to allow for starting and stopping the process on demand. This would be particularly useful for the implementation of PCDMIS program.

Slider Bearings



Implementing ~~a~~ linear bearing driven X/Y coordinate table would allow for off-center operation of the arms, and could potentially help by limiting the length of arms required to achieve all coordinate locations.

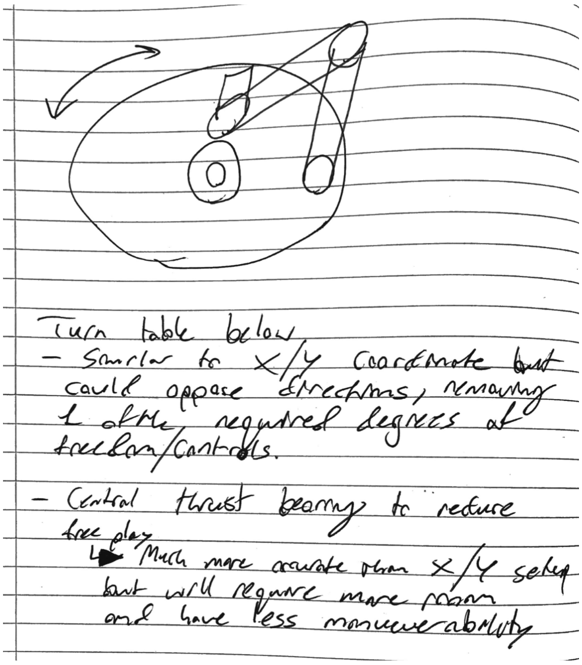
- Pros: Shorter arm requirements
    : Scale easier.
        ↳ only fixed height constraint

Cons: 2 more motors
    ↳ More heat
    : Induced play
    : higher cost
    : More complicated program.

Figure 7.80: Taylor Concept 22

In this setup, a slider bearing rail is used instead of articulating arms. This could be beneficial in that the play could be adjusted out of the system as it is worn. The only downside is that the moment of bar contact would be multiplied since all of the forces are nearly purely vertical.

Rotary Table



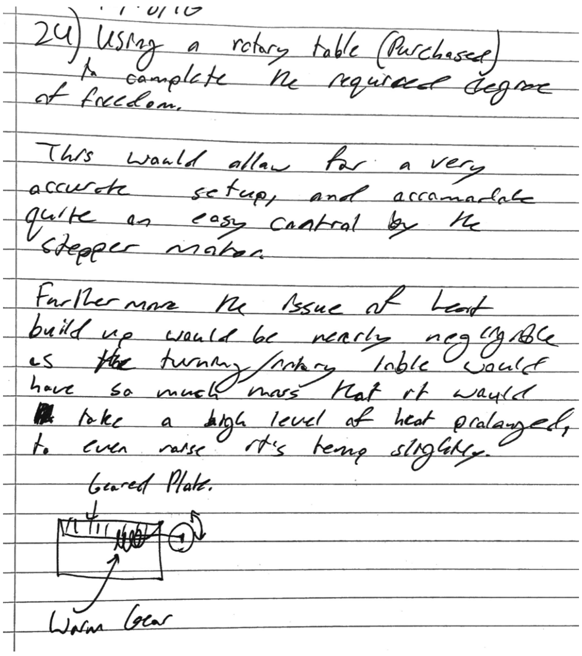
Turn table below

- Similar to X/Y coordinate but could oppose directions, removing 1 of the required degrees of freedom/controls.
- Central thrust bearing to reduce free play
  - Much more accurate than X/Y setup but will require more room and have less manueverability

Figure 7.81: Taylor Concept 23

Along the lines of the previous design, this design moves the base instead of a gang of arms. This rotary table is perfect for the implementation of thrust bearing. This would reduce nearly all the free play in the system.

Screw on Rotary Table



24) Using a rotary table (Purchased) to complete the required degree of freedom.

This would allow for a very accurate setup, and accomadate quite an easy control by the stepper motor.

Furthermore the issue of heat build up would be nearly negligable as ~~the~~ turning/rotary table would have so much mass that it would take a high level of heat prolonged, to even raise it's temp slightly.

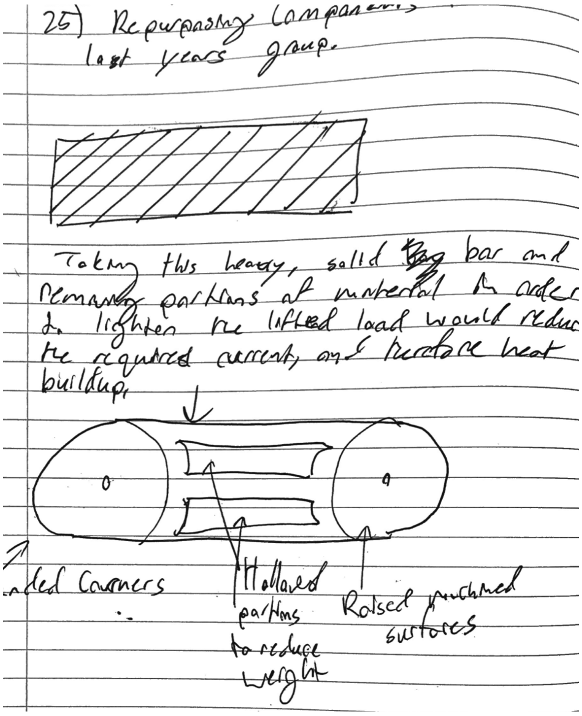
Geared Plate.

Worm Gear

Figure 7.82: Taylor Concept 24

By turning the rotary table with a worm gear instead of a direct drive system, a worm gear could be used to rotate and lock the rotation.

Re-purposing Applicable Parts



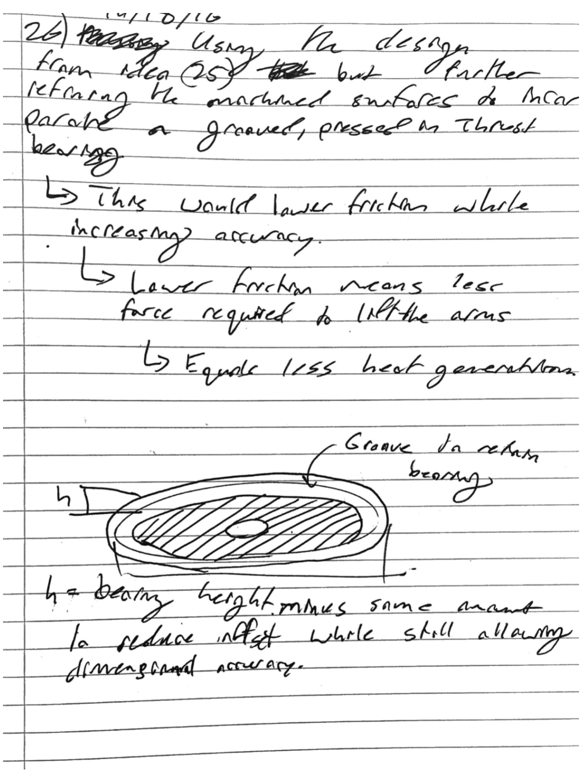
25) Repurposing Components
last years group.

Taking this heavy, solid ~~[illegible]~~ bar and removing portions of material in order to lighten the lifted load would reduc the required current, and therefore heat buildup.

Figure 7.83: Taylor Concept 25

To save on material for the proof of concept, the bars built by the last group can be re-cut and proportioned for our project. This is a huge saving because of the cost of raw stock.

Base Rotation Friction Joint



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26) Using the design from idea (25) ~~the~~ but further refining the machined surfaces to incorporate a grooved, pressed in thrust bearing.

↳ This would lower friction while increasing accuracy.

↳ Lower friction means less force required to lift the arms

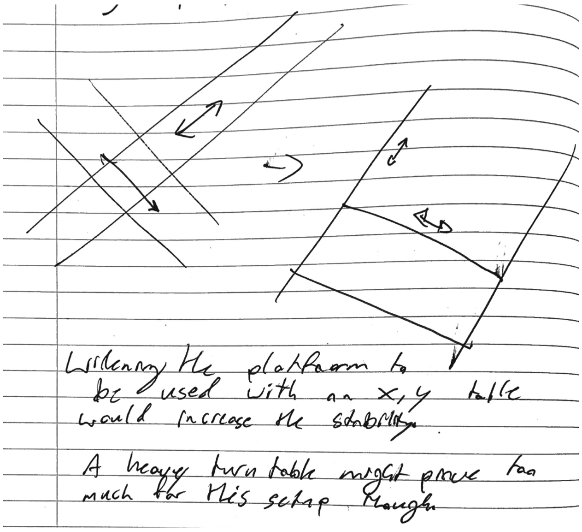
↳ Equals less heat generation.

h = bearing height minus some amount to reduce offset while still allowing dimensional accuracy.

Figure 7.84: Taylor Concept 26

When the base is rotated, it will need to be locked and unlocked. Rather than using a complicated locking mechanism, we can torque 2 machined surfaces against each other and use the friction to hold it in place. The motor could be used to simply overcome this frictional force.

XYZ Table



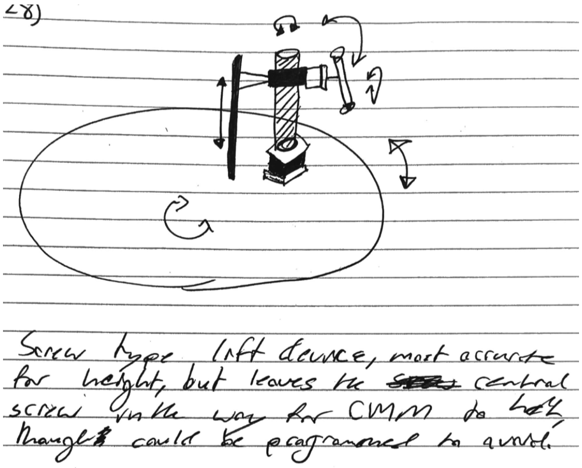
Widening the platform to be used with an x, y table would increase the stability.

A heavy turn table might prove too much for this setup though

Figure 7.85: Taylor Concept 27

Essentially turning a 3D printer inside out and mounting the ball bar to the cross carriage would allow the use of commercially available programs to control the movement of the mechanism.

Central Screw Tower



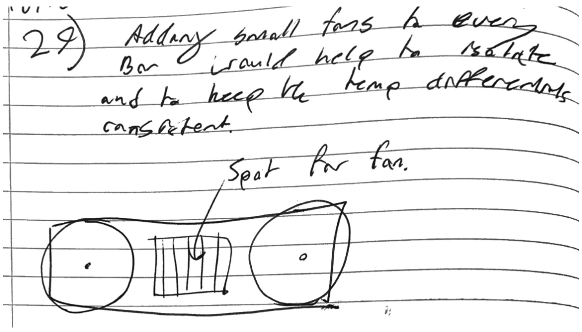
28)

Screw type lift device, most accurate for height, but leaves the central screw in the way for CMM to hit, though could be programmed to avoid.

Figure 7.86: Taylor Concept 28

Using a tower of a screw to move a carriage up and down could produce a huge range of positions while maintain an extremely high level of accuracy. This setup would induce a large friction on the screw which could cause premature wear of the system.

Fans in Arms

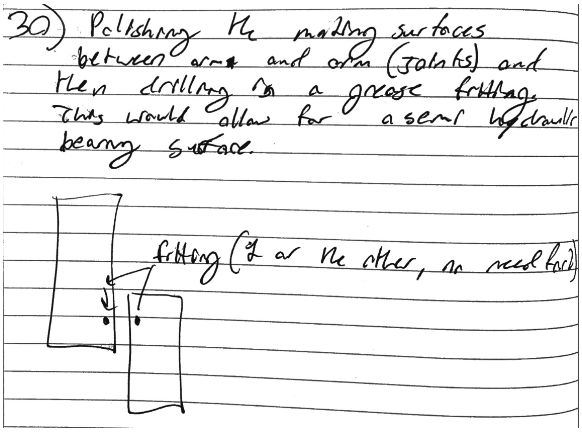


29) Adding small fans to every Bar would help to isolate and to keep the temp differentials consistent.

Figure 7.87: Taylor Concept 29

Heat is a major problem within these systems, so in order to maintain a more constant temperature fans could be placed on the arms themselves. This would increase the convective cooling effects on the arms and lower the risk of heating.

Polishing and Greasing



30) Polishing the mating surfaces between arm and arm (joints) and then drilling in a grease fitting. This would allow for a semi hydraulic bearing surface.

Figure 7.88: Taylor Concept 30

By polishing the mating surfaces at every meeting point, the friction can be significantly lowered in order to reduce motor strain. Grease fittings can be added to further lower the drag and the corrosive nature of the interface.

7.4 Jeffrey Costa Concepts

X Bar

This design was intended to decrease the run time of the ball bar calibration process by having two ball bars that are perpendicular to each other. A direct result of this design would call for less movement of the machine and less motors by removing the need for a motor connecting the arm to the ball bar to power rotation. Removing this motor removes the previous groups issue where the motor was heating up the bar to the point where thermal expansion was generating error between measurements at each position. Removing the motor also removed a moving part in the system. All moving parts in the system have a chance of causing error in the system. Thus the removal in the motor will make the process more accurate.

External Pneumatic

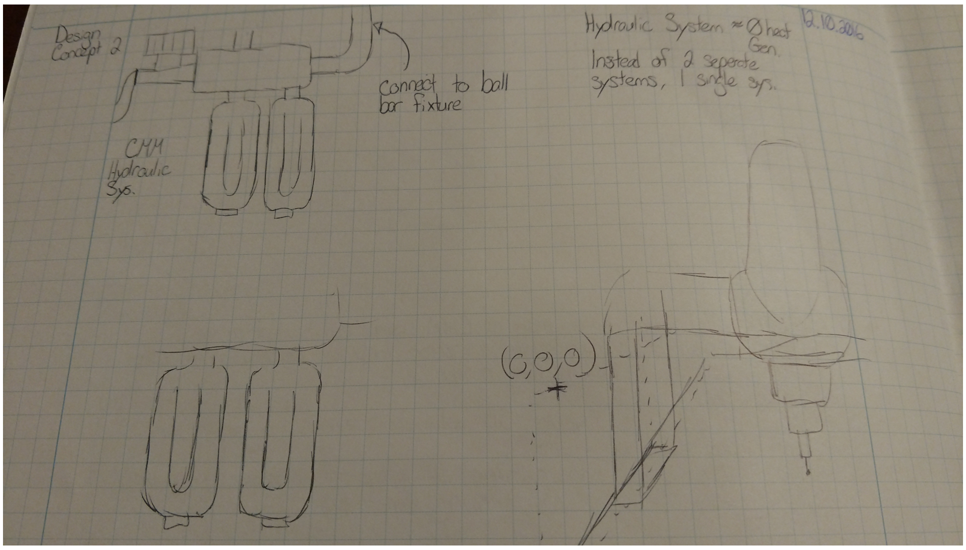


Figure 7.89: Jeffrey Costa Concept 2

Currently Hexagon uses air pneumatics to control the movement of the CMMs this is designed to reduce noise and prevent error with the movement. The current pneumatic system on the machines is located on one end of the machine as shown in Figure 11.3. This design modifies this system to add a device to connect any pneumatics from a pneumatic ball bar design.

Guided Track

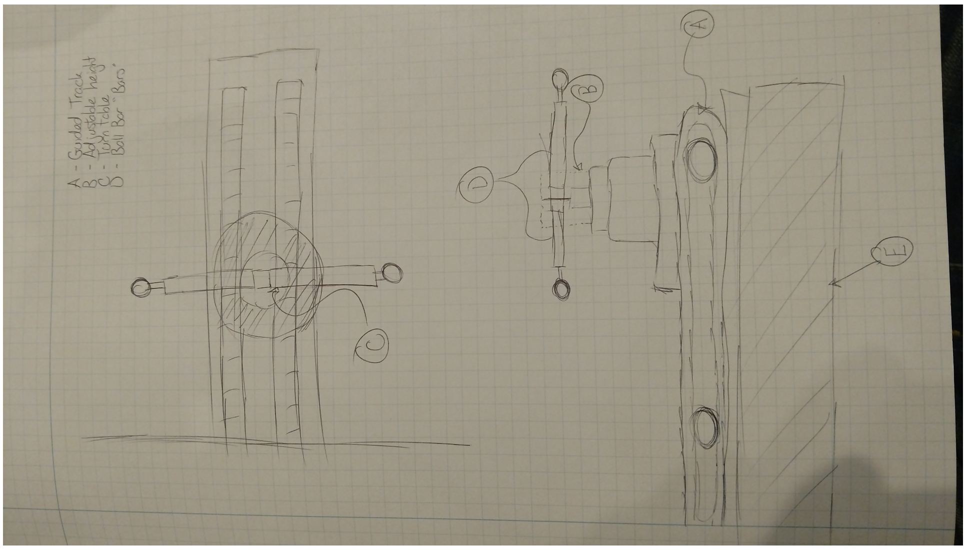


Figure 7.90: Jeffrey Costa Concept 3

As shown in Section 6, Design Specifications, the ball bar is required to reach 12 different locations. This design places the ball bar fixture on a motorized track that moves the fixture transversely in the X and Y directions. This moves the heat source further away from the ball bar and still allows for the fixture to move in all directions.

Pneumatic Tracks

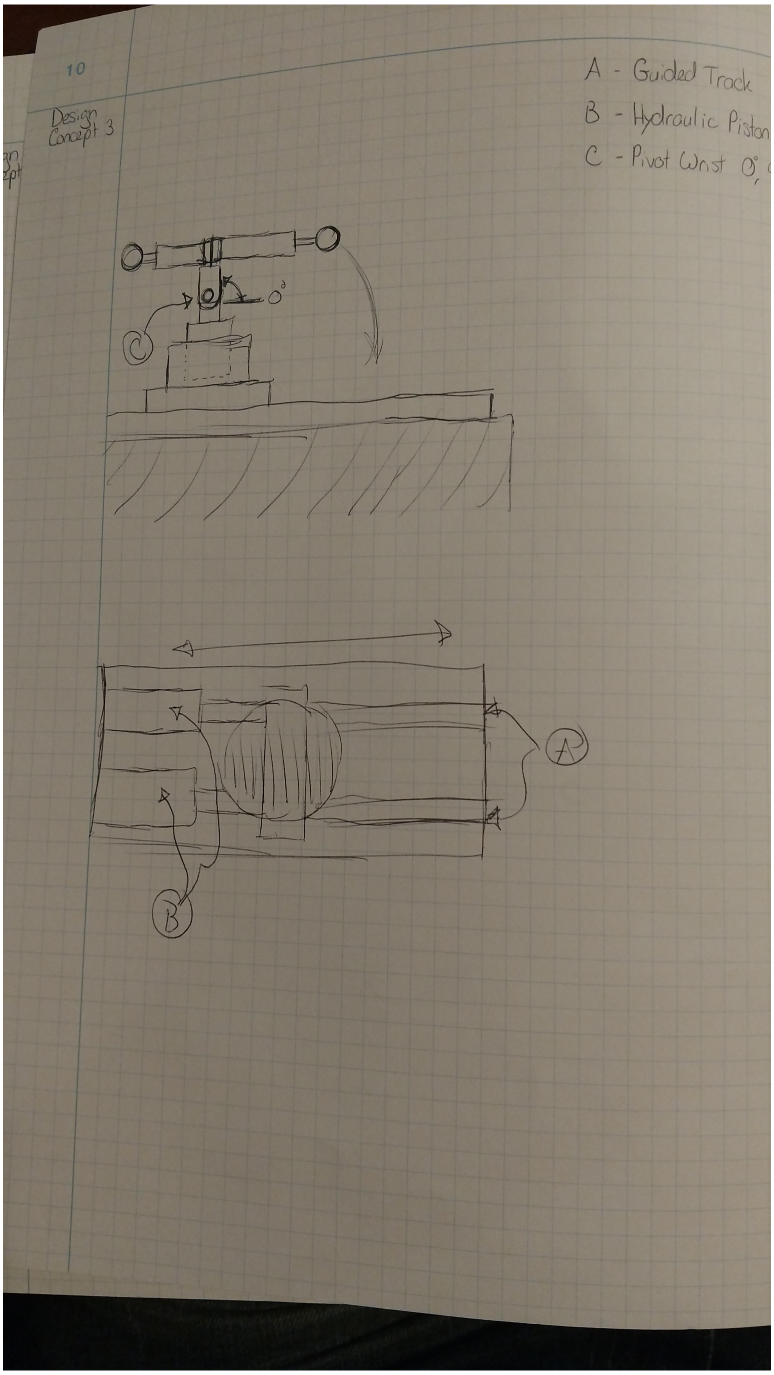


Figure 7.91: Jeffrey Costa Concept 4

This design is similar to the the Guided Track system however instead of the system being driven by motors, the system is driven via pneumatics. This design can be incorporated with the External Pneumatic design and accuracy can be increased in a similar fashion to method of movement for the CMM itself.

Screw Tracks

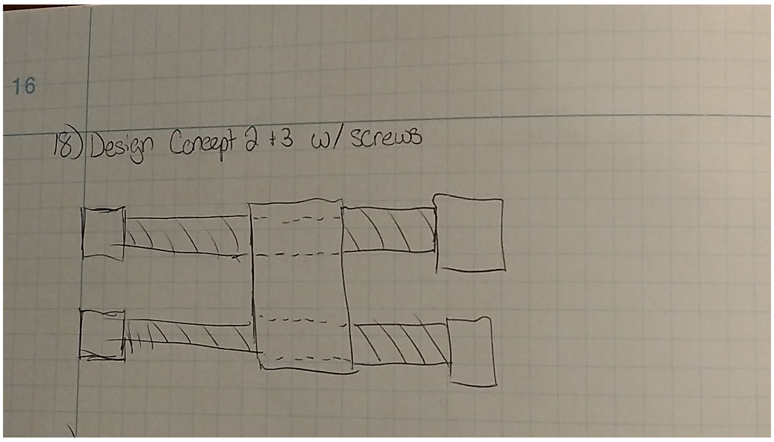


Figure 7.92: Jeffrey Costa Concept 5

Continuing with the track design another method to power the track movement would be with screws. Screws can be proven to be more accurate. Screws can be adjusted to control speed and accuracy down to the desired deviation of 1 micron.

Telescopic Stand

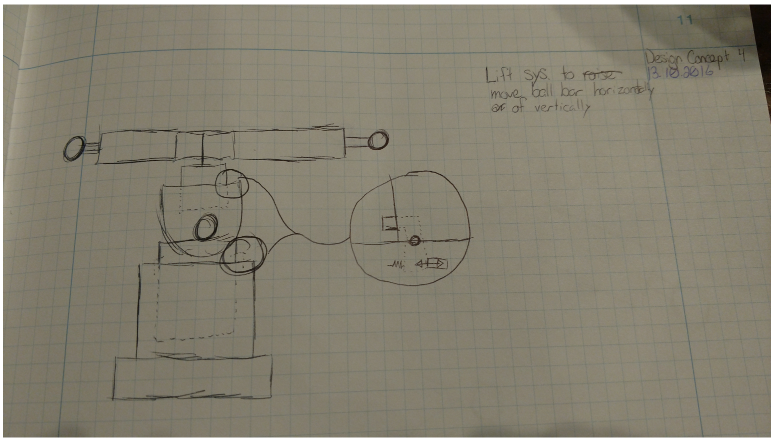


Figure 7.93: Jeffrey Costa Concept 6

The telescopic stand allows for the specified shafts to extend and contract in order to reach all locations. This can be operated mechanically or pneumatically. The ultimate goal of this design is to create portability for when the product is not in use as well as increasing the size of the product for different size machines.

Telescopic Bar

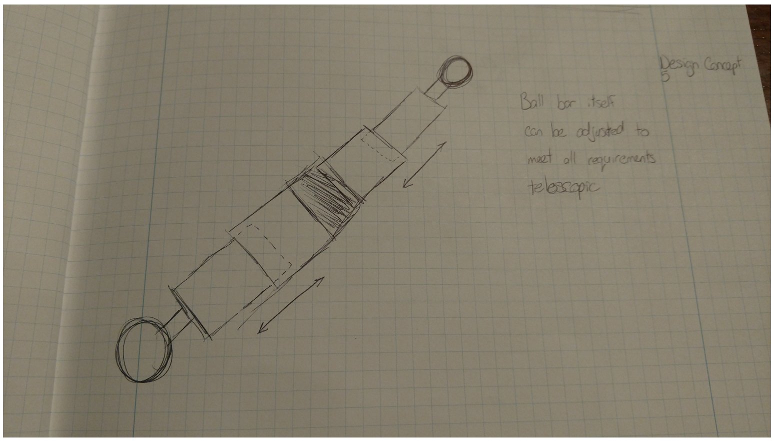


Figure 7.94: Jeffrey Costa Concept 7

This design is an addition to the telescopic stand however it is for the bar itself. The benefits of this design is for portability and different size machines for adaptability.

Pivot Gear

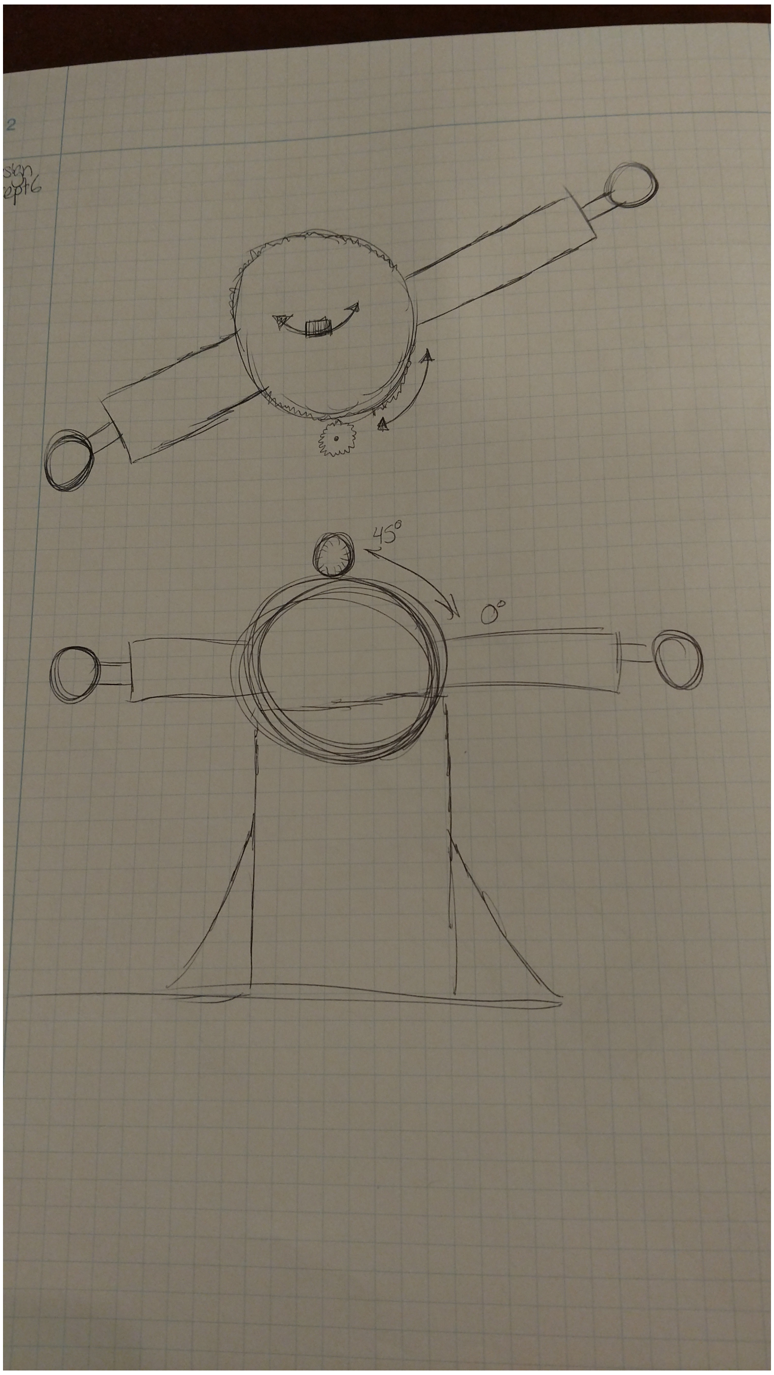


Figure 7.95: Jeffrey Costa Concept 8

This design is created with the idea that the ball bar is placed in a spherical device with gears around the surface. This will be connected to gears within the inner shaft of the product. These gears will allow for movement of the spheres to reach

Raised Track

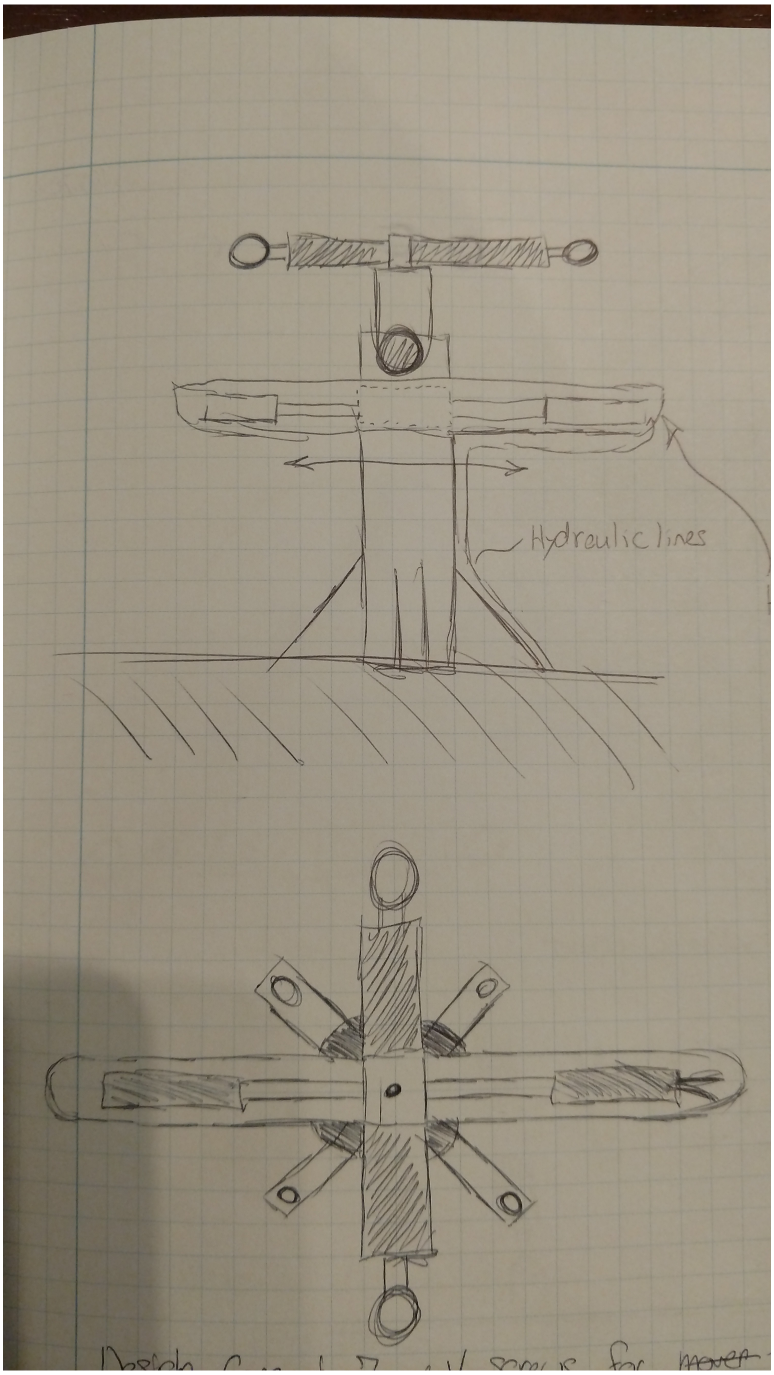


Figure 7.96: Jeffrey Costa Concept 9

The current ball bar fixture is placed at a required height for each machine. At the height this design proposes a track which allows the ball bar to ride along to reach all positions required for the calibration.

Ball Cube

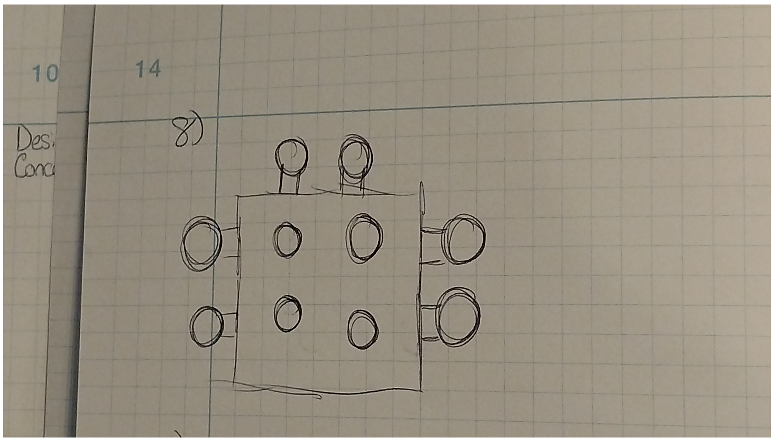


Figure 7.97: Jeffrey Costa Concept 10

This design was inspired by the patent 6,023,850 the Ball Cube. This design was intended to be used as a cube with qualification spheres placed in the movable space within the CMM where the machine will probe each sphere instead of a mechanized bar being required move into those locations. The probe can measure all sphere locations and calculate the distances for each orientation that would be required.

Telescopic Ball Cube

This design continues with the ball bar design however the telescopic design is added for each ball so the longer positions can be reached and the design considers adaptability for larger machines.

X Ball Cube

The X Ball Cube uses the the ball cube design to reach the points thus preventing movement of the device itself. The ball bars are mounted onto this cube in the same X pattern as in the previous design. This will create less moving parts if the telescopic design is incorporated into this design to allow for adaption to larger machines for calibration.

Two Axis Elevator

This design works in the concept of the ball bar and rotation motor are placed on a platform that allows for transverse movement in the X direction. The two towers attached to the sides of the platform that will allow for transverse movement in the Z direction.

Pneumatic Elevator

This design is constructed in a similar fashion to the two axis elevator with an exchange in method of power from motors to pneumatics.

Robo Arm

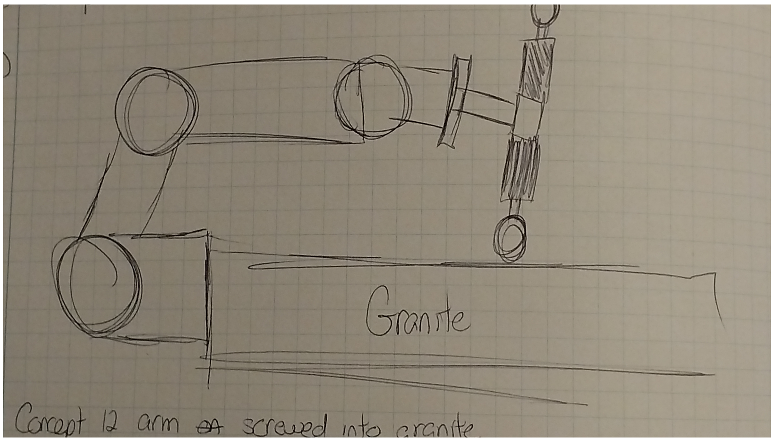


Figure 7.98: Jeffrey Costa Concept 15

This concept was conceived from the robot arms used in the white light machines at Hexagon. This arm will be mounted on the granite surface with the ball bar at the end. This will mimic an operator moving the bar from location to location.

Robo Arm Mod

This concept is the same as the previous robo arm design however the arm will be mounted to the rear of the granite. This will be beneficial for smaller machines to reach all points. With the previous design the arm could prove to be too large for the machine's move space.

Pivot Dome

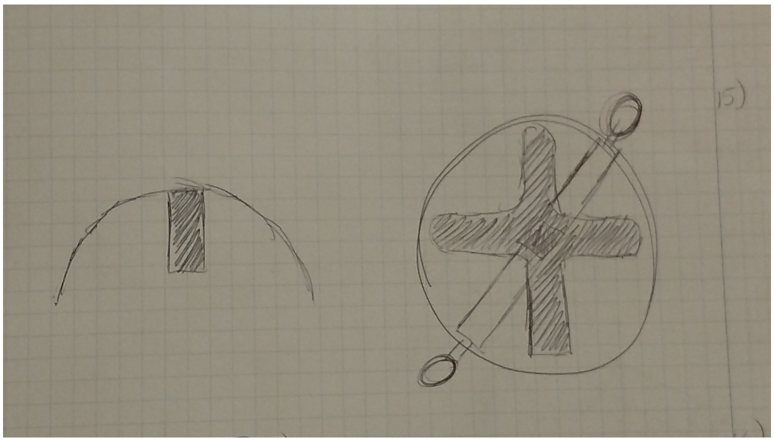


Figure 7.99: Jeffrey Costa Concept 17

The Pivot Dome design was conceived from the top of a screw. This design is a dome with the ball bar shaft placed within slots similar to a gear shifter. During the calibration process the bar will maneuver throughout the slot to achieve all required locations.

Ball Bar Drone

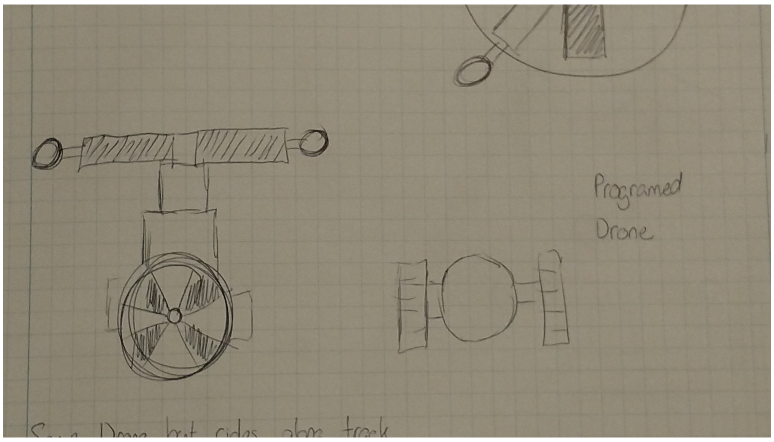


Figure 7.100: Jeffrey Costa Concept 18

A ball bar drone will be act similar to a roomba machines in homes. A ball bar will be fixed to a drone that will move across the granite surface in a pre-programmed pattern to achieve all locations for calibration.

Ball Bar Train

This ball bar designed similar to the to ball bar drone however it is similar to a model train set. The drone is placed on a track constructed into the pattern required achieve all locations for calibrations.

Pulley Bar

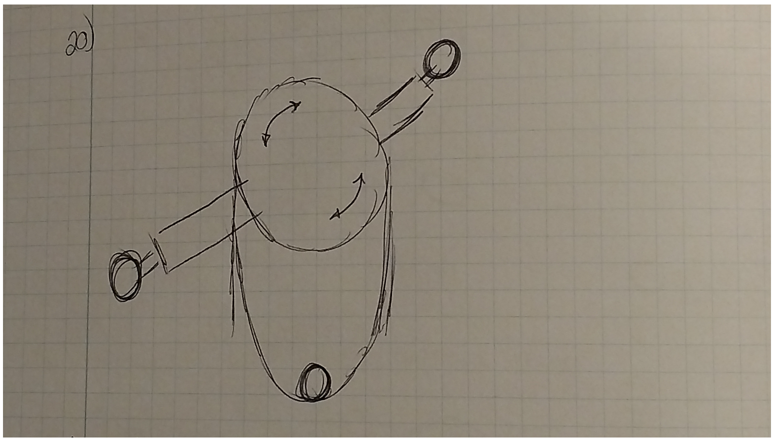


Figure 7.101: Jeffrey Costa Concept 20

This design operates with the idea that the bar is placed in a sphere similar to the pivot gear however a system of pulleys are used to rotate the ball bar to various orientations.

Elevator Ball Bar

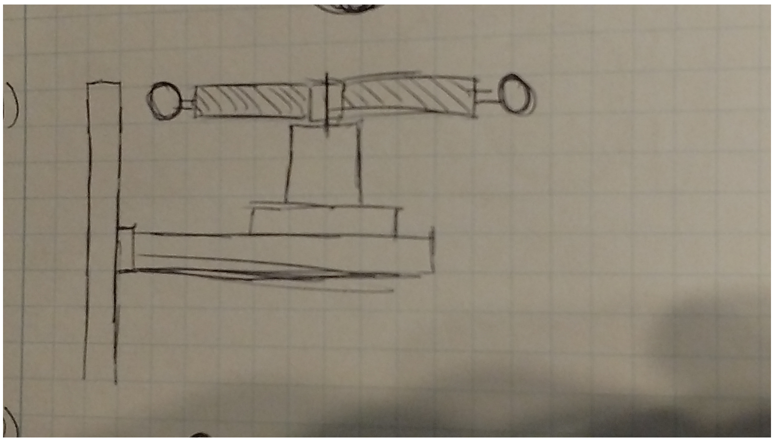


Figure 7.102: Jeffrey Costa Concept 21

This design places the ball bar fixture on a platform that raises and lowers along a tower.

Arc Track

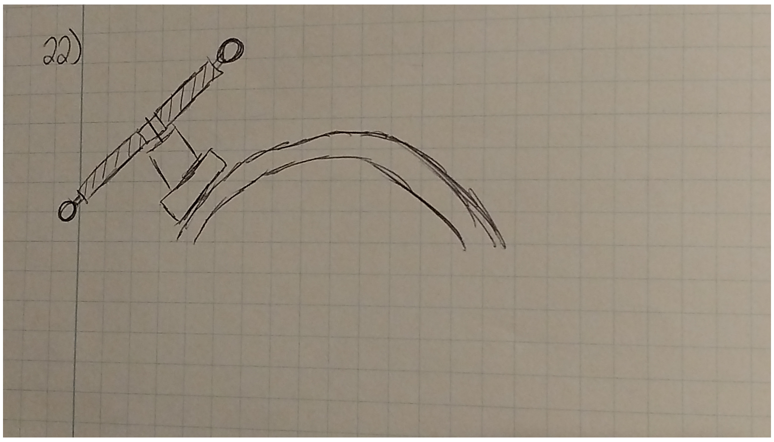


Figure 7.103: Jeffrey Costa Concept 22

The arc track design is the opposite of the dome design. The track is arched so the part can move along the track to reach all orientations.

Perpendicular Bar

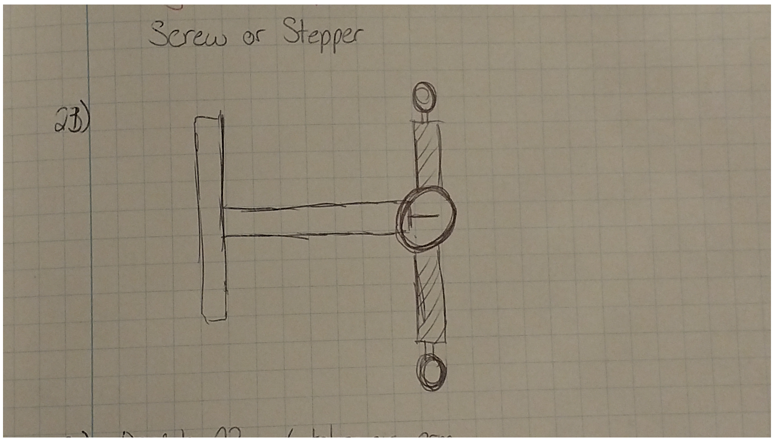


Figure 7.104: Jeffrey Costa Concept 23

The perpendicular bar is a modification of the elevator ball bar design and

Telescopic Perpendicular Bar

Similar to the previous telescopic ball bar designs this design utilized the telescopic bars and shaft on a perpendicular fixturing in order to have a scalable design for all size machines.

Ceramic Bar

The previous group that worked on this project had a issue with heat. Thinking of ways to prevent the issues with heat this concept technically removes the issue of thermal expansion all together. In section 6, the design is not required to use a specific material for the bar. With that being said using ceramic for the material of the bar will eliminate the issue of thermal expansion due to the fact that ceramic has such a low coefficient of thermal expansion.

Preheat

Again the thought of preventing the issue of thermal expansion throughout the calibration process. To prevent this issue there is the idea to heat the system up so that all thermal expansion that will happen during a normal run will happen before the process is executed. The requirement in the design specification only requires no change in temperature DURING the process. Therefore if the bar is heated before the process then there would be no change in temperature the process.

Arm Lift

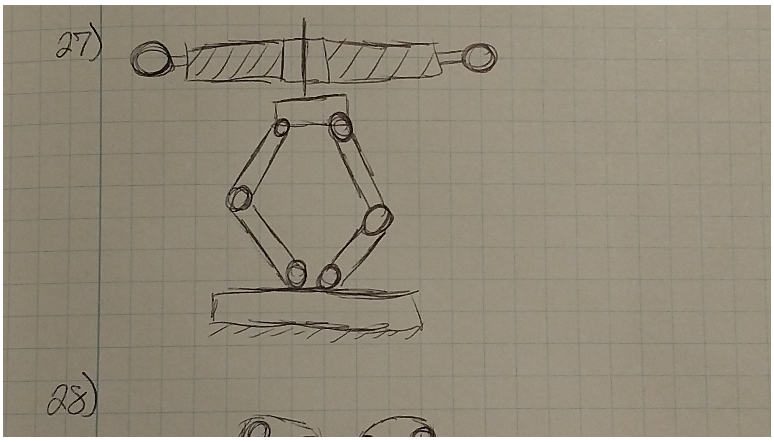


Figure 7.105: Jeffrey Costa Concept 27

The Arm lift was designed for mobility similar to robot animals. This design will allow for the raising and lowering of the ball bar. The legs can move independently of each other allowing for a sort of "bowing" to allow for all orientations to be reached.

Robo Pulley

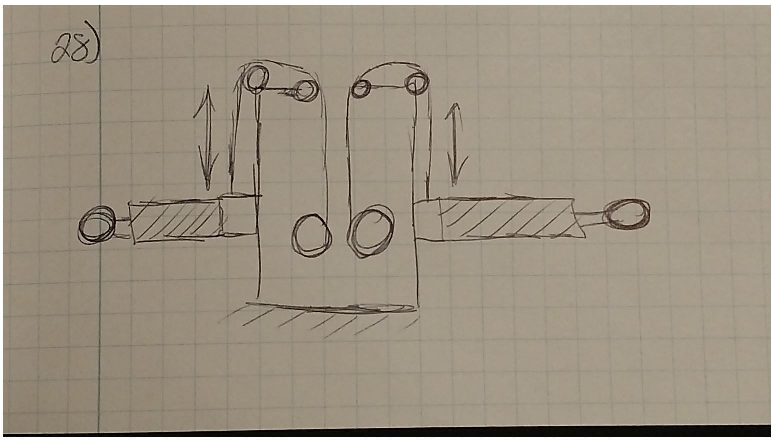


Figure 7.106: Jeffrey Costa Concept 28

This design uses pulleys to raise and lower the ball bar along the shaft of the apparatus. The benefits of having a separate pulley for each half of the bar is that the orientations could be reached with the two bars moving in different directions. This will allow for reduced run time because as one ball is being measured the other can be moving into position.

Perpendicular Arm Lift

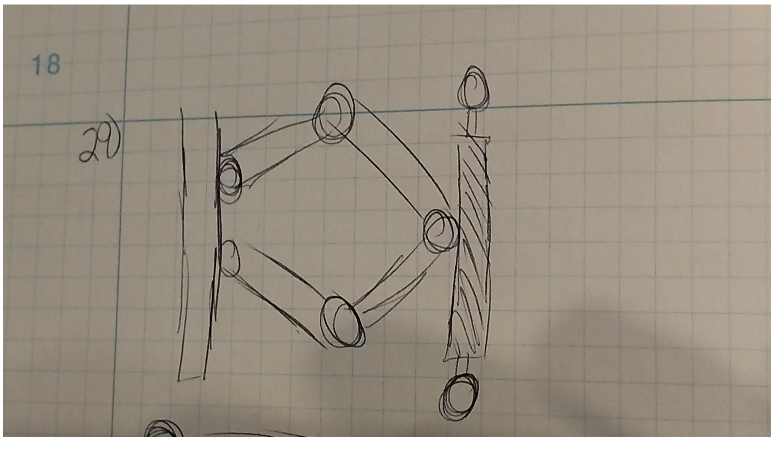


Figure 7.107: Jeffrey Costa Concept 29

This design follows the concept of the lift design just placed onto a fixture to allow for access to positions while being more mobile. This could be fixtured onto the side of the granite to allow for calibration of smaller machines as well.

Pneumatic Volcano

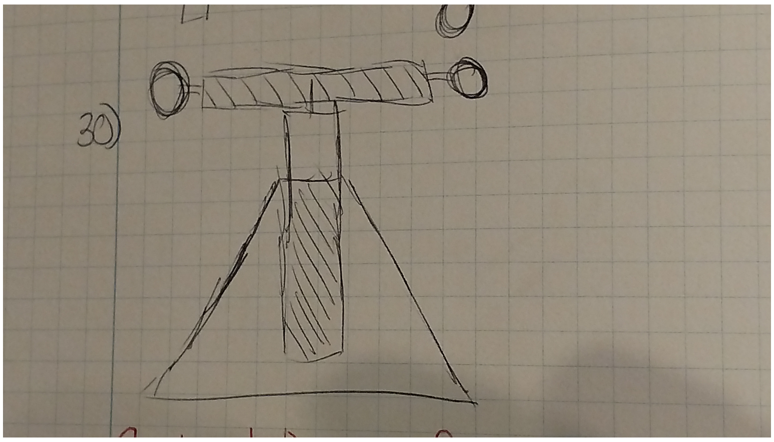


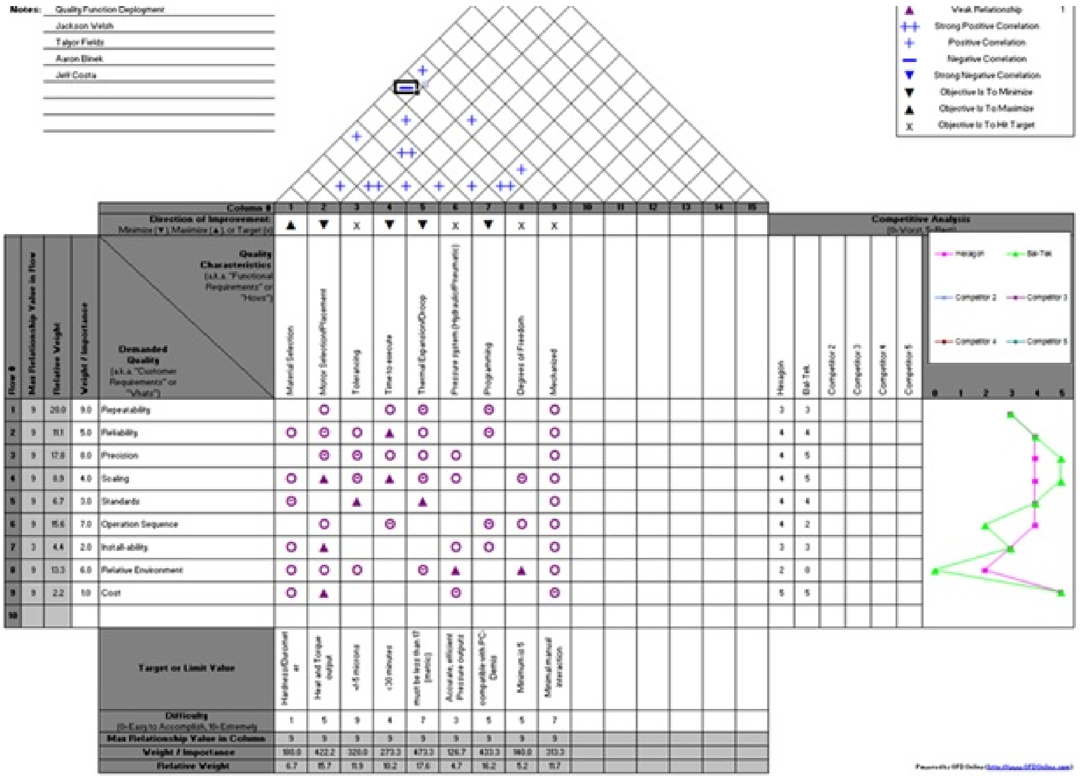
Figure 7.108: Jeffrey Costa Concept 30

This design is similar to the pivot dome. This will have the same slots that will allow for rotation and manipulation. This design can be designed to work for smaller machines due to its large angles so movements can reached with a smaller volume device.

8 Quality Function Deployment

As required by the course, a detailed quality function deployment was implemented. This Chart is extremely useful when prioritizing requirements and standards; as well as comparing competitors and their advantages and disadvantages. In terms of Hexagon standards, they stressed that repeat-ability, reliability, and operation sequence were of the utmost importance; while cost, install-ability, and scaling were rather irrelevant. After reviewing Hexagons demands, Team 19 determined that; precision up to microns, thermal expansion, and general automation would be the most challenging obstacles obtruding us from completing this project. A quality function deployment house of quality chart allowed us to identify the most challenging aspects and focus on the more important conflicts that we were projected to face throughout this project.

8.1 House of Quality



Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Demanded Quality	1 Material Selection	2 Motor Selection/Placement	3 Tolerancing	4 Time to execute	5 Thermal Expansion/Droop	6 Pressure system (Hydraulic/Pneumatic)	7 Programming	8 Degrees of Freedom	9 Mechanized	Hexagon	Bal-Tek
				Direction of Improvement	▲	▼	x	▼	▼	x	▼	x	x		
1	9	20.0	9.0	Repeatability		○		○	⊙		⊙		○	3	3
2	9	11.1	5.0	Reliability	○	⊙	○	▲	○		⊙		○	4	4
3	9	17.8	8.0	Precision		⊙	⊙	○	○	○			○	4	5
4	9	8.9	4.0	Scaling	○	▲	⊙	▲	⊙	○		⊙	○	4	5
5	9	6.7	3.0	Standards	⊙		▲		▲				○	4	4
6	9	15.6	7.0	Operation Sequence		○		⊙			⊙	○	○	4	2
7	3	4.4	2.0	Install-ability	○	▲				○	○		○	3	3
8	9	13.3	6.0	Relative Environment	○	○	○		⊙	▲		▲	○	2	0
9	9	2.2	1.0	Cost	○	▲				⊙			⊙	5	5
10															
				Target or Limit Value	Hardness/Durometer #	Heat and Torque output	±5 microns	<30 minutes	must be less than 17 (metric)	Accurate, efficient Pressure outputs	compatible with PC-Demis	Minimum is 5	Minimal manual interaction		
				Difficulty (0=Easy to Accomplish, 10=Extremely)	1	5	9	4	7	3	5	5	7		
				Max Relationship Value in Column	9	9	9	9	9	9	9	9	9		
				Weight / Importance	100.0	422.2	320.0	273.3	473.3	126.7	433.3	140.0	313.3		
				Relative Weight	6.7	15.7	11.9	10.2	17.6	4.7	16.2	5.2	11.7		

Figure 8.1: House of Quality

8.2 Compromises

In order to compensate for our largest challenges; we had to scrap the previous design concept and re-construct with appropriate technological advances. One aspect that shows how we accounted for our biggest challenges was the choice of motors. Motor selection went through three different trials before the final product was chosen. At first, Stepper motors were the primary product; however, after engineering analysis and finite element simulation, group 19 determined that stepper motors would not agree with the temperature requirements for the fixture. With a heat generation of about 320W over a distributed heat flux, which is equivalent to 20 degree centigrade temperature change; this would overshoot our original temperature specifications by 19deg, ensuring that stepper motors were the incorrect solution. The next choice of motors that caught our attention was the direct current BEMONOC self-locking worm-gear motors. The main attraction of these motors was that if no current was supplied, the motors were practically fixed in 3-D space; practically generating no heat and wasting little power. The third choice of motors was an alteration of the previous worm-gear motors. The main attraction of these motors was that the reduction ratio was almost 2 times that of the original worm-gears, increasing from 1700 RPM to 3000 RPM respectively. Another feature that drew our consideration, was that the output shaft of the new worm-gears penetrated through the gearbox; allowing attachments to go on either end of the motor. This is ideal for our fixture because it allows for the placement of accurate potentiometers and absolute rotary encoders; permitting high accuracy, while also trimming excess material off of our arms. In turn this would decrease our moment, and motor amperage/power output. This would in theory decrease our percent error by limiting the amount of generated heat flux entering the specimen area, and obstructing the fixture.

The next issue team 19 wanted to address was the precision of the overall fixture. Hexagon Metrology is a prestigious institute, which prides themselves on their high standards and quality products; so it is without question that the requirements for this project are challenging. Hexagon stressed that it was essential for the fixture to be accurate within microns. This is the most basic of conflicts that arose throughout the semester. An exception to that rule, is that the fixture itself is not mandated within microns; only the ball-bar has to be precise within that limitation. This allowed team 19 engineering analyzers to focus more on the outside sources affecting the ball-bar, rather than the physical manipulation of the fixture itself. Factors such as thermal expansion, durometer, and moment calculations. After Thermal expansion analysis, Invar was selected as the superior material for compensating. Outside sources were researched in manufacturing the ball-bar itself. Team 19 contacted a ball-bar distributor, Bal-Tek in order to get a quote on an Invar bar. Another issue that team 19 had to address, included the CMM probe contacting the ball-bar. The CMM probe distributes a total contacting force of 1N; which is significant if attempting to be precise up to microns of a meter. To assure that the probe would not disturb the bar when contacted; we implemented the worm-gear motors that were 'self-locking'.

The last imperative topic that was addressed, was the operation sequence. Time and resources are a enormous reason of why this project was instigated; that is why team 19 wanted to stress the importance of the operation sequence. The central concept of this project is the automation feature. Hexagon Metrology desires the fixture to be self-sufficient and as optimal as possible; allowing for maximum efficiency. Currently, it requires 45 minutes for an employee to calibrate a CMM machines, using one of these bars. Ideally, with an automated fixture, an employee would initialize the operation sequence, and would not have to supervise the situation. Also freeing this employee to contribute elsewhere. As mentioned previously, the ball-bar itself has to achieve twelve different orientations; creating an accurate and error free measuring space. To automate this process, the usage of Arduino micro-controller and visual basic software serial communication was installed. To enhance the operation, team 19 created a transition diagram; plotting the sequence as its happening; and allowing the fixture to plan its next manipulation, and to reach a particular position as requested. Although this process is tagged as high priority, team 19 decided that it would be best to focus on that aspect after the physical fixture was built; future planning and optimization of this process will be the bulk of next semesters effort.

After the major requirements were highlighted, team 19 concentrated on the central concepts associated with completion. The QFD house of quality allowed team 19 to emphasize the quality characteristics of manufacturing our product. These characteristics are specific to our project and imperative for success. The quality characteristics include; Material Selection, Motor Selection/Placement, Tolerancing, Thermal Expansion, Mechanizing/Automating, Programming, Time of Execution, Manipulation/Driving, and Degrees of Freedom. Obviously these were just the overlaying concepts that arose when talking about completion; although each of these concepts includes its own challenges. A feature of the house of quality is that it ranks the weight/importance of each concept and requirement by cross-referencing them with each-other. In order to execute this feature, the user has to rank each task by its difficulty, relate each concept to each requirement, and determine how strong the correlation is with each other. It is a tedious task, although the hard-work is rewarded as the house of quality enlightens what should be addressed or focused on next. The house of quality also demands us to contrast the competition with a competitive analysis; this requires a team member to rank the confidence of quality or success for each requirement. Currently there is no competition for a mechanized ball-bar fixture; however, there are distributors of ball-bars and certain techniques that out-stand them from Hexagon Metrology. This feature of the house of quality is also useful when comparing different critical concepts; team 19 utilized this feature in order to decide which idea we would execute as our proof of concept.

9 Design For X

9.1 Design for Repeatability

Repeatability as defined in the design specifications as the ability to consistently hit the same positions with high accuracy, while also responding isometricly to the one N dynamic force that the CMM exerts during measurement. For the first aspect of this design the team decided that closed-loop feedback would be the ideal solution. Potentiometers are placed on each point of actuation, at each joint and at each point of rotation. Potentiometers were selected for feedback because they are absolute, regardless of memory or power cycling, this method of feedback will return accurate angular position at any point. Moreover, their analog output can be used in an analog, op-amp based controller, or coupled with AD converters and used in digital control. For the second consideration, dynamic response, the decided method of design utilized the robust design also selected, along with optimization of geometry. Gravity and static friction work in tandem in order to keep each linkage in place. The use of .75 in flat plate steel for linkages means that each link has substantial mass when compared to the extremely small force of one N. As long as the center of mass of any section of the machine, is not directly above a pivot point or joint, the gravitational force will keep the piece in place. Separately the static friction naturally created between all joints is utilized in order to keep the linkages steady. Again because the force is so low, the static friction created is large enough that the dynamic force cannot overcome the friction force. The motors have been sized as such to be able to overcome both these forces.

9.2 Design for Scalability

One of the design specs considered that contributed most to the overall design of the manipulator is that of scalability. It is desired that the design be scalable, and the requirement is such that a single manipulator can be fit to one machine, built and used in that one machine. The team decided that most designs conceptualized would be able to reach all the positions for a large machine, while also being able reach those of a smaller machine. Certain designs, such as the linkage manipulator, would also be able to fit into the measurement volume of the smaller machines and can therefore could be used for more than one size of machine. Through optimization it is possible to find the optimal length of each linkage in order to manufacture a single manipulator that can be used in a variety of CMMs. Design consideration was also taken for the ability to easy change the size of the manipulator, this was achieved by designing for modularity. In the current design, the two major linkages are the same piece at different lengths. By changing these lengths and keeping all other dimensions constant, the reach of the manipulator can be changed and therefore a manipulator can be manufactured for use in any size CMM.

9.3 Design for Optimization

The design chosen by team 19 consists of a three linkage manipulator. Because of this highly non-linear design there are several aspects of the design that depend on each other such as torque and positioning, moments, and even scalability. With regards to positioning it is possible to create an equation to solve for the angles required to hit a particular positon. It is also possible to write equations to solve for the moments created and the torque required to actuate at the correct speeds. Because of the non-linear design these equations generally end up as a system of equations parametrized by at least one free variable. In this case different design aspects can be combined in order to set a certain variable to an optimal, desired, value and then solve for the angles that produce these values. Optimization will be more closely considered in the redesign of the manipulator but must be considered for any size machine produced.

9.4 Design for Manufacturability

When this project was done by the previous capstone team, one of the major problems faced was their ability to manufacture their parts to the design and tolerances required. Because of this, manufacturability was stressed during the design process. Many of the design concepts presented in the conceptual design section of this report were identified as good designs that could meet the requirements set forth by the design specifications. However, in many cases their complexity was identified as a problematic with regards to manufacturability. The first step was identifying the tools which could be utilized for the manufacturing process. The tools available from The University of Rhode Island engineering department include additive manufacturing in the form of several 3d printers, a CNC milling machine, and standard tools in a machine shop. The use of additive manufacturing presents the opportunity to design complex geometries, however Because of the precision and repeatability required, the materials used for 3D printing are not a valid option. Therefore, more simplistic designs were considered. The concept chosen was designed to be completely manufactured from flat plate steel stock, and bar stock, using the processes of cutting, drilling, milling, welding, and turning. The two main linkages can be seen in figure 11.4, these are the simplest pieces and will be produced with small section of bar stock and flat plates. After drilling all holes and missing the rounded edge, the bar stock is inserted into a drilled hole and welded into place. All joints will be manufactured in a similar manner, with the shaft for the joint placed into a drilled hole and welded in place. The Base and third linkage present slightly more complex methods of manufacture. As seen in figure 11.5, the shaft for the connected joint is directly attached to the side of the block, this required the rounded object to be milled to a circle. Seen in figure**??**, the base of the manipulator is compressed of two pieces of flat stock, welded together. This simplistic design only presents difficulty in the placement and fixturing of the smaller drilled piece while welding takes place. Overall these pieces have been designed for easy manufacturability and are considered very likely to be able to build accurately for the functional prototype.

10 Project Specific Details and Analysis

As was stated in section 9, this product has no direct competition and it will enter the precision measurement and tooling market. Along with this, and the fact this in the scope of this project, the market being considered is strictly internal to Hexagon, the product was considered in three ways, the precision measurement tooling of the Bar Ball, the current fixturing methods available, and the use of currently available robotics in this application. It is shown that the concepts and designs generated by the team have many distinct advantages over any currently available product. In regards to the current, purely mechanical and stationary fixturing solutions, the automated manipulator has the advantage of its automation. The current fixtures do not meet the designs specs and are the cause of all the problem this project seeks to fix. The current robotics market this product can potentially compete with can be separated into two sections, desktop and industrial use. Potentially ether of these products could be attached to a bar ball and used in this application although both have major drawbacks. The desktop manipulators are small, inexpensive and poorly made, the low build quality make them poor choices for this application as they would struggle too meet many of the design specs. The industrial versions remove the issue with build quality, however, they present issues with cost and in most cases, geometric physical limitations. These industrial robots are designed for high throughput, demanding manufacturing environments and due to the lower frequency of use these machines will see at Hexagon, they are not reasonable choices. The market analysis shows that the designs generated by team 19 have a distinct advantage over other options available on today's market.

Referring to Figure A.5 in Appendix A, it is shown that the cost of the preliminary design is projected to be \$1,540. Re-analyzing the cost predictions by incorporating the initial cost of the new product, a new column of Table B.1 for Savings as shown below in Table 3.1. From the table generated it is evident that after 5 months (approximately 100 CMMs) the new product will have paid for itself and begin saving Hexagon money as well as time. After one year the new automated Ball Bar process will save the company \$4,000. The only demand of this product initially will be Hexagon. However, because this calibration process is performed a second time when the machine arrives at the clients location, the demand for clients to have an automated process performed to decrease cost to have a Hexagon employee there calibrating the machine.

Addressing thermal expansion, team 19 utilized Abaqus cae to perform finite element analysis. Abaqus cae was used instead of Soliworks simulation because of its extreme accuracy, and user-friendly interface; as well as its accessability at URI. Since the ball-bar measurements were required to be precise up to micrometers, Abaqus cae was the perfect simulation software to do so. The primary usage of this program was to determine which materials and products would suffice for the fixture; it aided our decisions toward the material of the ball-bar, material of the fixture arms, and ultimately the types of motors that were necessary for our proof of concept. Since there are is curently no competition for a mechanized ball-bar fixture; we are pioneering the industry for extremely accurate ad precise robotic maniuplators.

11 Detailed Product Design

With 120 concepts to choose from, it was a tough process to narrow down the best fit for this project. A number of factors had to be evaluated in order to make the decision that would best fulfill every aspect of the intended application of this device. After going for a tour of the production area in which this machine will be utilized, as well as seeing the current setup in action, we were able to make an assessment of the most important design specifications needed to successfully fill the needs of Hexagon. The first and most important aspect of design is consistent operation. In order for the calibration process to take place in which this device stars, the ball bar must remain exactly motionless and at one constant temperature throughout the measuring process. The parameter for expansion is 1.5 micrometers due to thermal expansion, and virtually no movement due to the probing tip contacting the ball bar. With such a narrow window for error, the thermal expansion constraint essentially locks the total temperature increase of the bar to 1 deg Celsius over ambient (room) temperature.

To overcome this issue of heat buildup and subsequent transfer to the ball bar, three steps have been taken to date. The first innovation required switching from 4-phase stepper motors to 2-phase direct current driven motors attached to a self-locking worm driven gearbox. The biggest advantage to switching to a direct current motor is that they produce less heat, as whenever power is being applied the rotor is in motion. This differs from stepper motors in that they move incrementally, so at any speed there is a brief transition between motion and rest where current is still being applied, but is not causing motion. The next addition is the application of a worm gear drive reduction that mounts in between the motor and the arm linkage. This gearbox allows us not only to have greater accuracy when moving, but also provides an intermediate component that heat must first travel through in order to reach the arm. Lastly, and of greatest consequence, the worm drive in the gearbox is self-locking. This mechanism allows us to shut off power to the motor when it doesn‚Äôt need to move, and still have the arm remain in the correct position for the duration of the sequence. This is a huge improvement over the previous stepper motor setup, as they had to use maximum current to hold everything in position. The majority of time spent while the coordinate measuring machine measures the ball bar ends is spent with this device being motionless. With these innovations, the total power needed to perform the series of 12 positions is a mere fraction it was prior. This translates into savings in terms of power over its lifetime, and also over the wear of the parts in this mechanism.

The savings acquired from this switching of the motors is sufficient enough to warrant their implementation. The motors cost between $40.00 and $75.00 depending on the vendor, gear ratio, and speed of delivery. This blend of cost to power and durability falls within the budget, and is very justifiable. The motors are able to produce much more torque than is needed in this application, while still using much less energy, and being more accurate. The motor and gearbox assembly is approximately 5 inches long, 1.5 inches wide, and nearly 2 inches tall. The operate on 3 to 12 volts, allowing for different speeds to be achieved. This is particularly useful when the part begins to move, and ceases to move, as we are able to ramp the power up and down to reduce the effects of inertia. With an output shaft 8mm in diameter, the motor will be durable and controlled in motion.

The second most important aspect of this project is repeatability. While this may be confused with consistency, it is taken in a different meaning as to placement of the ball bar in space. The coordinate measuring machine in which this ball bar assembly will articulate in order to calibrate must be programmed to find the bar in time and space. There is a tolerance of 1 millimeter. This means that the ball bar ends must return to the same position within the position, and can only deviate by 1 millimeter in any direction. If this parameter is not met, the expensive ruby tipped measuring probe could strike the ball bar and cause damage, or fail the test procedure. While this may not seem difficult, it essentially boils down to having better than 1 degree of accuracy over all the positions on the linkages. This is because the error in the angle set of each arm linkage will be multiplied by the length of the arms themselves. This small 1 degree error can be seen in the below diagram, shown in inches. The arm (red and green) is shown at 10 inches in length, and the coordinate plane shown from the pivot point left to right. It is clear to see that the small error in angle has a huge effect on position of a linkage just 10 inches away, much larger than acceptable.

This issue with angle will be taken care of by using a motor and gear box that reduces 3000 revolutions of the motor down to just 1 revolution of the output shaft that attaches to the arm. This will theoretically yield an accuracy of 0.12deg, with the potential for a higher accuracy if the motor can be controlled at half or quarter turn increments instead of full revolutions. Such a control process will be made possible through the use of transistors instead of relays, which operate significantly faster allowing for more precise starting and stopping of the motor. The motor speed will also be slowed down as it approaches its target location, reducing the chance of passing by the location and having to retract. To further mitigate the issue of location uncertainty, a potentiometer with a 10bit resolution is used to show the absolute position of the arm. This 10bit position

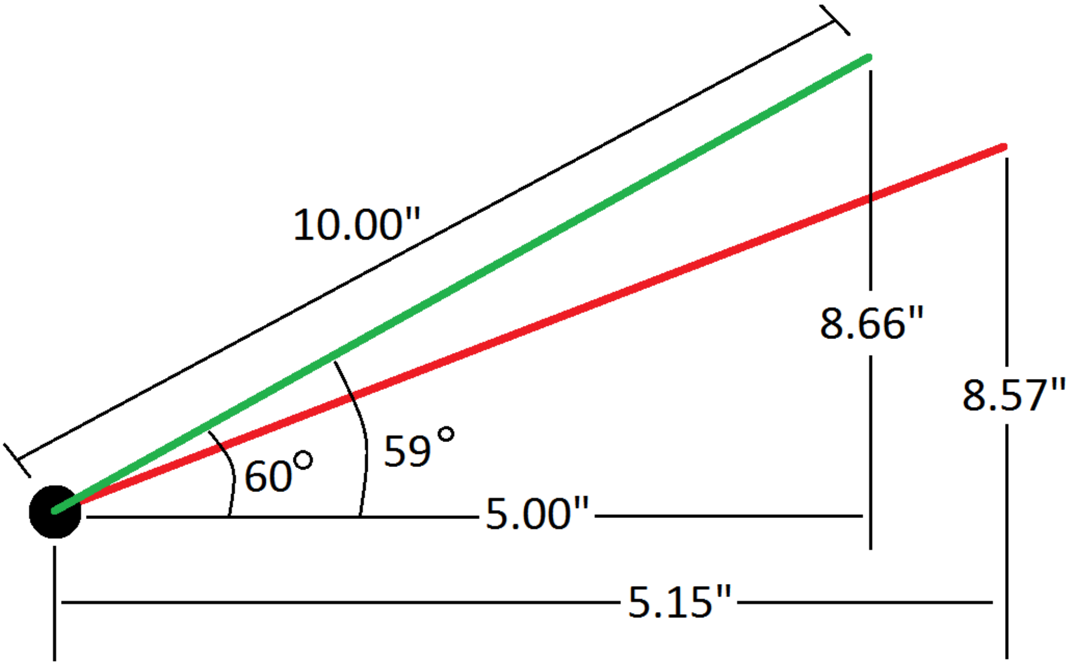


Figure 11.1: Sine Angle Error

allows accuracy of the position to within .3 of a degree, but due to the angular loading of the device, the arms will always be pushed toward one side or the other of this 0.3deg uncertainty. Essentially this allows for an accuracy of about .15deg, which will put us within our intended range.

The previously mentioned 10inch length is the current length of the first arm in the assembly of our device as can be seen in the included drawings in this section. This length is subject to change based on the intended application. This was another design consideration that Hexagon had requested, as they manufacture different sized coordinate measuring machines and want to be able to scale these devices up or down. The included drawings show the dimensions which will best suite Hexagon‚Äôs most widely implemented measuring machine. The approximate dimensions of the volume this machine has to reach resembles a 0.5 meter cube, with 12 positions inside this volume requiring various articulations. For exact dimensions of the most common setup, the drawing included show all the machined parts. Only one arm is included because the other lengths are variable, and have the identical dimensions besides length. These lengths will be made of 1018 cold rolled steel, and all operations can be completed on a milling machine. There should be no need for CNC capabilities, which significantly cuts down on production costs. The base will also be made of 1018 cold rolled steel, with a nonslip coating applied to the bottom such as stiff rubber mat.

With so many parts, it is easy to visual the large amount of inertia stored in the moving parts. In order to keep this device from falling over when it starts or stops motion, the base is constructed of the same heavy steel with a wide diameter. This wide diameter will provide support and structural rigidity to compensate the mass moving around. One approach considered is to remove some material on the arms themselves, which would indeed lessen the effects of inertia on the system as a whole, however the trade-off is structural rigidity. The mass of each arm is all critical in that is provides a weigh force on each arm joint. This force pulls arm down, which places the free-play within the gear assembly on the leading edge of the gear teeth. This essentially allows us to remove all uncertainty within the gear train by experimentally checking the position the first time. This same force also provides a resistance to the force applied by the probing tip on the coordinate measuring machine. This solution is the simplest solution to a fairly high tech problem, and requires no maintenance. All engineering analysis shows that this weight force is sufficient to negate a force much larger than the impact of the measuring probe touching the ball bar ends.

In order to control this system, a electrical control system is employed. This control system is spearheaded by an Arduino Mega, powered by an ATmega2560 processor. The code to program this microprocessor can be found in appendix C. The basic procedure entail many steps, but is in its core fairly simple. The first step is to check the current position of the arms, which is processed as a linear voltage readout. These values are then used to decide if the arm is moving clockwise or counterclockwise. Once decided, the program sends a PWM signal to the drivers corresponding to the motor that is being moved. As the bar is moving, its position is constantly metered and once it enters the acceptable range the program stops send the PWM signal, stopping the motor. This is repeated for each link as needed. Once a serial input of greater than "5" is received, the program will advance to the next stored position. These positions can be altered by changing an array of value in the STAGES tab. These have been left easily editable as they will likely need to be experimentally changed depending on the setup of the machine it is specifically used on.

The last major component involved in this project is the ball bar itself. Theoretically, there should be less than 1 degree change at the ball bar to motor interface. The engineering analysis show that at steady state the heat generated by the motor is not enough to transfer through to the bar, however this is one of the most critical design criteria so extensive testing will take place before a definitive ball bar solution is determined. At this current state of testing, the stainless-steel bar currently employed by Hexagon should work just fine. In the case that more heat is generated than theorized, we have selected a material that is both stiff enough, and has the lowest thermal expansion of any reasonable material for this task. The material utilized is inconel, an alloy of steel that has one tenth the thermal expansion of standard steel. This has been kept as a backup plan, because for just the one bar of inconel, it will cost upwards of $800.

This selection of materials and components lend themselves to the successful completion of this project. Each material has been carefully screened and selected over other options to best fulfill the requirements and stay within the budget. At this point in the design and prototyping process, we believe that there are no better options available, whoever this may change as this device goes through the manufacturing process.

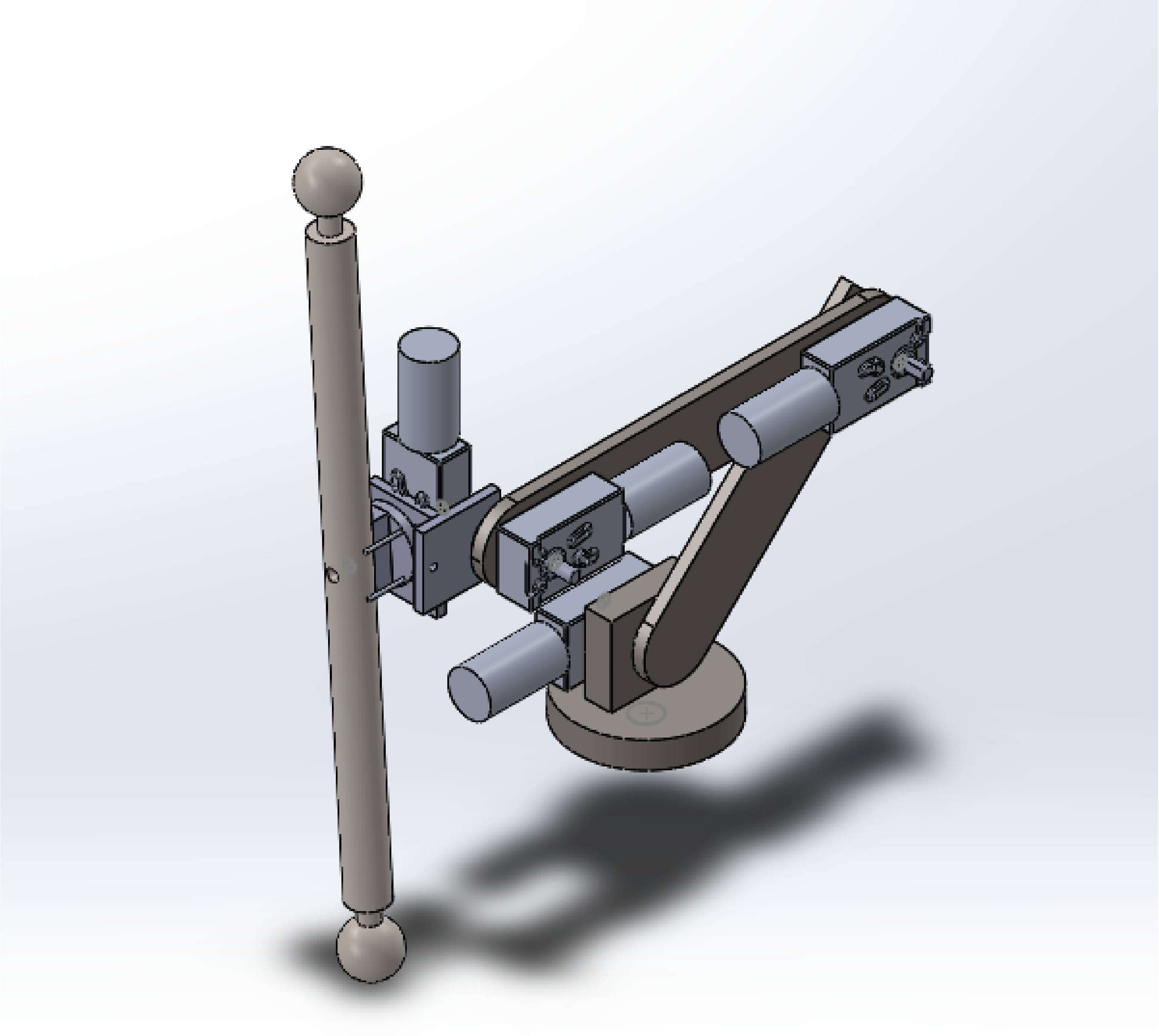


Figure 11.2: Isometric view of solid model

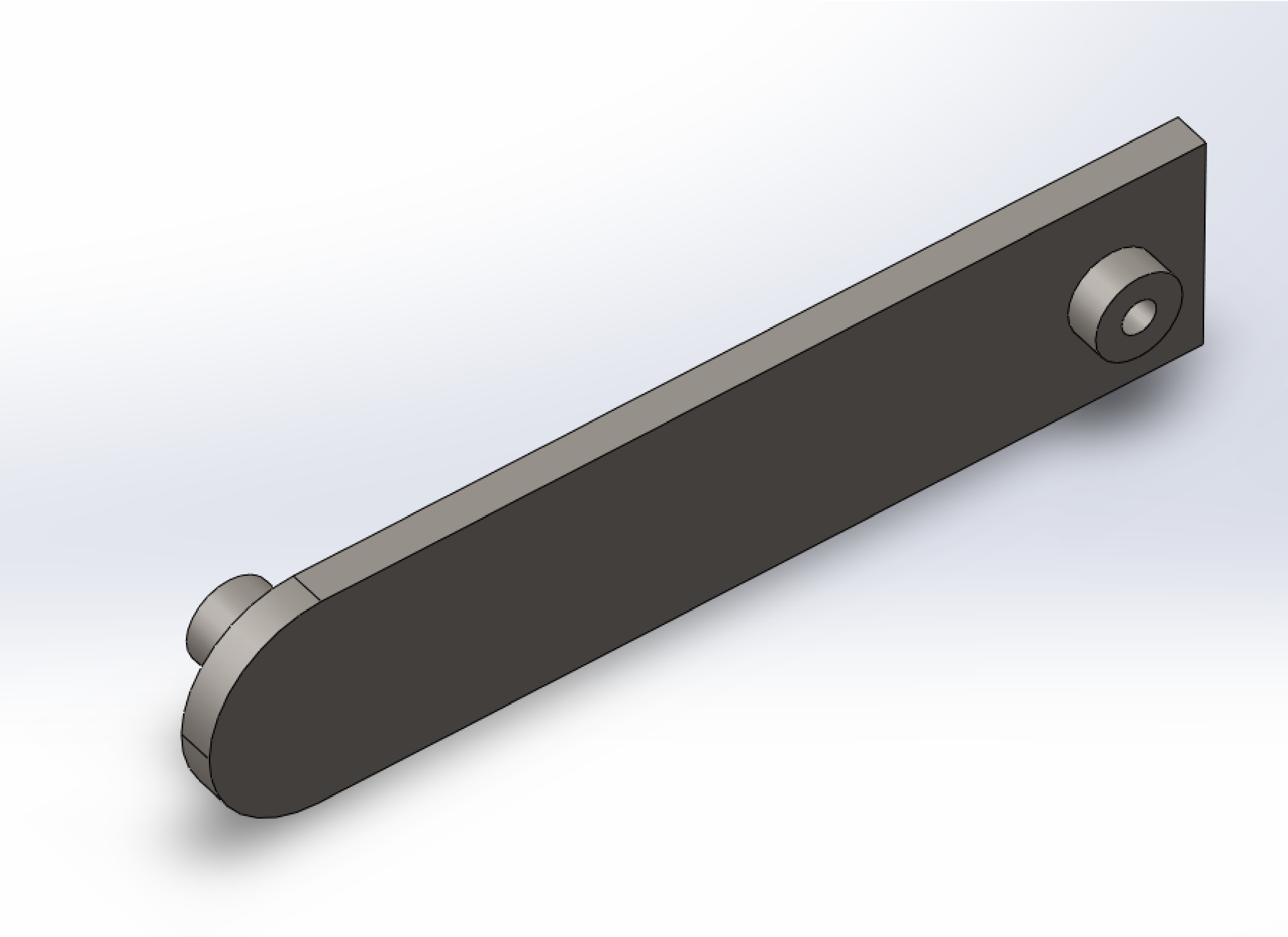


Figure 11.3: 1st Arm Preview

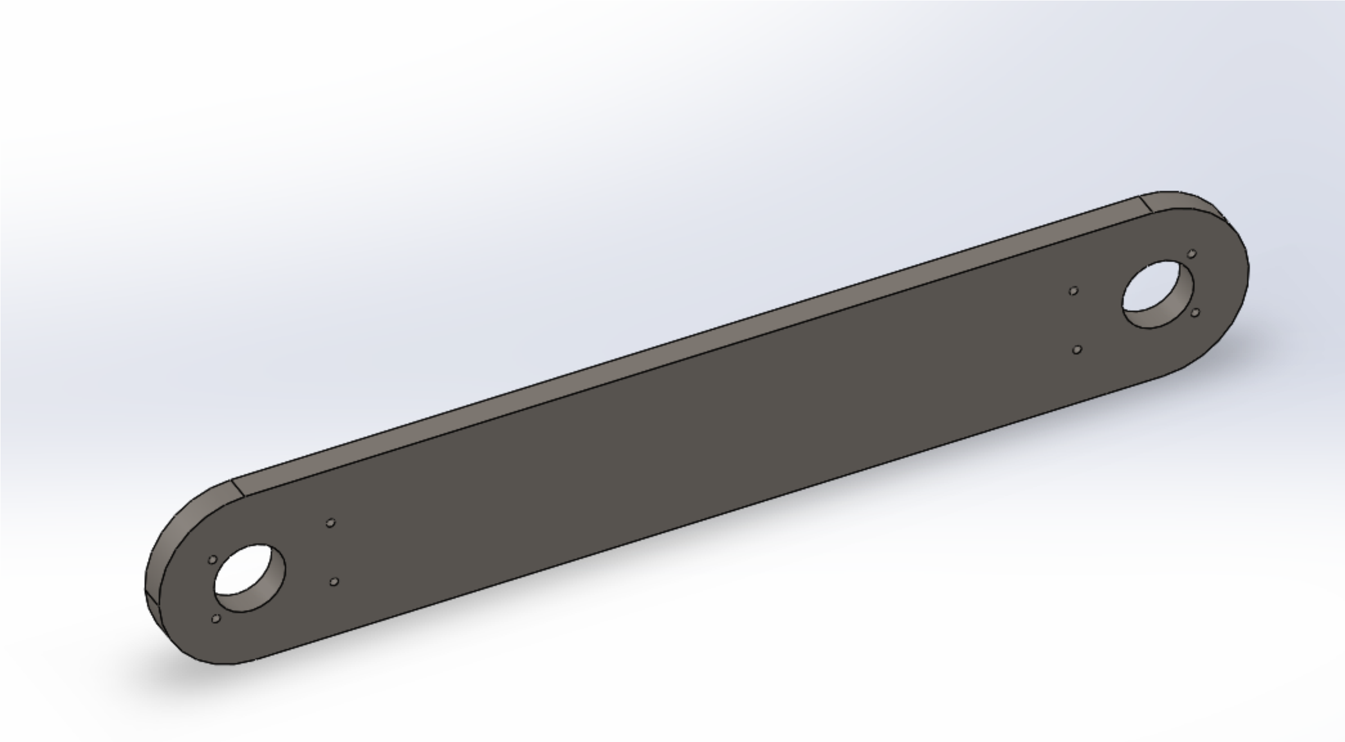


Figure 11.4: 2nd Arm Preview

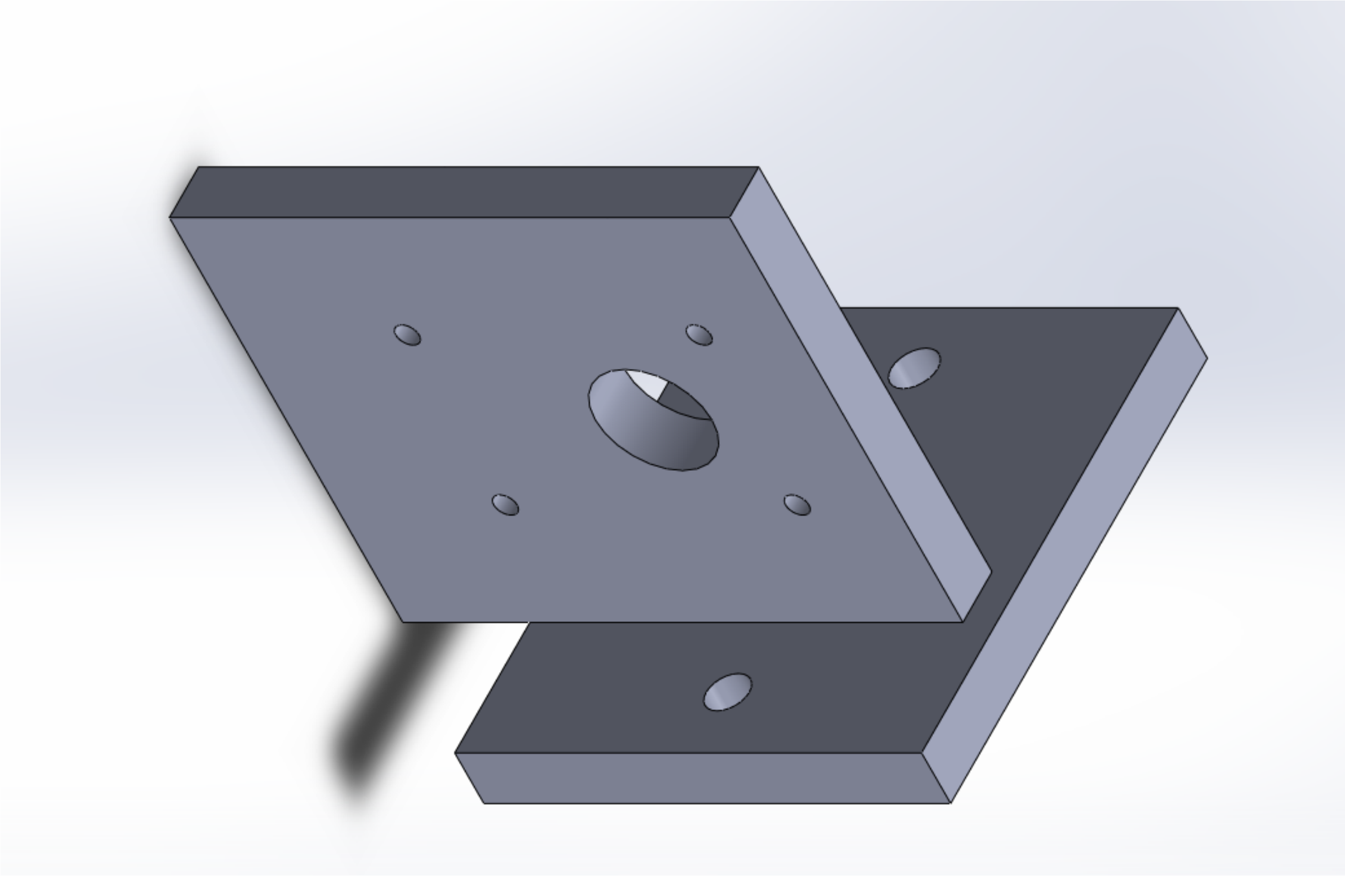


Figure 11.5: 3rd Arm Preview

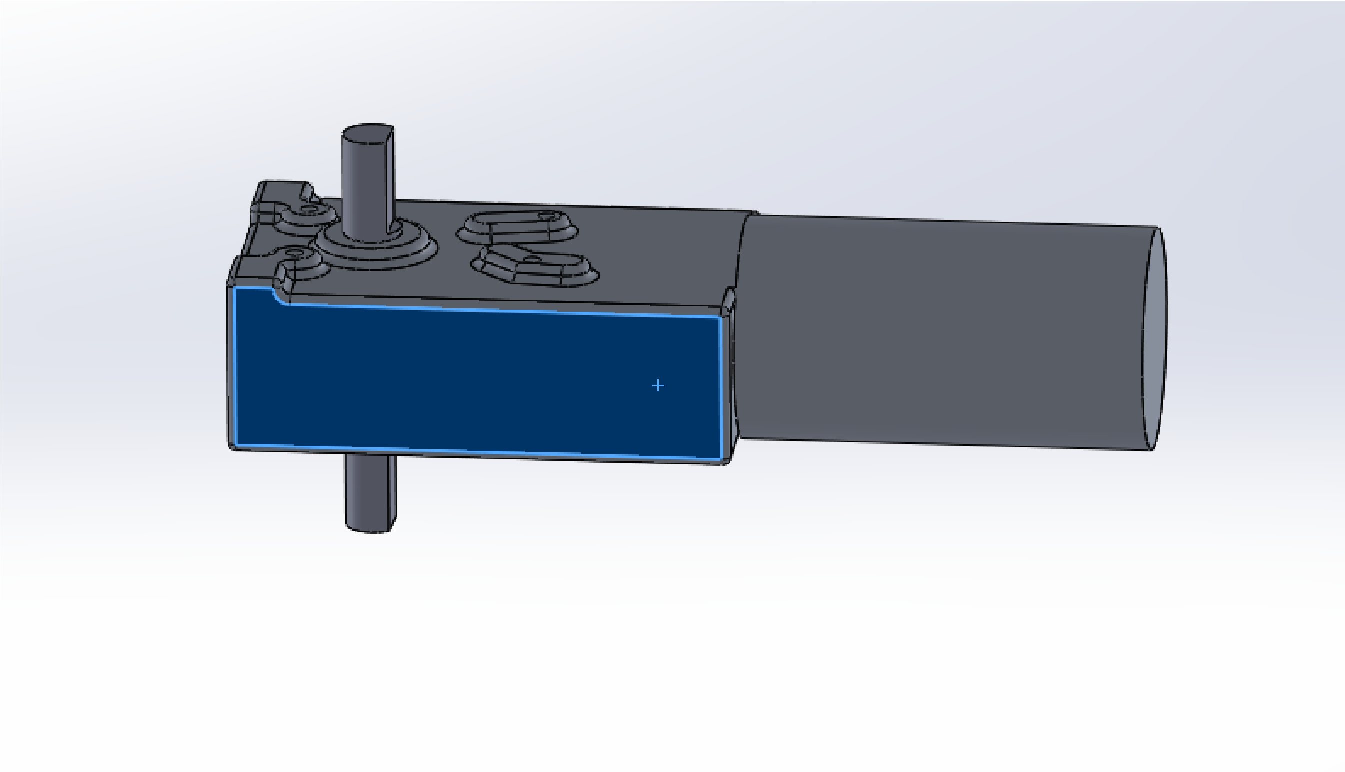


Figure 11.6: Worm-Gear Motors

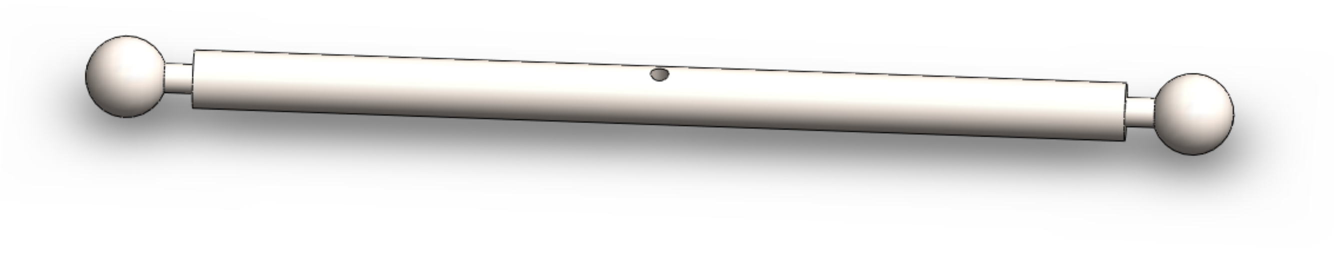


Figure 11.7: Ball-Bar Preview

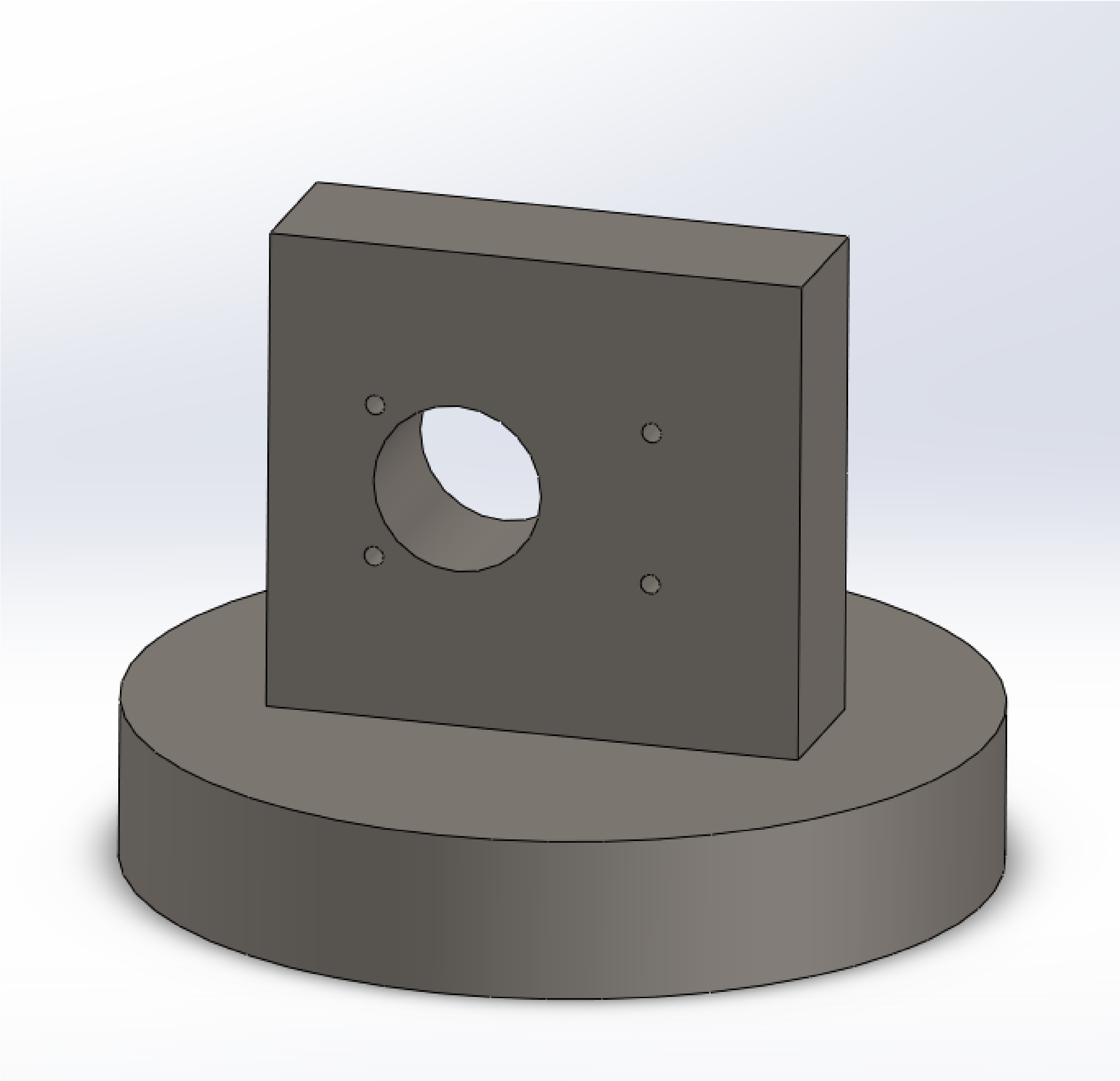


Figure 11.8: Base Preview

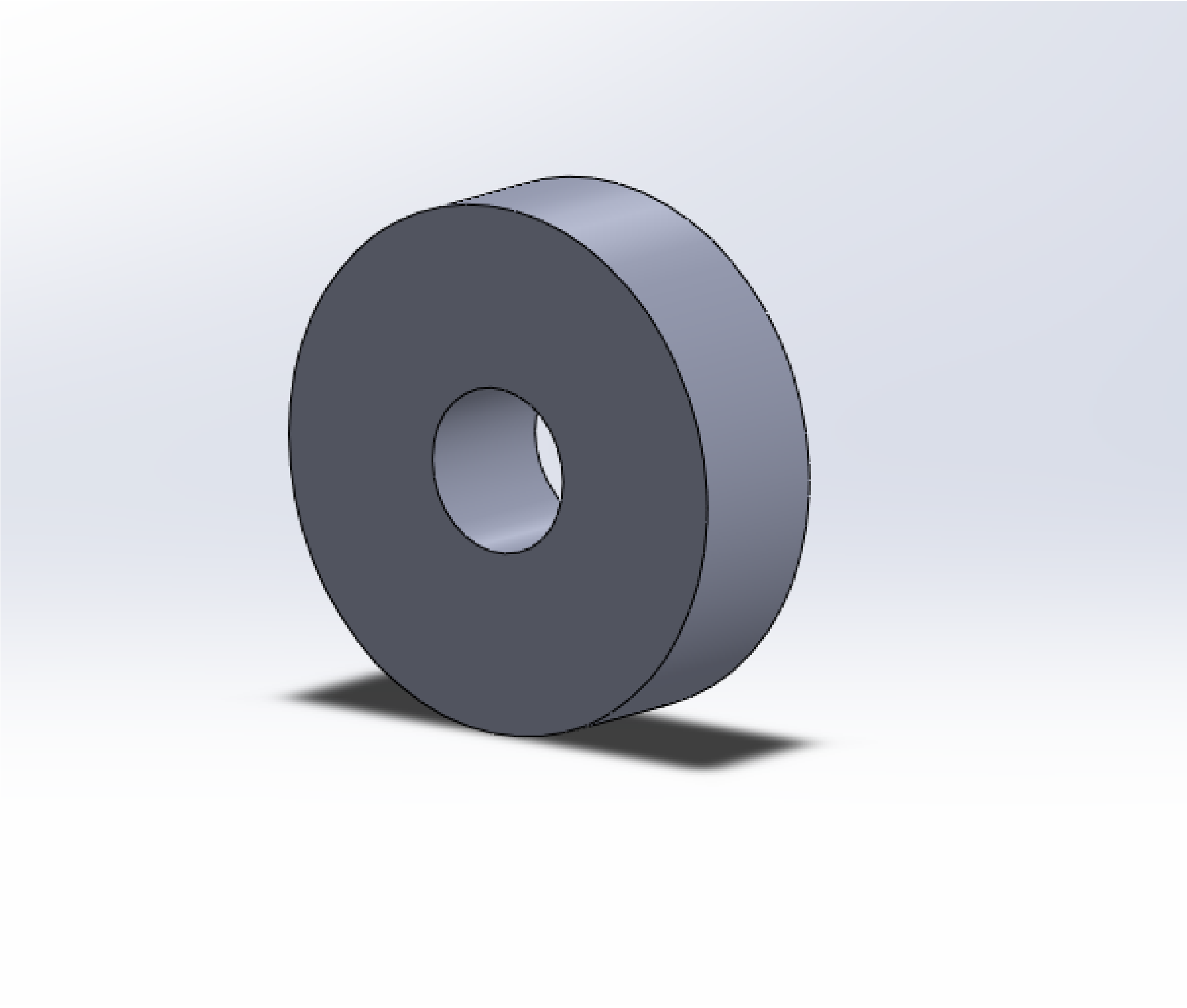


Figure 11.9: Collar Preview

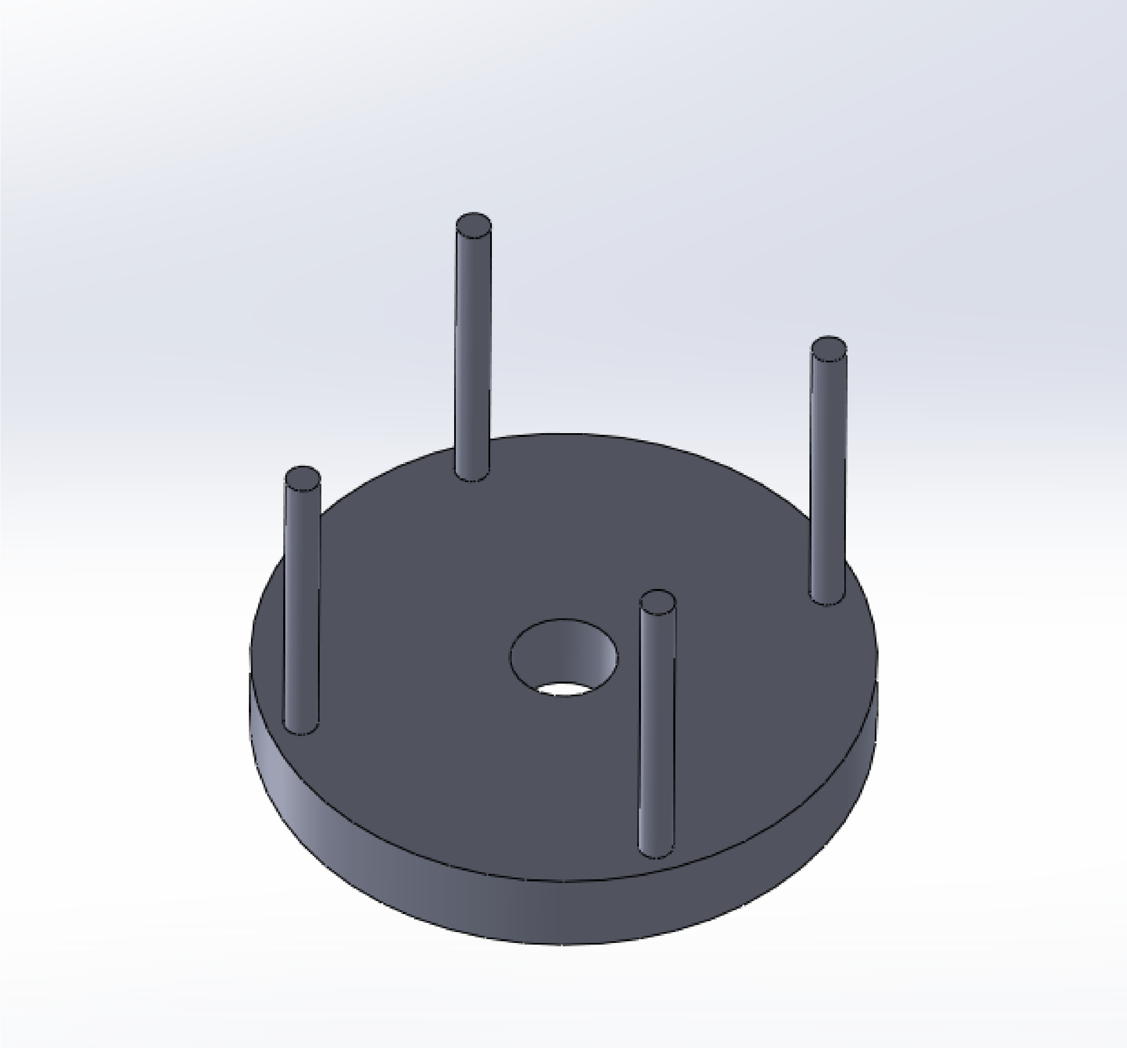


Figure 11.10: Disk Preview

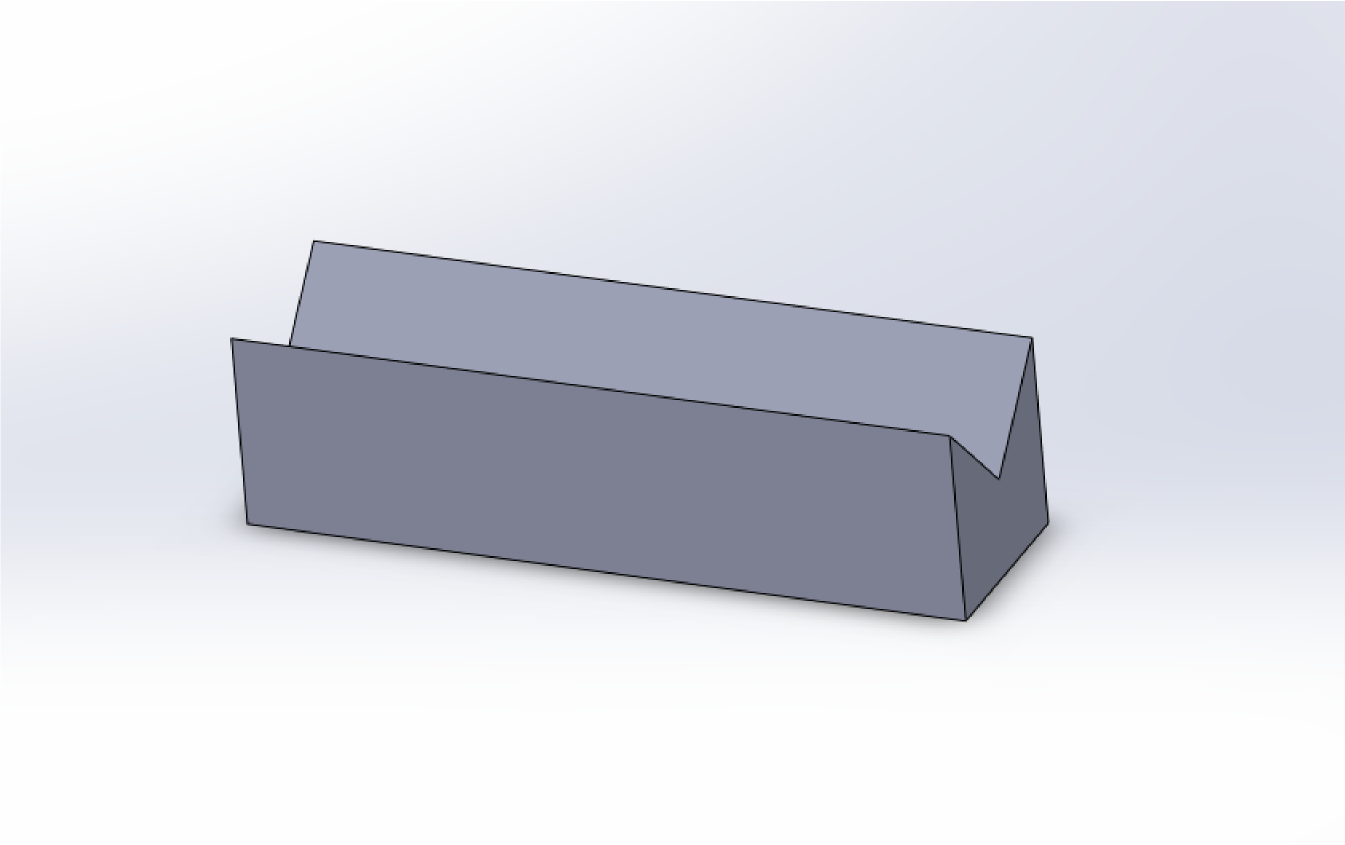
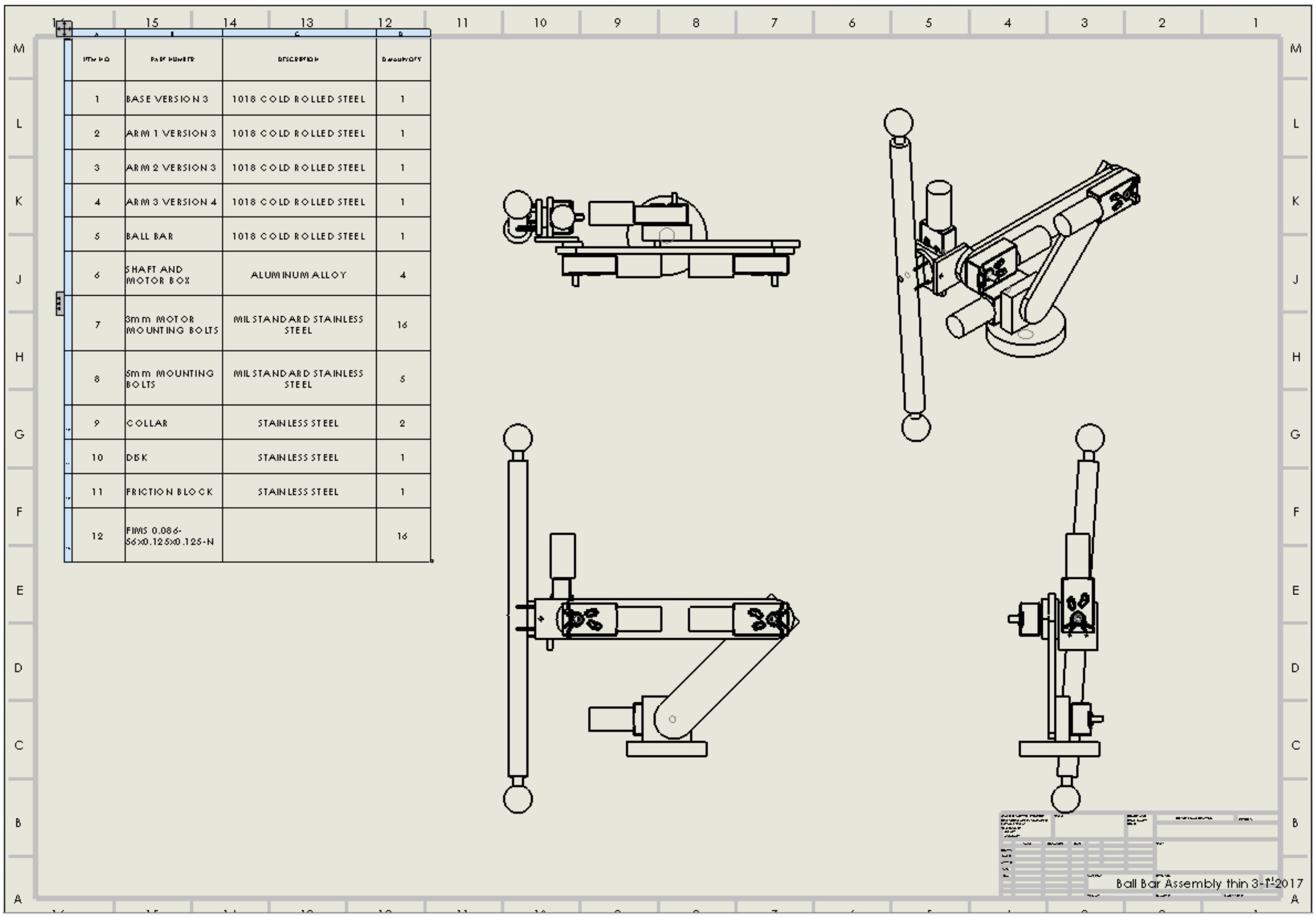


Figure 11.11: Friction Block Preview



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	BASE VERSION 3	1018 COLD ROLLED STEEL	1
2	ARM 1 VERSION 3	1018 COLD ROLLED STEEL	1
3	ARM 2 VERSION 3	1018 COLD ROLLED STEEL	1
4	ARM 3 VERSION 4	1018 COLD ROLLED STEEL	1
5	BALL BAR	1018 COLD ROLLED STEEL	1
6	SHAFT AND MOTOR BOX	ALUMINUM ALLOY	4
7	3mm MOTOR MOUNTING BOLTS	MIL STANDARD STAINLESS STEEL	16
8	5mm MOUNTING BOLTS	MIL STANDARD STAINLESS STEEL	5
9	COLLAR	STAINLESS STEEL	2
10	DISK	STAINLESS STEEL	1
11	FRICTION BLOCK	STAINLESS STEEL	1
12	FIMS 0.086-56x0.125x0.125-N		16

Figure 11.12: Ball-Bar Drawing

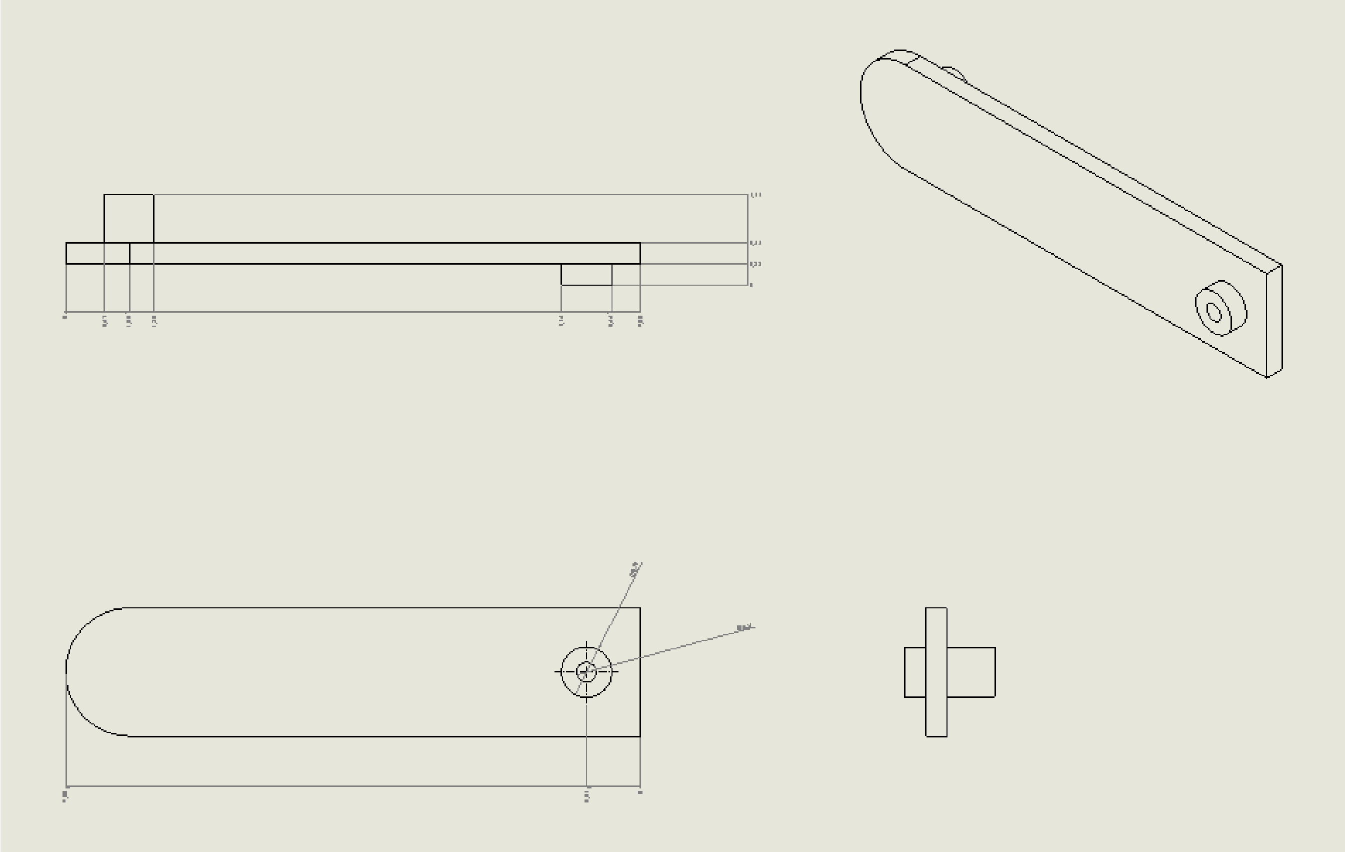


Figure 11.13: Arm 1 Drawing

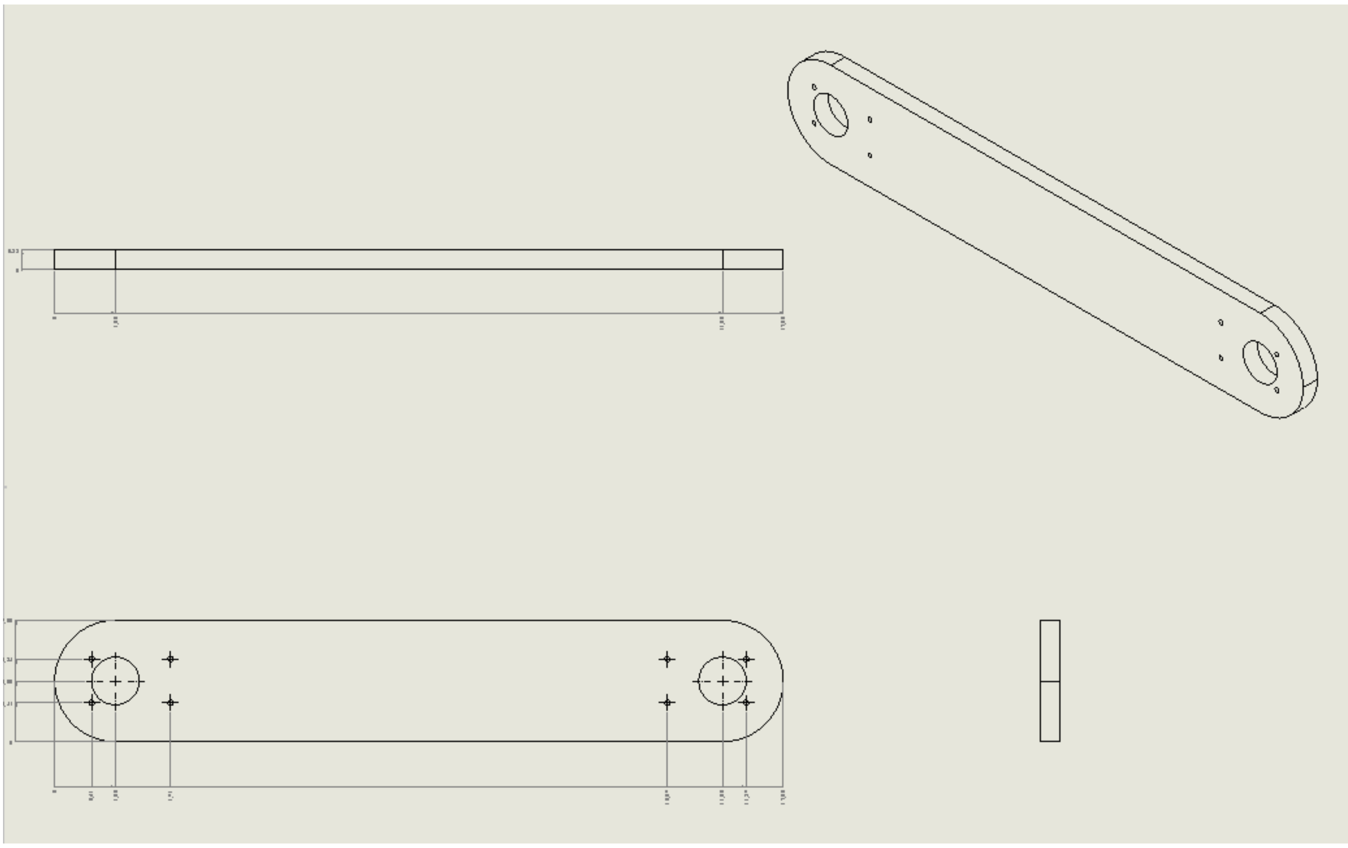


Figure 11.14: Arm 2 Drawing

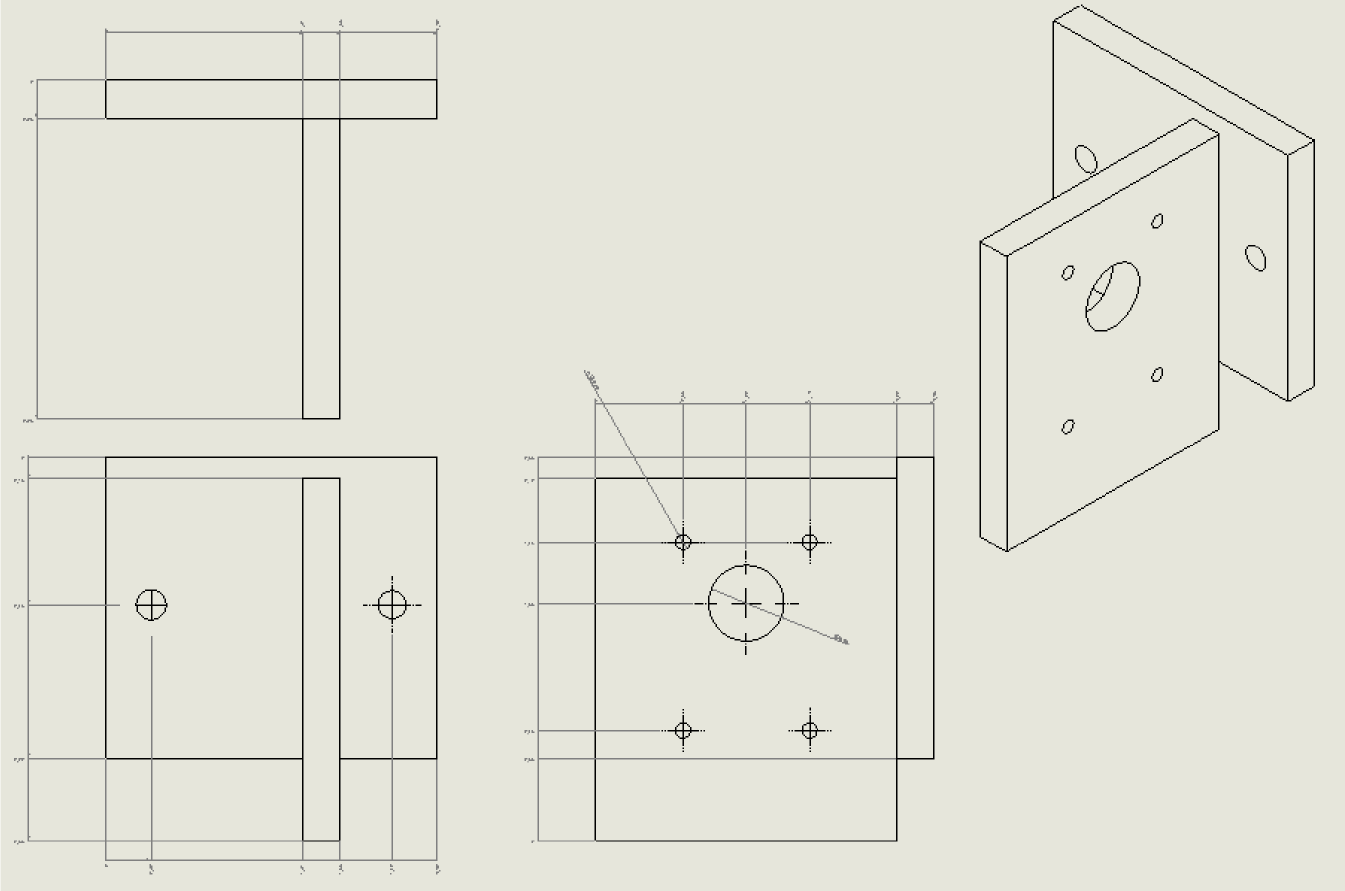


Figure 11.15: Arm 3 Drawing

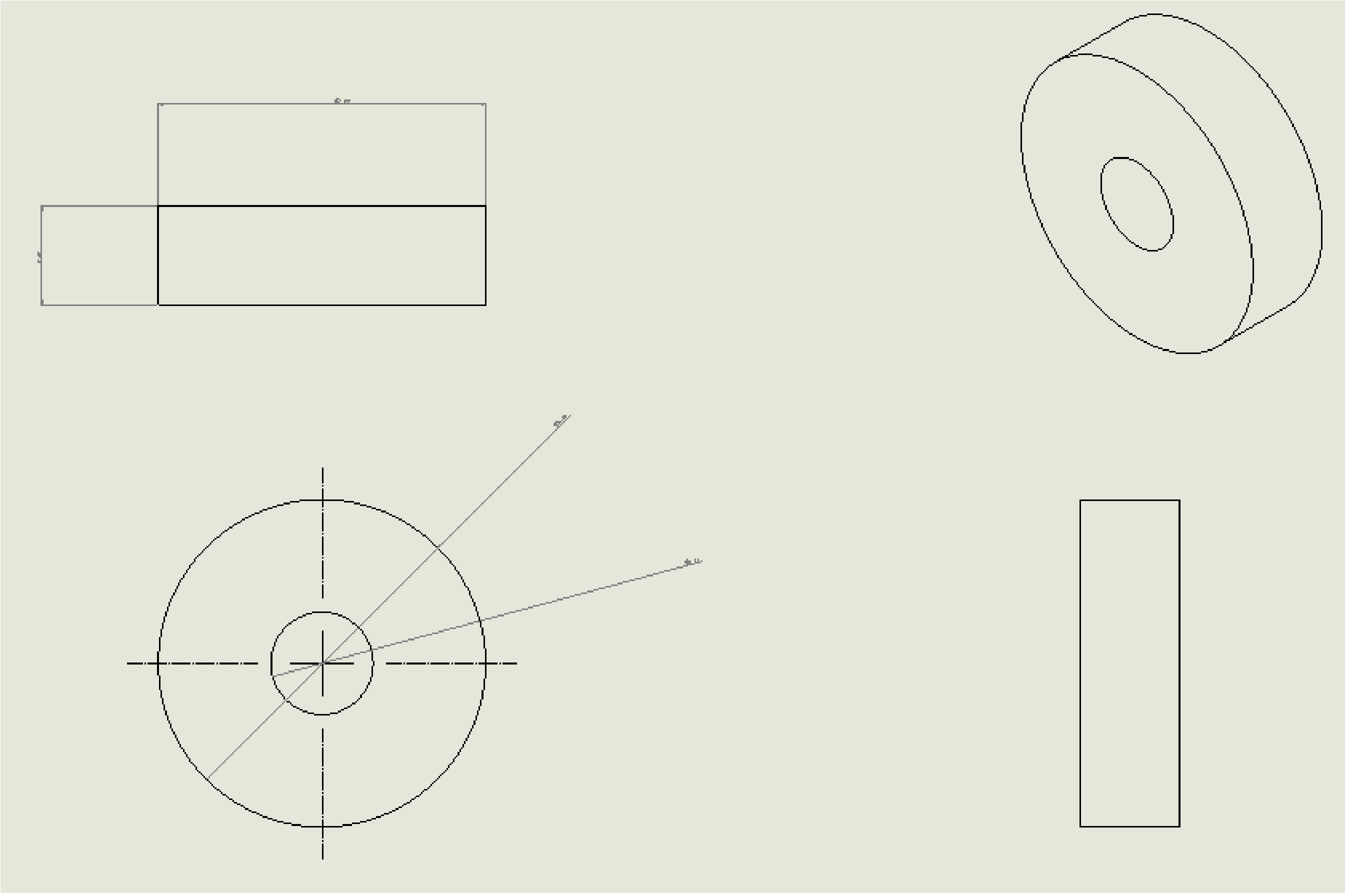


Figure 11.16: Collar Drawing

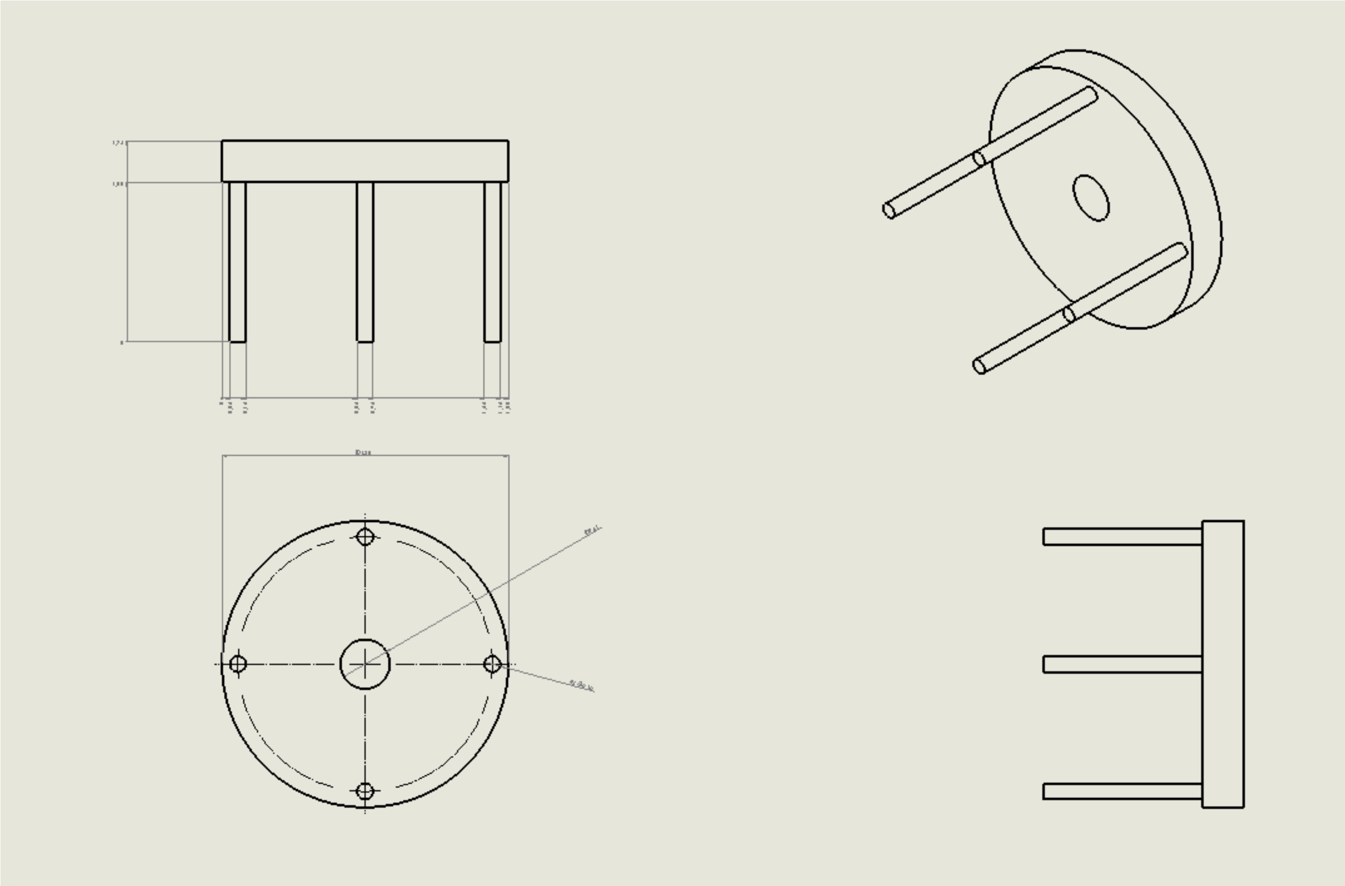


Figure 11.17: Disk Drawing

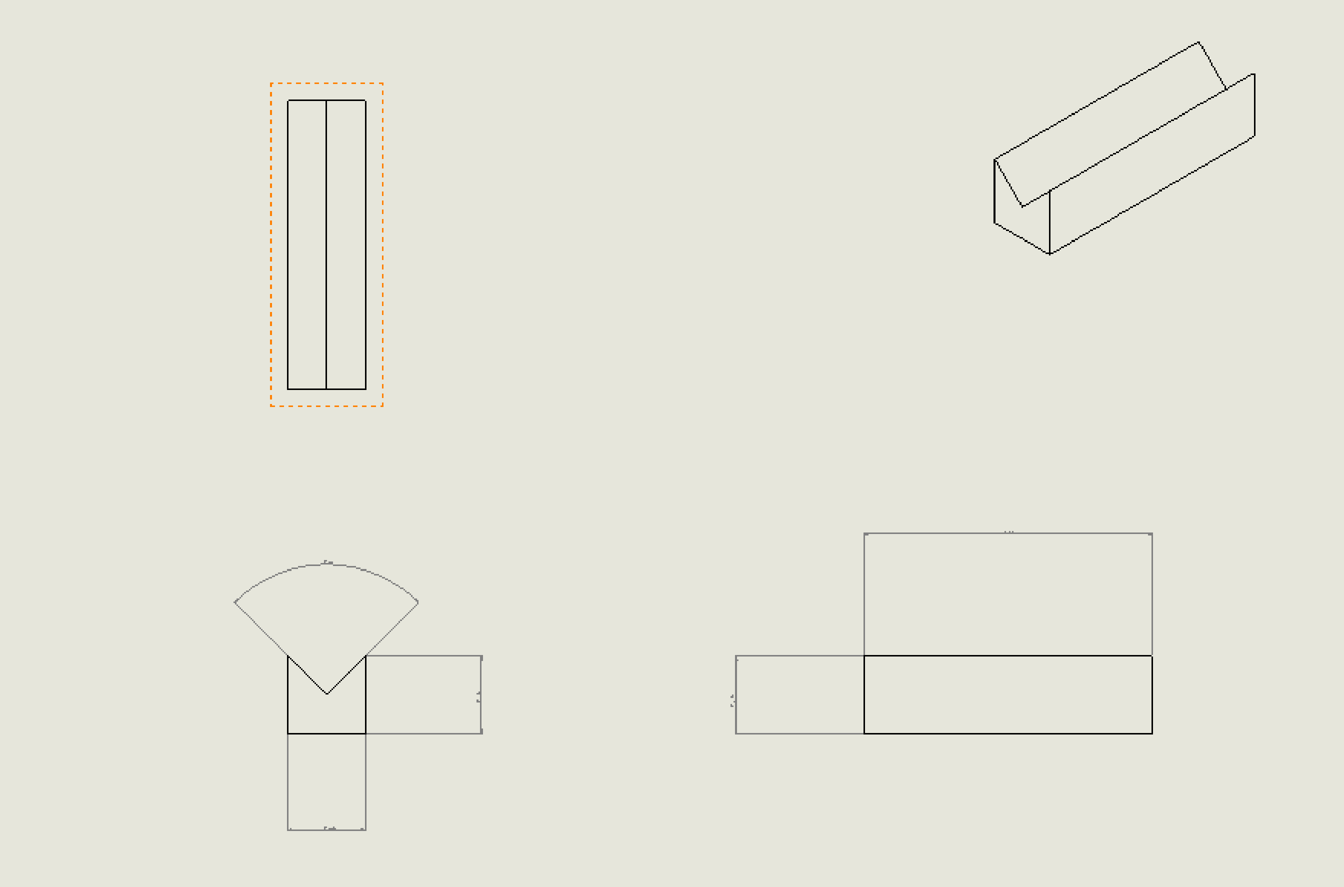


Figure 11.18: Friction Block Drawing

12 Engineering Analysis

Since extreme precision is a requirement, our design concepts must go through extensive Engineering analysis. As mentioned before Thermal Expansion was the largest obstacle the previous group faced when attempting this project. To address this problem, team 19 performed finite element simulation with Abaqus cae software. This software is extremely useful in determining nodal displacements, internal and external stresses, Heat flux and much more.

12.1 Thermal Expansion

The first trial that was attempted was a steady state heat transfer, subjected to the ball-bar. This was useful in determining the type of material needed to meet Hexagons requirements. Team 19 analyzers tested 4 various materials that were expected; this included, Invar, Stainless steel, Glass, and Acrylic. Drawings are allowed to be imported from Solidworks to Abaqus cae in order for direct dimensions to be achieved. As seen in figure 12.1, the simulation only included the ball bar itself; while in reality, it is much more complex. To specify, the heat subjected to the bar, is generated by the adjacent direct current wormgear motor. Through conduction and convection, a constant heat flux is applied onto the ball-bar, consistently warming and deforming the ball-bar through thermal expansion. Through Research and development, team 19 discovered that the total temperature change would not exceed more than 2-3 degrees centigrade; to compensate for extreme cases, the simulation was executed at a temperature difference of 20 degrees centigrade. For the first trials, the constant heat flux was applied directly about the aperture located centrally throughout the ball-bar. This was due to the fact that the motors output shaft would have been connected to the ball-bar via this orifice. Without any other disturbances such as gravity, droop, or creep, the only boundary condition applied to the specimen, was a 20 degree temperature difference. Since team 19 was only able to simulate steady state conditions, the results assumed that a constant heat flux would be applied to the bar for an infinite amount of time. Roughly outputting the total nodal displacements that the ball-bar would achieve. Results for maximum displacement turned out as followed; for Invar, Stainless Steel, Glass, and Acrylic, the maximum deflections were 20μm, 63μm, 130μm, and 10mm respectively. From the results we can determine that the thermal stress the ball-bar was experiencing was too great for our design requirements. However, this simulation was helpful in determining what material should be utilized for maximum efficiency.

The next trials of thermal expansion, were much more complex simulations. As shown in 12.2, a direct current wormgear motor is contacting the ball-bar via the motors output shaft. Each part was drawn to specification in Solidworks, and Imported over to Abaqus for further analysis. Contact force in Abaqus is complex to say the least; it is required that friction and general contacting force inputted for the simulation to execute correctly; through research and development, these values were achieved. For testing purposes, team 19 thought it would be best to run the D.C. wormgear motor for an extensive amount of time, to determine the temperature differential, and the maximum local of the temperature change. Through this test, we were able to determine that the location of maximum heat generation was on the motor shaft cylinder protruding from the gearbox. From here, a steady state heat flux/generation simulation was performed with a temperature change of 10 degrees centigrade. Maximum deflections were determined to be 11μm; which is over our tolerance for thermal expansion. Although, this was still a steady state analysis, which assumes the boundary conditions are applied infinitely. When in reality these temperature differentials will only be applicable for the time it takes to execute the operation sequence; which would be from 30-45 minutes. It is possible to execute a transient (over a time interval) analysis; however, team 19 was unable to complete that simulation within this semesters time period. Further work will include a transient analysis of heat flux.

12.2 Finite Element Analysis

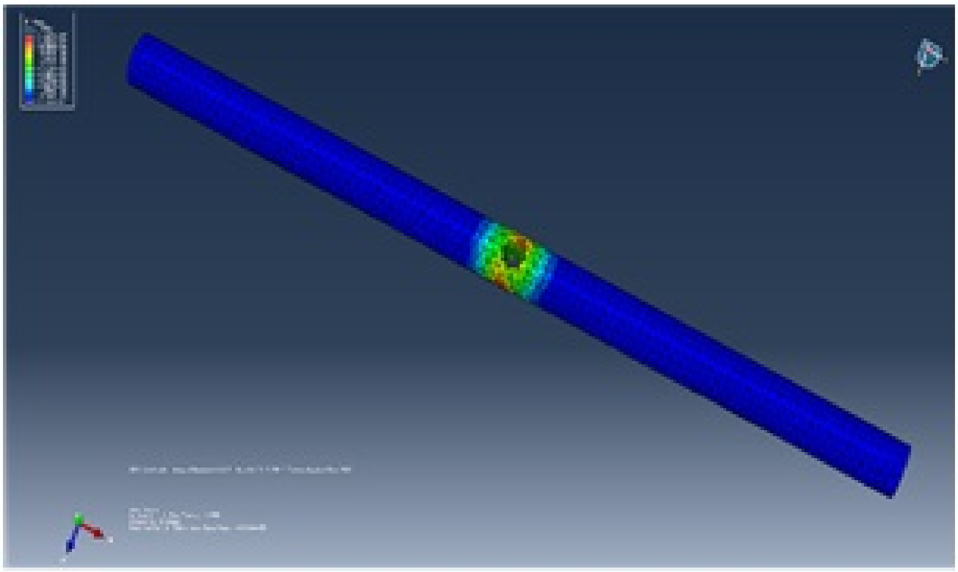


Figure 12.1: Steady State Heat Transfer

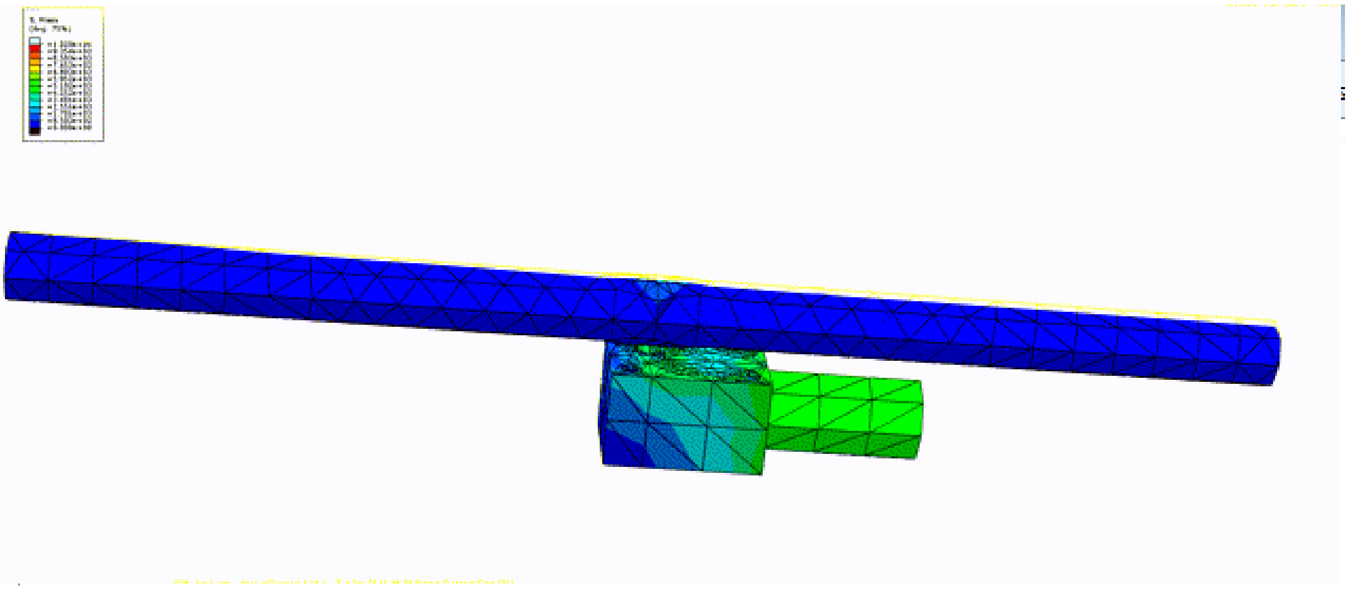


Figure 12.2: Bar Analysis

12.3 Moment Analysis

As seen from figures 12.3, 12.4, 12.5, the next focus was to determine the internal stresses throughout, while manipulation is occurring. To determine internal stresses, team 19 engineering analyzers first calculated moments about the base of each member. To simplify, team 19 thought it would be best to simulate the mechanized fixture in an orientation that would induce the maximum stress on one or more members. Team 19 determined that the fixture extended 180 degrees perpendicular to the base would produceinduce a maximum stress on the motor output shaft connecting the base and the base arm. To determine the moments the following equation $moment = P * d$ was utilized. An ideal simulation was attempted including the entire fixture with all its members contacting each other; however, this simulation was unable to execute due to contrasting contacting forces. So team 19 decided it would be much simpler to simulate each member indivivually; inducing a maximum point load or pressure distribution that would mock the realtime manipulation. So each member was separated in the assemblage, and analyzed separately, with a pressure distrubution mimicking a 50 pound point load on each section that would be experiencing the disturbance. For this analysis, two different materials were tested in order to determine which would maximize efficiency and precision for our fixture; the two materials icluded 6066 Aluminum and 1018 cold rolled steel. 6066 Aluminum was chosen because of its low cost and high yielding strength; it is often used as a framing metal alloy for fixtures and robotics. 1018 cold rolled steel was analyzed because of its cheap cost as well, and its hardness; it is also the stock metal that Hexagon utilizes for theirri current fixtures, so it is readily available. The results from this analysis concluded that 6066 Aluminum has the smaller deflection at around 19nm; where 1018 cold drawn steel nodal displacements resulted around 620nm. This deflection is the maximum displacement induced anywhere along the member; while the total deflection sums to about 14 (μ),m, and 26(μ),m for 6066 Aluminum and 1018 Cold drawn steel respectively. This is near negligibe because of the fact that the fixtuer itself has a tolerance of about 1mm when it needs to be contacted in three-dimensional space; while the ball-bar is the only member that has to be accurate of up to microns. However, the total summed deflection for each member together could potentially expose a design flaw in our concept. Further analysis will be performed on the assembly of the fixture; team 19 plans on simulating, creep, droop, general contact, transient heat flux analyses, and eventually full operation sequence.

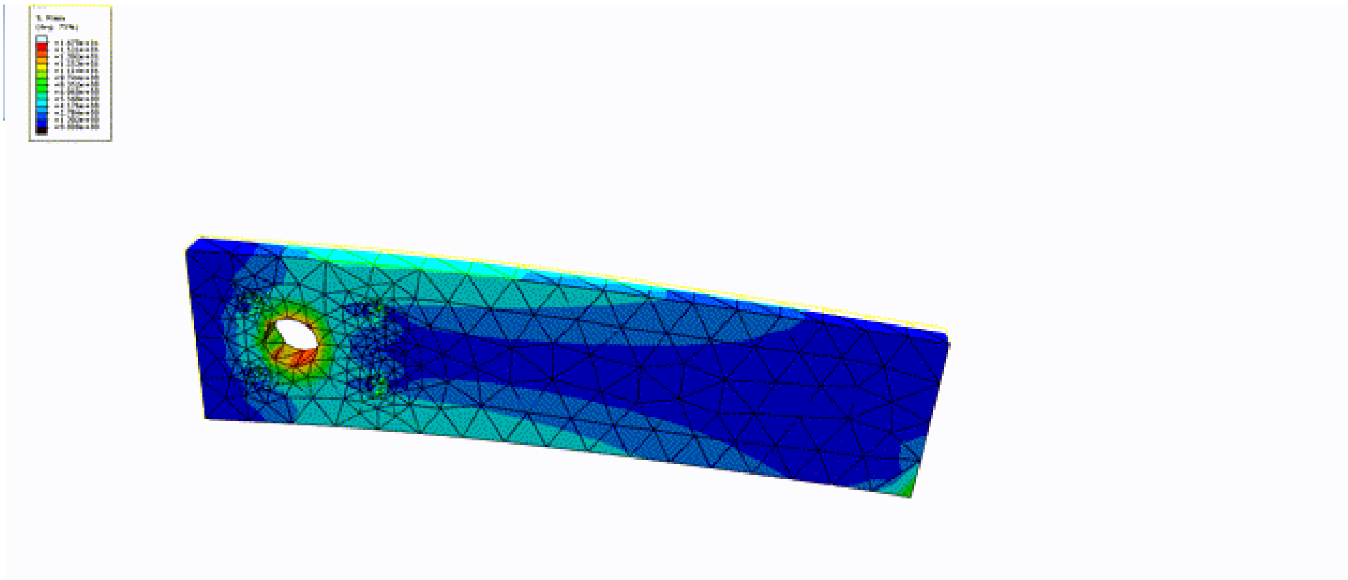


Figure 12.3: Moment Arm Simulation

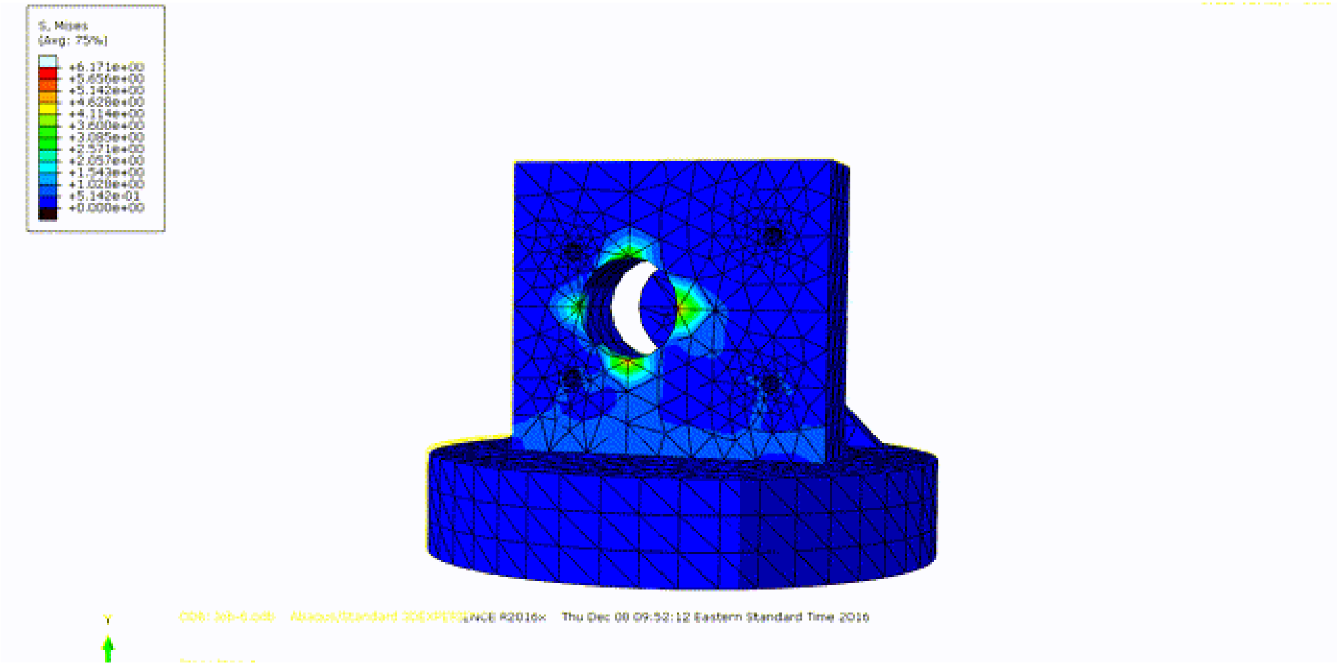


Figure 12.4: Base Analysis

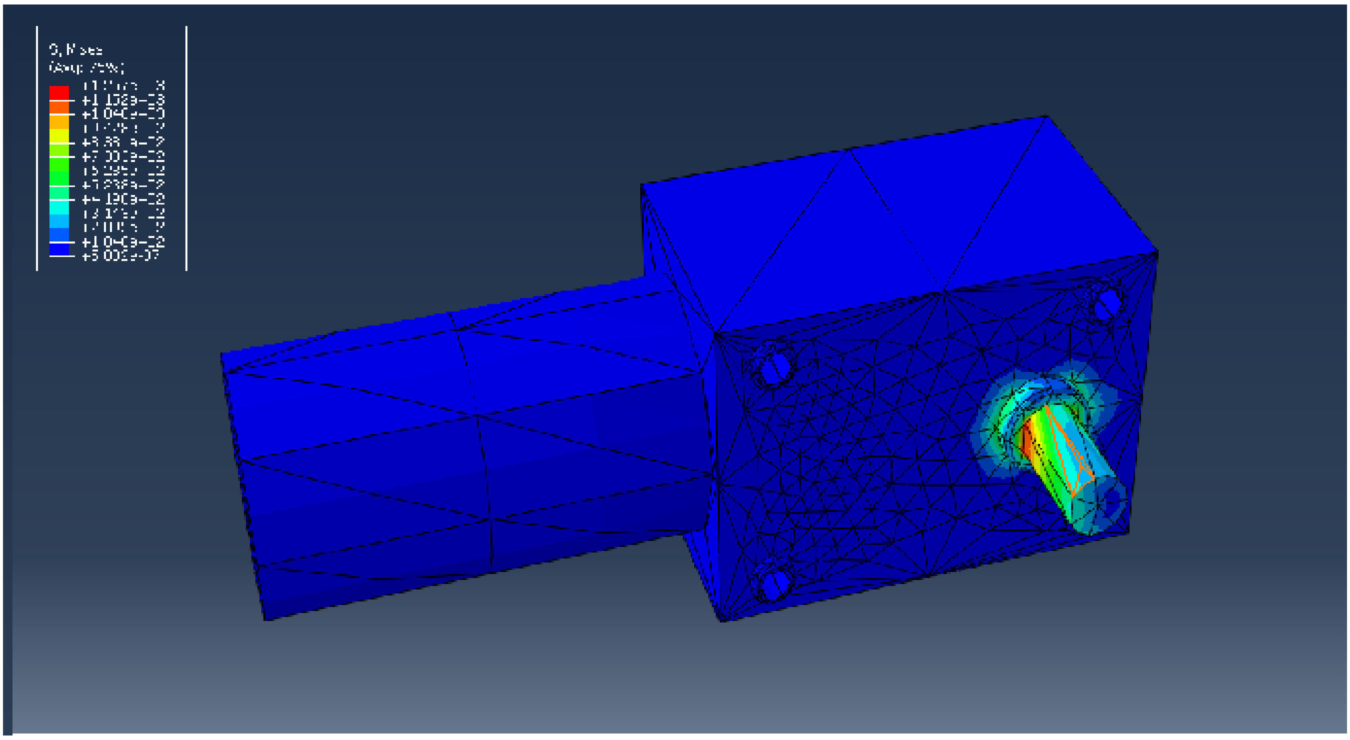


Figure 12.5: Motor Moment Analysis

12.4 Geometric Analysis

The design proposed by Team 19 consists of a three linkage manipulator. The system of equations that describe this system are based on the diagram presented in figure 12.6.

$$X = \cos(\theta) + \cos(\theta + \phi) + \cos(\theta + \phi + \beta) \tag{12.1}$$

$$Y = \sin(\theta) + \sin(\theta + \phi) + \sin(\theta + \phi + \beta) \tag{12.2}$$

$$C = \theta + \phi + \beta \tag{12.3}$$

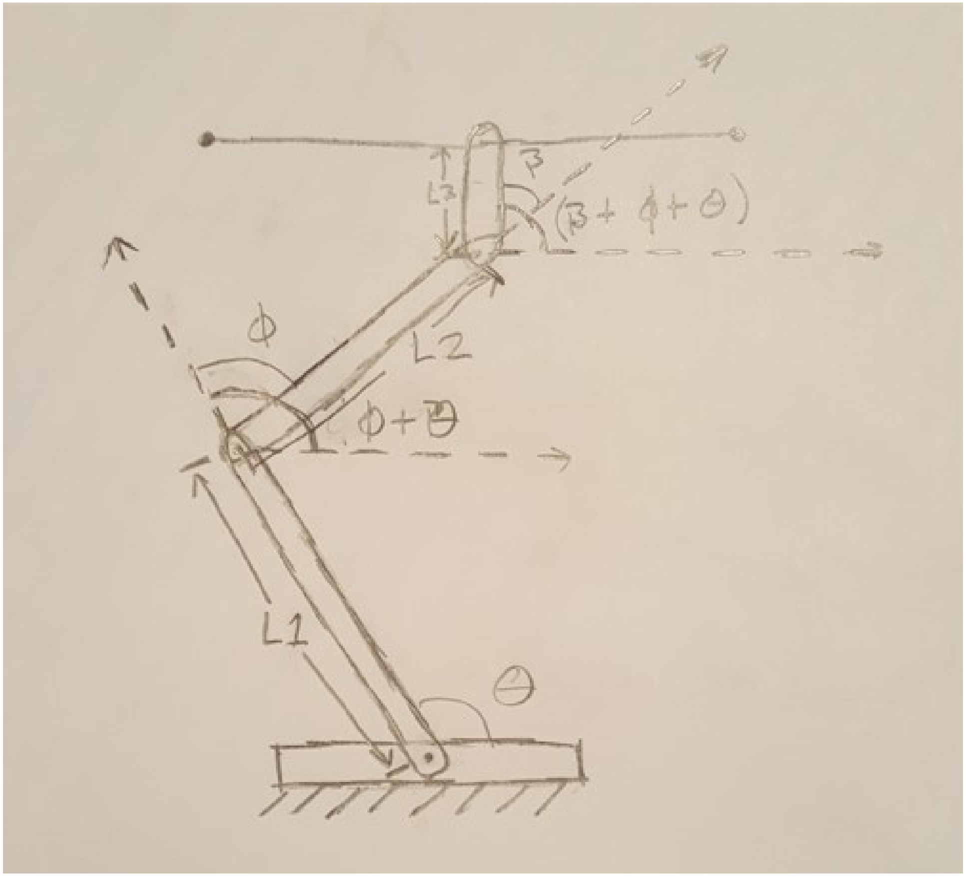
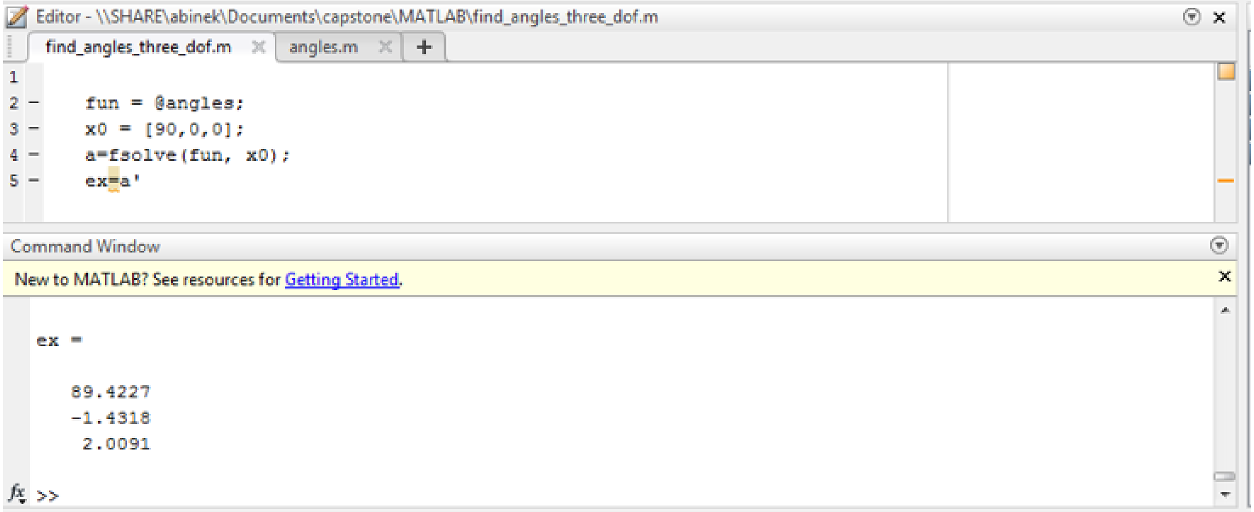


Figure 12.6: Geometric Diagram of three linkage manipulator



```
fun = @angles;
x0 = [90,0,0];
a=fsolve(fun, x0);
ex=a'
```

```
ex =

   89.4227
   -1.4318
    2.0091

>>
```

Figure 12.8: Example of angles solved by MATLAB functions

```
function F = angles(a)

L1= 8;
L2=10;
L3=2;
x=10;
y=10;
c = 90;


F(1) = -x+L1*cos(a(1))+L2*cos(a(1)+a(2))+L3*cos(a(1)+a(2)+a(3))
F(2) = -y+L1*sin(a(1))+L2*sin(a(1)+a(2))+L3*sin(a(1)+a(2)+a(3))
F(3) = -c+a(1)+a(2)+a(3)

%
% F(1) = -10 +L1*cosd(a(1))+10*cosd(a(1)+a(2))+2*cosd(a(1)+a(2)+a(3));
% F(2) = -3+8*sind(a(1))+10*sind(a(1)+a(2))+2*sind(a(1)+a(2)+a(3));
% F(3) = -90+a(1)+a(2)+a(3);
```

Figure 12.7: Non-linear solve function in MATLAB

These equation were created in MATLAB and can be seen in figure 12.7, this system non-linear and therefore can be optimized to different aspects of design. Equations 12.1 and 12.2 describe the point in the Cartesian that the tip of the third linkage reaches. Equation 12.3 describes the necessary constraint on the system in order to place the last DOF, the rotation of the Bar Ball, into the correct plane in 3D space. The variable C is chosen as the angle directly perpendicular to the plane of the desired position. In order to model these geometries lengths of the linkages are selected and a position is entered into the MATLAB scripts.

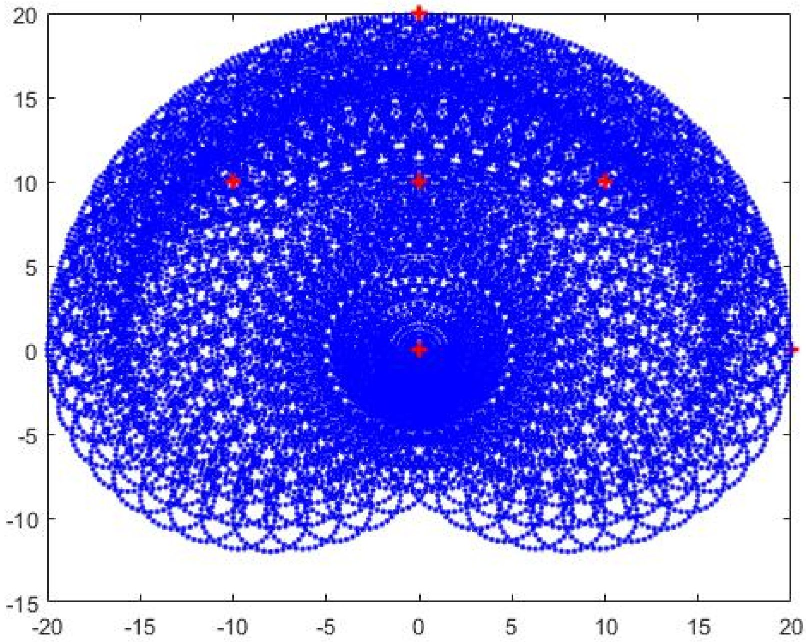
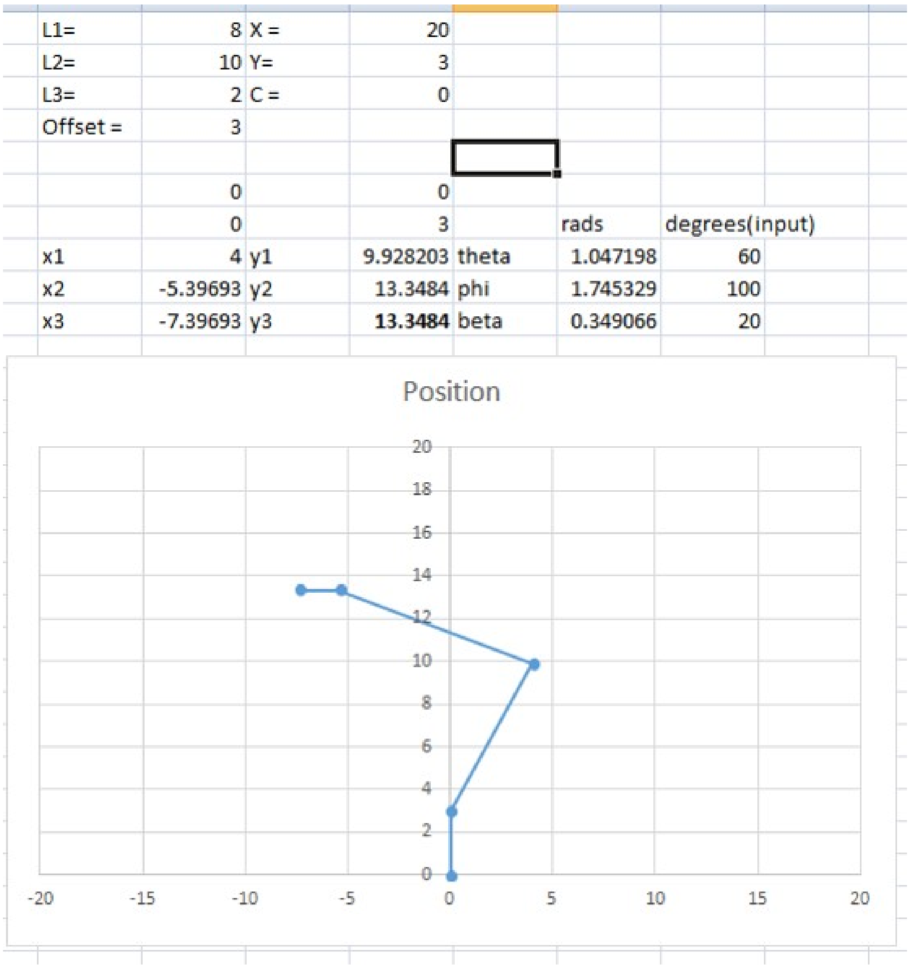


Figure 12.9: Plot of all points reachable by three linkage manipulator

Applying these methodology figure 12.9 presents a plot every solution to this system. This shows every point in the plane reachable by the manipulator by calculating every combination of angles with the, constraint of ($0 \leq \theta \leq 180$).



L1=	8	X =	20			
L2=	10	Y=	3			
L3=	2	C =	0			
Offset =	3					
	0		0			
	0		3		rads	degrees(input)
x1	4	y1	9.928203	theta	1.047198	60
x2	-5.39693	y2	13.3484	phi	1.745329	100
x3	-7.39693	y3	**13.3484**	beta	0.349066	20

Figure 12.10: Motor Moment Analysis

Once the correct angles have been identified by the solver, the angles can be placed in an Excell program for visual analysis and optimization purposes. From here more analysis can be performed in order to optimize the manipulator for desired aspects.

13 Proof of Concept

In order to arrive at a point where a proof of concept could be determined, the key features that had to be met were selected, while others were neglected. The most important features that were included consist of positioning, accuracy, consistency, and fitment. By just judging these parameters we were able to utilize rapid prototyping additive manufacturing techniques to produce parts that were dimensionally accurate, but that could be easily replaced if broken. This was necessary because the motor used was the same one that would be used in the final version, and therefore was run at full strength, which is enough to break itself if a steel bar was in place. Using this lighter material also allowed for a more stringent testing of the positioning program. Being that the PLA plastic used in this prototype is much less dense than steel, it actually reduced the damping force that this system uses to hold the bars at rest. This in turn required a more accurate positioning program than that of the steel setup. The code written to control the microprocessor can be found in the abstract portion.

In this code, the position of the test arm can be determined by the reading of the single potentiometer. This potentiometer uses a 10bit resolution within our system which allows for a reading of 0 to 1023 for a single 360-degree revolution. This is useful because it allows for an accuracy of slightly better than one third a degree. The potentiometer also always knows exactly where it is, as it reads in absolute position and not by the change in position. We felt this was the most secure method for this setup because if the process were to be interrupted, the arm position would always be known and would not require a calibration process to resume. This same theory also prevents any wild movements if the power was removed, and then resumed during the process. With the mass and strength of this system, it is possible to do real damage to the surroundings if it were to deviate from its expected travel.

Once the position is gathered, the microprocessor (Arduino ATmega2560) specifies a target location for the arm, and then uses a series of relays to manipulate the direction of the dc motor travel. The DC motor is operated by 12volts, so the relays are necessary to step up both the current and voltage of the Arduino. This motor torque is amplified by 1700 to 1 reduction of the worm drive gearbox it is attached to. This reduction enables a much higher accuracy than would ever be possible with a direct drive system, but the best benefit of this setup is that it is self-locking. Without having to keep the motor powered in its holding state, the amount of heat generation can be cut very significantly. Actual testing will provide an exact value, but estimates through the use of engineering analysis quote this temperature rise at less than 1 degree Celsius. This process will repeat for each arm involved in the manipulation of the ball bar one at a time, but for the final edition we hope to move then all simultaneously in order to reduce motion time. This may be unnecessary once the testing provides quantifiable data about the exact angles and move times required for each incremented motion. It is theorized that the movement required by each arm once it is in the first position will be less than 30 degrees at any given point, at which point further optimization would not be necessary as movement times would be very short.

The proof of concept that was unveiled at the end of the first semester was a single iteration of the process described. That is, it was one arm moving from location to location on demand without any physical input from the operator. The point of this demonstration was to show that the same position could be obtained using our code over and over again. This is critical to the operation of this device in the field, so we chose to demonstrate that first and foremost. The attached picture will show the test jig built for exactly this purpose. A dial indicator is positioned where the arm can contact it, and the attached program was run repeatedly. This test showed a deviation of about 0.003 inches, which is acceptable considering this arm is made of plastic and will flex a certain amount. For the proof of concept presentation, we also attached a larger metal arm to the plastic one to show that even with dynamic loading, one exacting moving could be made repeatedly without the effects of inertia causing issues. As a product of this testing, we found that the added mass helped to keep the bar in position as the effect of loading the leading edge of the gear train (as discussed previously) did provide a holding force. This boils down to the worry of the force of the probing tip moving the device beyond our acceptable limits all but dissolving.

14 Build/Manufacture

Over the course of this design project, there were many instances where apprehensions that are only present when working on the micron level appeared. In order to build and design a device that could meet these specifications, special tactics had to be employed. While many projects require material selection for one reason or another, this project required the utmost regard to stiffness in order to meet a 1.5 micron deflection when loaded with a 1 newton force. In addition to material selection, the proper method of attachment between materials had to be used, as at this level of stiffness one joint could throw out the entire system. Factors such as motor case rigidity, power fluctuation, temperature stability and positioning accuracy, to name a few, were areas in which careful consideration was exerted. The end result was a highly accurate four degree of freedom arm capable of moving between any number of incremental positions in order to hit 12 critical positions, and repeat within 1 centimeter every time.

The first problem encountered during the design phase of this project was selecting a material that was both rigid enough to counteract a 1 newton force and still be light enough to no over-tax the motors. The material that ended up fitting this bill was 1018 steel, milled to 1/4 inch thick and 2 inches tall. This configuration allowed for more than the required stiffness while still maintaining a total mass within the parameters of the motors. Through motor selection, the issue of heat buildup was eliminated as the motors chosen used less than 1/10 of the power used by the last build. This is accomplished by utilizing a high reduction of 3000/1 in the form of a worm gear drive. The advantage to the worm gear drive, in addition to its very low input torque requirement, is that it is self locking and reversible. The self locking feature allows for the motor to only be active while the arms are physically moving. While this may seem like a simple concept, the previous build used stepper motors for this task, which require full holding power at every position, and when the power is cut they would drop to the ground. The most recent version built this year can resist power surges through regulation, and can return to its previous position even in the even of power loss.

With use of the worm driven gear boxes, another major concern included accounting for free play in the motors/gearing. Without spending thousands of dollars on zero-backlash motors, the highest quality motors that were sourced still induced a few degrees of free play at the output shaft. These motors even utilized bronze low-clearance bushings to prevent the shaft from flexing and sagging, but the free play occurs within the contact between the many gear teeth in operation within the reduction housing. The solution for this free play, being that it is an angular/rotational uncertainty within the measurable plane, was to affix the position sensor to the physical shaft itself, rather than count increments on the motor side. This allows the program to test the absolute position of the physical arm/shaft interface after the free play rather than before, and is then able to direct the motor as to compensate for over or undershoot. A further benefit of this external monitoring system is that it will continue on the desired path until a position is positively met, therefore there are no instances within which a power loss or interruption could cause issues. Lastly, if power is lost in the middle of a positioning cycle, the program will immediately know where the arms all are as soon as it is booted, and will either return them to the first position, or continue where it had left off depending on user input. This design feature will in theory eliminate all possibility of collision with the very expensive measuring heads that are used on the CMMs. Furthermore, the system is programmed to accept input from the CMM machines, allowing the positions to change with command of the CMM rather than on a time based system which could come out of sync.

Once all the components had been selected, building the device brought up another full set of considerations. The first task was to cut all of the bars to the correct arm lengths. This was done by using a horizontal gravity bandsaw, which makes a cut without heating up to a point which could change the properties of the steel in an unpredictable way. This cut was then squared on a milling machine in order to obtain perfectly repeatable positioning without the need of compensation. The coordinates of the motor mounting holes were then laid out by using a stencil that was 3D printed to fit the exact dimensions of the bar and motor gearbox. Having a stencil that fit in this manner allowed for 100 percent repeatability, rather than relying on a coordinate system and measuring distances for each hole where error could propagate. Once the holes where punched/marked the wholes where drilled through the bar using an aggressive angled drill bit and a powerful drill press to ensure a fast and straight cut without heating the metal. Caution was exerted at each machining process to ensure the metal was not heated to a point where it would transition into a state that would alter the properties of the steel. Not much heat is needed to harden steel to a point where it would become more brittle than was required for this project. With the holes drilled and the motors mounted with high grade fasteners, the next step was to attach the all of the arm assemblies to each other. This was accomplished by welding stop collars to the points where the motor shafts protruded from the arms. Welding was the chosen method of attachment for a few reasons. The first being that it was necessary for the collars to be exactly flush with the arm, leaving no room for bolts, and the second being that there had to be no free play nor flex in the collar/arm interface. To deal with the large influx of heat pumped into the arms during the welding process, the arms were misted with oil and allowed to cool slowly. The collars were also welding in a manner that applies small sections of welds incrementally across various positions, known as tack welding. This lessens the maximum temperatures observed in the arms throughout the process. The base was built in a similar manner, with a vertical bar welded to a heavy base.

In order to attach the potentiometers directly to the output shafts, 3D printing methods were utilized. The advantages to 3D printing were that any geometry could be produced without advanced machining and holding techniques. The geometry used mirrored the shape of both the potentiometers and gearcase backings. The mount screwed to the motor gear case, and then the potentiometer glued into the mount. A small, simple coupler was then pressed onto both the potentiometer and the output shaft eliminating all play between these two surfaces, as this is the most critical interface of the entire positioning system.

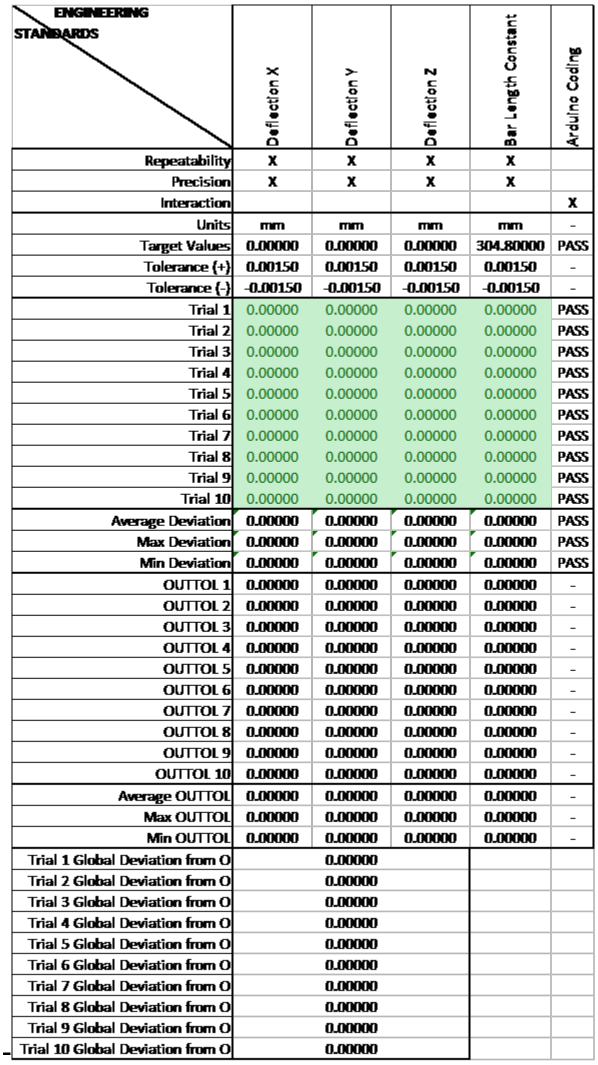
With the machining processes complete, the assembly could begin. This mainly consisted of positioning the arms so that the flat spots on the shafts lined up with the stop collar set screws. These screws were then tightened as firmly as the arms were turned a few degrees forward and backward, allowing the set screw to push directly perpendicular to the flat on the shaft. This was repeated for each motor, and the ball bar mount. The end result was a highly repeatable, very rigid device that could be manipulated to hit any desired position.

15 Testing

In order to confirm that the device passes all design specifications required by Hexagon, mentioned in Section 6, a test matrix was designed to evaluate all tests that needed to be completed.

15.0.1 Deflection

The figure 15.0.1 identifies the standards required by Hexagon on the right column. The three key standards (repeatability, precision and interaction) are what need to be tested in the horizontal row at the top of the matrix. At each position each sphere on the bar must be measured to determine its XYZ position. Using the position of the two spheres the length of the bar is calculated. This test is performed on a CMM to accurately determine the location position down to the 1.5 micron required tolerance. In the skew square calibration, both spheres are probed five (5) times for the CMM to recognize the object it is measuring to be a sphere and determine its XYZ location relative to the machines local coordinates. Hexagon's program, PC-DMIS, to operate the machine then calculates the length of the bar by using the Pythagorean theorem. The output values for the sphere locations and bar lengths are then input into the matrix. The matrix then evaluated the recorded values with the target value and tolerances to produce if the values are within tolerance. If they within tolerance the cell will highlight green and if out it will highlight red and the out of tolerance values will be calculated. The test will be performed ten (10) times for each orientation in order to obtain an average deviation. This matrix in figure 11.3 is only one of the 12 orientations. Overall there will be 12 test matrix sheets to collect all data.



ENGINEERING STANDARDS	Deflection X	Deflection Y	Deflection Z	Bar Length Constant	Arduino Coding
Repeatability	X	X	X	X	
Precision	X	X	X	X	
Interaction					X
Units	mm	mm	mm	mm	-
Target Values	0.00000	0.00000	0.00000	304.80000	PASS
Tolerance (+)	0.00150	0.00150	0.00150	0.00150	-
Tolerance (-)	-0.00150	-0.00150	-0.00150	-0.00150	-
Trial 1	0.00000	0.00000	0.00000	0.00000	PASS
Trial 2	0.00000	0.00000	0.00000	0.00000	PASS
Trial 3	0.00000	0.00000	0.00000	0.00000	PASS
Trial 4	0.00000	0.00000	0.00000	0.00000	PASS
Trial 5	0.00000	0.00000	0.00000	0.00000	PASS
Trial 6	0.00000	0.00000	0.00000	0.00000	PASS
Trial 7	0.00000	0.00000	0.00000	0.00000	PASS
Trial 8	0.00000	0.00000	0.00000	0.00000	PASS
Trial 9	0.00000	0.00000	0.00000	0.00000	PASS
Trial 10	0.00000	0.00000	0.00000	0.00000	PASS
Average Deviation	0.00000	0.00000	0.00000	0.00000	PASS
Max Deviation	0.00000	0.00000	0.00000	0.00000	PASS
Min Deviation	0.00000	0.00000	0.00000	0.00000	PASS
OUTTOL 1	0.00000	0.00000	0.00000	0.00000	-
OUTTOL 2	0.00000	0.00000	0.00000	0.00000	-
OUTTOL 3	0.00000	0.00000	0.00000	0.00000	-
OUTTOL 4	0.00000	0.00000	0.00000	0.00000	-
OUTTOL 5	0.00000	0.00000	0.00000	0.00000	-
OUTTOL 6	0.00000	0.00000	0.00000	0.00000	-
OUTTOL 7	0.00000	0.00000	0.00000	0.00000	-
OUTTOL 8	0.00000	0.00000	0.00000	0.00000	-
OUTTOL 9	0.00000	0.00000	0.00000	0.00000	-
OUTTOL 10	0.00000	0.00000	0.00000	0.00000	-
Average OUTTOL	0.00000	0.00000	0.00000	0.00000	-
Max OUTTOL	0.00000	0.00000	0.00000	0.00000	-
Min OUTTOL	0.00000	0.00000	0.00000	0.00000	-
Trial 1 Global Deviation from O	0.00000				
Trial 2 Global Deviation from O	0.00000				
Trial 3 Global Deviation from O	0.00000				
Trial 4 Global Deviation from O	0.00000				
Trial 5 Global Deviation from O	0.00000				
Trial 6 Global Deviation from O	0.00000				
Trial 7 Global Deviation from O	0.00000				
Trial 8 Global Deviation from O	0.00000				
Trial 9 Global Deviation from O	0.00000				
Trial 10 Global Deviation from O	0.00000				

Figure 15.1: Test Matrix for One Orientation

The current design was fabricated using some 3D printed parts made of plastics. The motors have proven to have more free-play than what was described in the specifications when the team purchased them. In section 16, Redesign, all design considerations are evaluated to correct for these complications. Once these are corrected then the deflection testing can be completed.

15.0.2 Programming

Another column is labeled from testing the electronics and programing of the device. This column is a simple "PASS/FAIL" check to determine if the device can reach the same position each time consistently. As in section 15.0.1, this process will be testing by running the program a total of ten (10) times and ensuring the arm will reach each position correctly without any anomalies.

15.0.3 Thermal Expansion

The biggest concern the previous capstone team had with this project back in 2011 was the issue with heat. The teams design was very elegant however with the amount of steel that was used the arm became heavy as a result. Therefore, more powerful motors needed to be used. With powerful motors quite a bit of heat was generated and as the laws of heat transfer can explain, thermal expansion was happening which caused a change in position of the spheres thus decreasing the accuracy of the device.

Team 19 decided that their first priority of this project was to eliminate the issue of thermal expansion. With self locking motors the motors will not run once they arrived to the programmed position. Also, the advancement in technology since the previous groups design has brought about the motors the team used which generate little to no heat. Figure **??** is a graphical representation of the temperature of the motor while running over a period of time. It is evident that the temperature fluctuation is minimal proving to cause thermal expansion in the steel members that is within tolerance of the design specifications.

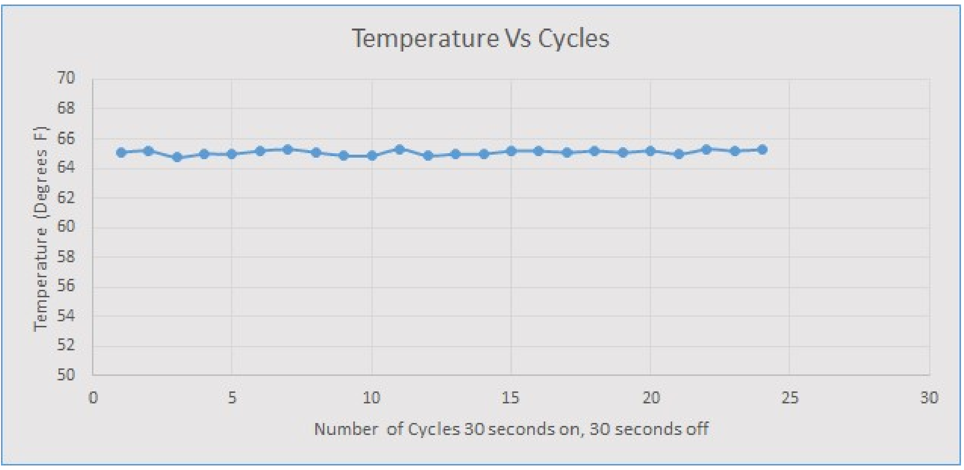


Figure 15.2: Temperature of Motor over time while cycled

16 Redesign

During the manufacture and testing of proof of concept along with initial and final prototyping, weaknesses in the initial design were discovered. Team 19 employed several redesigns in order to meet the design specifications set forth by Hexagon. Where possible, these design changes were incorporated into the final prototype before final testing was done in a cmm.

16.1 Geometry Changes

The first issue identified was the angular precision, the initial worm gear driven motor was replaced with a similarly designed gear motor with a higher reduction and lower RPM. While this increases the measuring time overall, it greatly decrease the precision error; which is a project specification that falls on top of our priority list. The geometry of the rest of the manipulator was then reconsidered. Due to the slightly different size of the motors, the orientation of the motors was changed, as well as some features of the arms themselves. The solution was that two motors would be bolted to the second linkage, one to control the second joint and one to control the third joint. Also it was mandated the length of the second arm to be at least the length of the first and the third arm in order for the two motors to fit and also to allow enough room for the third linkage of the manipulator to have the angular freedom required. Initial bar geometry and lengths were selected to help make the manipulator as scalable and usable in as many different sized machines as possible. Later in the design process more in depth abacus modeling revealed that the geometry and lengths of the two main linkages of the manipulator could lead to unacceptable flexing under one newton dynamic forces. This forced the team to reconsider design for optimization in order to meet design specs. New lengths were selected with all these factors in mind so as to yield a manipulator to meet all specifications.

16.2 Bar Attachment

The initial design of the manipulator employed both inertial forces and friction forces to prevent motion at certain joints. In particular, the attachment of the bar-ball to the third linkage was identified as problematic. In certain orientations the bar-ball is placed flat in the xy plane. In this position friction becomes the only force opposing the rotation imparted by the dynamic force of the prob. The initial design implemented a friction plate between the third linkage and the bar. The bar would need to be pressed against the plate and fixed in place with a set screw. This was identified as a weak design as it was expected that this apparatus would ware very quickly and have issues with keeping the correct amount of pressure between the bar and friction plate. A separate piece was designed to affix the bar to joint 4 than directly fixing the bar to the forth motor shaft. This design utilizes a thumb screw which applies pressure a round friction disk perpendicularly to the axis of rotation. The force of friction acts tangentially to the circle directly opposing any rotation as shown in the block diagram below.

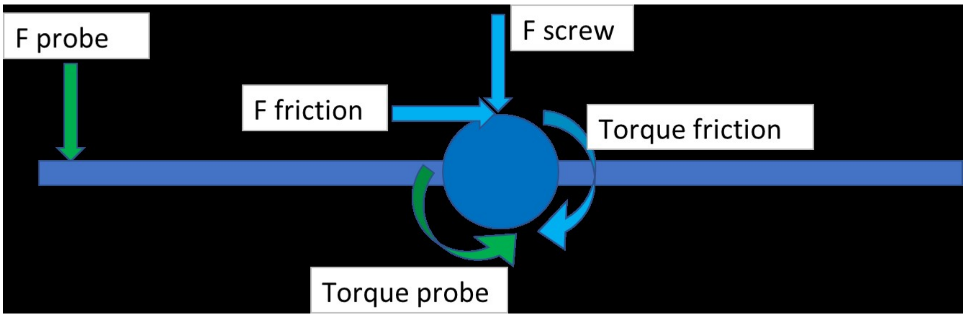


Figure 16.1: Bar friction block diagram

This circular friction plate is attached to the shaft of the fourth motor with a coupler and set screw with the bar affixed to the top. The bar is placed in a v grove cut into the top of the friction plate so as to self center and with bolt pressure pushing directly down on bar, resist any side wiggle. In order to press the thumb screw against the friction plate the third linkage was modified. The length of the L bracket extended past the motor, keeping the L of the bracket the same distance from the joint. The flat plate that extended past motor four was then drilled and tapped and the thumb screw added. With this design the friction opposing rotation can be set and modified to compensate for ware on the screw and plate.

16.3 Future Recommendations

16.3.1 Motor Selection

Based on the previous teams design and the problems identified, the first priority for this design was removal of heat generation. As described in section (add), high torque, worm gear driven, self locking dc motors were identified as a solution because of their ability to power cycle and keep their position under force. By effectively removing heat generation and thermal expansion from the manipulator this problem was solved. However, in testing the team discovered problems with the initial design and how these motors were utilized. The current design uses the motor shafts as the joint, a method used in most industrial robots such as Kuka or Epson robotics. Differences in initial abacus simulations and actual purchased motors relieved an issue with the free play induced in the joint by the bushings and gear train of the motors. The self locking nature of the worm gear motors is also what presents difficulties in design. A solution identified to alleviate this issue while also solving problems of heat induced to the system is the use of a different kind of motor. Direct drive stepper motors with active low spring force breaking have the ability to by power cycled while still maintaining accurate position under load. However, these motors can still possibly cause issues. Because these motors require higher torque direct from the coil and shaft they require higher current to drive. Also because of their position locking method, during the power high portion of the cycle they will require a active solenoid or similar actuation in order to oppose the spring force. The holding torque, spring force and current requirements to open are then directly dependent on one another which in scaling of the manipulator can lead to heat generation issues. The solution here is to increase the power low portion of the cycle in order to actively or passively cool the manipulator. This will negatively affect cycle times while increasing the accuracy of the manipulator. In the research stage of this project it was found that there are very few of these motors currently on the market with the appropriate specs. With this in mind this design recommendation should only be applicable at larger scaled manipulators.

16.3.2 Joint

A second redesign option identified by the team to alleviate the issues these motors present was redesign of the joints on the manipulator. The current motors have a through shaft which has the ability to drive actuation of ether side of the gearbox. This is used to provide accurate position feedback which in conjunction with control and de-bouncing code will compensate for most of the error. Additionally a fixed, direct linkage to linkage joint should be employed to further reduce any possible free play to acceptable levels.

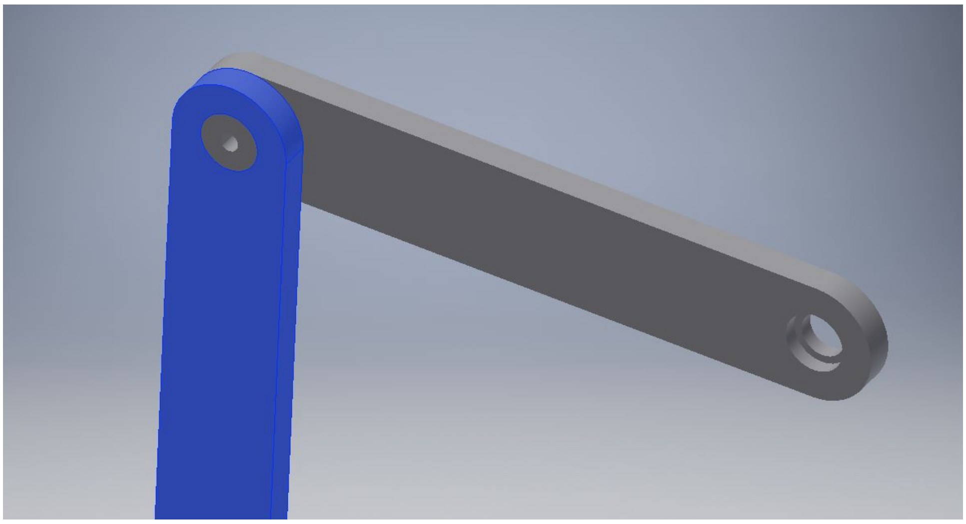


Figure 16.2: Future Joint Concept

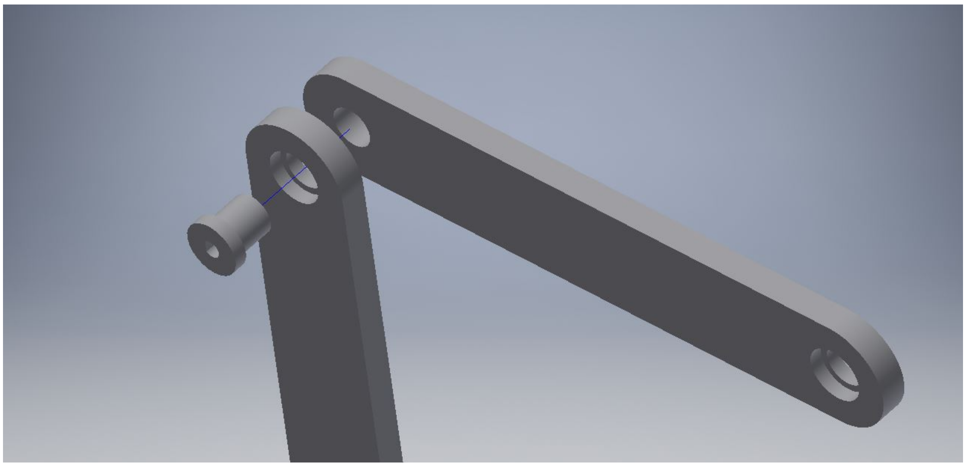


Figure 16.3: Future Joint Concept Exploded View

This design is based on a small shaft which is affixed to one link and is supported by bearings affixed in a whole bored in the other linkage. With added thrust bearings and friction disks each joint will stay together and hold its position under the appropriate forces. Motors can be affixed to the second linkage and actuate the first link. In this way the motors only need to actively move the linkages and can be power cycled.

17 Operation

17.1 Software Integration

Team 19 originally planned to synchronize the host software, PCDMIS, with that of the Mechanized ball-bar fixture, arduino. The objective is to connect the wormgear motors to the host software using timers or special characters, through serial communication. We would then monitor the exact positioning of the motors via potentiometers mounted on the counter-shaft; and ideally integrate the motors so they are able to adjust based off of one another; essentially creating parallel communication. The real-time communication the potentiometers produce, will give emergency signals and troubleshooting tips, if the device is out of sequence. Another commodity the software will include, is a feature where the operator can command the fixture to repeat an orientation if the first measurement was not satisfying enough. The objective is to make the device as user friendly and intuitive as possible, therefore minimizing room for error.

17.2 Installation

Our mechanized ball-bar fixture is designed for ease of use. Once all of the components are assembled, the first step is to mount the motors to the correct position on each arm linkage, which will be carefully marked. The potentiometers must be mounted on the 'rough' side, where the arm linkages are secured to the 'flat' face; since the motors have varyious mounting faces. The motor output shaft must be connected to the arm linkage via a 1/4" shaft collar; while the motor box is bolted (using a phillips head screw driver or drill) to the corresponding holes using 2/5" bolts on the arm linkages. After that, the ball-bar needs to sit on the third arm linkage, connected via shaft collar. The base linkage of the fixture is secured by 4, 3/4" bolts mounted to the base of the particular CMM machine; the base is comprised of 1018 cold-rolled steel, which was heavily simulated and exceeded expectations for our design specifications. Ideally, there would not have to be an operator for the fixture to succeed in completing the calibration process; this is a goal that will develop over time, as the device improves. The Installation process should take no more than 1-2 hours to complete, which would also minimize costs due to employee costs, and maximize efficiency.

17.3 Fixture Sequence

The fixture itself is designed for optimization and efficiency. Team 19 consciously programmed and purchased materials based off of speed and efficiency. The operating sequence of the fixture is designed to 'flow' between positions; meaning the fixture will finish measuring in the current location and then begin to orient itself to the next critical locus within proximity to the last point. Ideally, the fixture sequence will be affiliated with a mounted touch screen; and updated periodically with real-time datum positioning sent from the potentiometers. The device can be remotely operated, pausing and continuing at the operators command. When the calibration is complete, the process is paused, or the sequence is misconstrued, a flashing light/alarm will initiate to signal the operator must intervene. For the safety of the operator and the machine integrity, nothing should be obstructing the calibration process. Since this must be an extremely precise process, minimal contact with any of the measuring and calibrating equipment is necessary. Loose clothing should be prohibited around the equipment and in the calibration rooms.

18 Maintenance

18.1 Standard Maintenance

The 4 arm ball bark system has been designed to be exceeding robust in order to counteract the necessary forces. As a result, there are very few wear points. The only areas which will need routine replacement will be the bushing on the motor output shafts, however these motors are estimated to last many hundreds of hours being that they will never turn more than one full revolution. The shafts should be checked for free-play every 10 hours of use, and if needed the bushing or motors should be replaced. No other maintenance is necessary with this system.

A visual observation of the electronic system should be performed every 10 hours of use, and if anything looks heated or wires melted. In this case, the wires should be replaced and the corresponding motor should be replaced, as it is drawing too much current.

18.2 Repair

If the fixture were to break, there are several precautions that should be followed. The first is to disconnect all power to the device, so no unintentional grounding or shock can occur. If the ball-bar needed to be exchanged, then simply loosen the bolt securing the collar of the ball-bar, and swap the novel component for the worn out one. If a motor or arm needed to be replaced, each part connected to the decrepit must be disconnected for accessibility.

19 Additional Considerations

19.1 Economic Impact

Hexagon Metrology is an international corporation that is present in 5 continents, to countries ranging from Ecuador and peru, to France and Azerbaijan. Hexagon deals with precision measurement devices, which promotes quality and efficiency amongst all product lines. As the demand for cutting edge nano-technology increases, so does the precision, and quality, of coordinate measuring machines. Tolerances are narrowed constantly throughout manufacturing, and industries need a reliable source they can refer to for quality measurments. CMM machines are a finicky subject, where careful calibration is needed to ensure an acceptable measurement. This is where team 19 mechanized ball bar fixture thrives. The ultimate goal is to have little to none human interference; which would decrease the error significantly, increasing quality and therefore revenue. Also, this would eliminate any employee who would previously have to manually manipulate the ball bar, and measure the fixture itself; ridding labor costs and increasing efficiency/time distribution. Another significant economic impact would be the speed of calibration; as our fixture develops, so does the process and technology that accompanies it. From the start, the process is mroe efficient because an employee does not have to physically ’tighten’ and ’loosen’ the fixture; halting the calibrating process and efficiency. With self-locking wormgear motors on a mechanized fixture, the ball bar is either halted, waiting for the CMM machine to make the proper measurements; or in the process of moving to the next orientation.

19.2 Health, Ergonomics, Safety Considerations

A

A Mechanized Ball bar fixture will have a major impact on ergonomics throughout industry. The goal of this contraption is to eliminate any and all human interaction throughout; therefore eliminating ergonomics entirely. As the process develops and the fixture improves, so does the control of efficiency itself. The system will most likely include emergency and troubleshooting pre-cautions, decreasing any and all risks associated with contacting both the fixture or the CMM itself. However team 19 plans on programming software to track mounted potentiometers on the bar as it orients within 3-d space; allowing for datum positioning and minimal error.

19.3 Sustainability

Team 19 chose materials based off of past conflicts that occurred to the previous capstone team. Before any purchase, team 19 analyzed, compared, and performed finite element analysis upon many different materials. The process mainly comprised of discussing which material property trade-offs we had to comprimise. The ultimatum ended with aluminum alloy self-locking wormgear motors, 1018 cold-rolled steel for the arms and base. The sustainability and maintenance for these components would allign with that of the fixture lifetime; and if industry demands tolerance within a micron, then creep and wear would be the common foreseeable conflicts. Each material has its own creep constant and exponent that would fit into the accepted creep equation; given a tolerance of 1 micron, the calculation for product maintenance can be easily attained.

$$\varepsilon = (C\sigma/d^{b}) * e^{-Q/(kT)} \tag{19.1}$$

distributing values corresponding to aluminum and 1018 cold rolled steel, we can see that the lower limit the fixture will suffice around around 5 years. The 1018 cold-rolled steel is prone to creep more often than the aluminum; so the reliability and lifetime of the fixture and its components would have to be replaced or maintained before that critical moment.

19.4 Ethical Considerations

A Mechanized Ball bar fixture would have a significant ethical affect. Since the main goal of this project is to essentially replace a human employee with a mechanized system that is self correcting; many ethical questions would arise. Problems such as, is our product going to replace jobs? Is it going to be more efficient? Will industry be replaced by mechanized and automated systems? The answer to the first question is definitely yes. Our fixture may sacrifice jobs for efficiency; however, it may as well create jobs in itself. If the fixture has potential to streamline into a product, then they would have to be manufactured themselves. This means one mechanized ball-bar fixture per CMM. The material for the compnents would have to be purchased, machined, and assembled, creating its own branch of work and obviously creating new jobs. Hopefully, the ball bar fixtures would become efficient enough to surpass the traditional measuring techniques. As for automation integration in society, that comes down to ethical decisions based on the populous.

19.5 Environmental impact

Environmentally, a mechanized ball-bar fixture would not have a significant effect. The components for the arms after wear and tear could be smelted down and easily converted from ferretic to austenitic material. The components that have significant detrimental effect on the environment would be the motors and the ball-bar itself. The motors contain plastic elements that would not degrade well in the environment, if they were to be replaced or re-purposed. As for the invar ball-bar, after the invar material has 'crept' passed the desired tolerance, there is little to no use for re-purposing an invar ball-bar; and very little industry that yields great success addressing the melting process. The impact that the mechanized ball-bar fixture is going to have on the environment depends upon the customer.

20 Conclusion

The design of the bar ball manipulator designed by team 19 must meet the specifications set forth by Hexagon Manufacturing Intelligence. As discussed in section 6, the specifications were set out in 8 major sections; Reach 12 positions, Automation, Precision, Transient Stability, Repeatability, Scalability, Control, and cost. The previous design for this product presented weaknesses in several of these specifications including most notably Transient Stability, Repeatability, and Control. Therefore in the initial stages of design these shortcomings were the focus for the new design. Through testing and analysis it is shown that the current design meets all design specs with few future improvements necessary.

The most basic specification met by the design is ability to reach all positions. This comes down to geometry of the manipulator selected. The previous design utilized a 5 DOF manipulator in order to reach all 12 positions. Through geometric analysis it was discovered that this could be improved and reduced to 4 DOF. The DOF removed from the system was the rotation of the base. By utilizing the third linkage of the manipulator, and optimizing the lengths of the other linkages it was possible to reach the positions one as seen in Table 6.1. These positions are presented visually in Figures D.7 and 20.

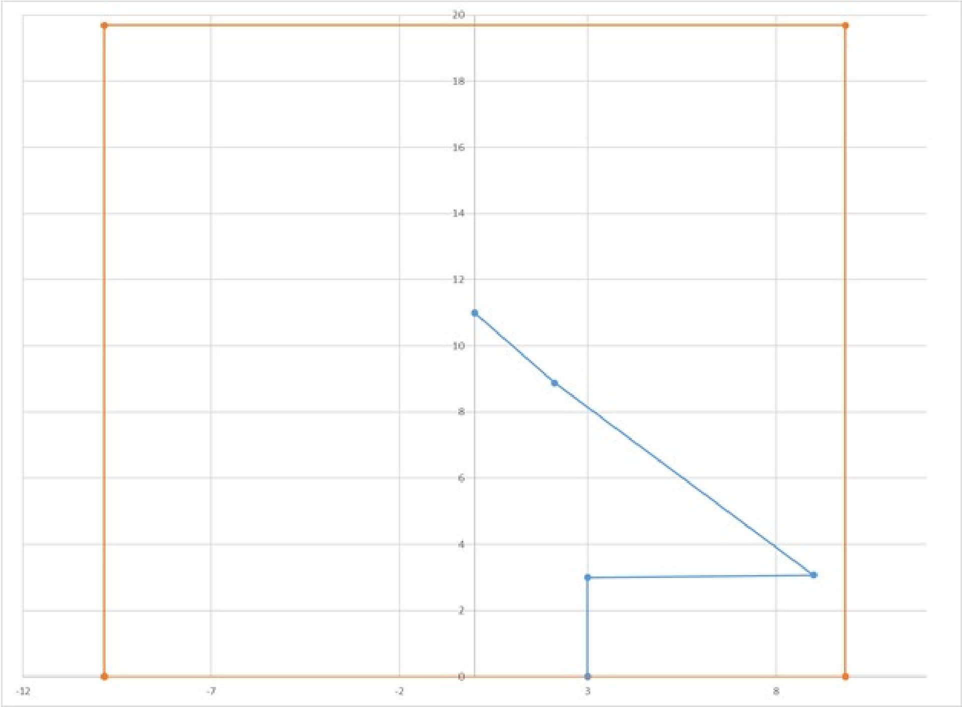


Figure 20.1: Position one

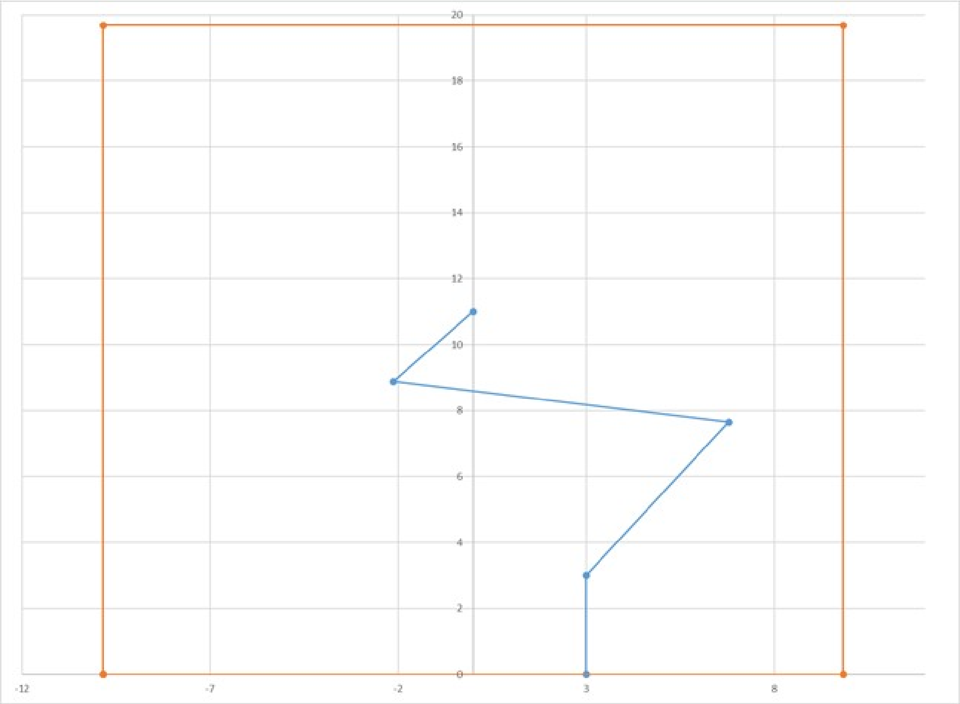


Figure 20.2: Position two

Analytically the geometry and angles were found for each case and during testing of the prototype it was proved that the physical system was capable of reaching each position.

Automation went hand in hand with the 12 positions. The design uses the arduino AVR micro controller platform for control of the system. This was a chalenge for the team of mechanical engineers to design with only a limited background in writing code and the methodologies for automation. Being totally automated is solely dependent on the code written for control. During the design process a basic skeleton file of scripts were written. These were modified and used for different applications in testing. With minor modifications to this it was possible to produce several forms of automated function based on the desired method of trigging movement from point to point. The decision could be made to have a button press to move from point to point and achieve partial automation or it could be placed on a timer or respond to other stimulus. For simplicity the specification was given that it should be set to a timer. This was tested by setting several positions in the code. The machine was run from position to position for several hours on running on a timer. The manipulator was observed to never miss a position and required no human interaction.

Automation also relates closely to design spec 7, control. The CMM's produced at Hexagon are controlled with a software called PC-DMIS. Although it was acceptable for the the automation to be based on a timer it was deemed that integration to the PC-DMIS software was a safer option in avoidance of possible crashes. Therefore the code can be simply modified to respond to serial communication between the arduino and the computer running PC-DMIS.

As the process is totally automated cycle time is not of large concern, as operators can be doing other tasks while the machine is working. With this in mind however it is still imperative that the cycle time is not much longer then current. Therefore the precision of the manipulator is important. As stated in Section 6, the CMM has the ability to search in a defined about of space for the item measuring. Team 19 set a goal that the manipulator should be able to position the bar ball within a 1x1x1 CM cube in space. This was achieved by using a system for absolute position feedback. As described in section 10, potentiometers were mounted to each output shaft in order to measure very accurately the position of each linkage. The manner that the potentiometers were fixed to the motors they capture all error induced by backlash in the gear train of the motors. Code was written to mimic a feedback controller in order to account for all error and place each joint accurately and achieve end precision in the acceptable range. During the multiple cycle automation test the manipulator was able to repeatably and precisely place the bar ball within the acceptable region of space every time for many cycles over several hours of operation.

Transient stability was imperative as a design consideration. The weakest portion of the prior design was heat generation and its effect on the temperature and thermal expansion of the bar. This was therefore the main basis for design for team 19. The solution identified was the use of self locking worm gear driven DC motors. For many reasons described in Section 10, these motors theoretically would produce negligible heat during the transient portions of the automation cycle and would produce no heat during the steady state portions. As was seen in Figure 15.0.3 these motors were run, cycling on and off for the duration of a automation cycle and had negligible change in temperature. The design therefore effectively removes heat generation or thermal effects as a consideration in regards to bar ball design.

Repeatability and dynamic stability proved to be the most challenging part of the design. When team 19 initially analyzed the prior design in order to improve on past progress, it was noted that no analysis or testing was done of stability under dynamic force. Therefore there was little information to build on. The largest CMM's will produce a 1 N probing force, therefore this was the design spec set for team 19. In testing the prototype created failed under this condition as a the dynamic response of the manipulator was more then .5 Microns. Under further consideration it was deemed that more than the initial .5 Micron movement was acceptable with the stipulation that it was equal in opposite directions. The method used to measure the Bar Ball consists of measuring the ball ends and calculating a center. This is what makes equal and opposite deflections acceptable as regardless of the size of the sphere measured the center will remain the same.

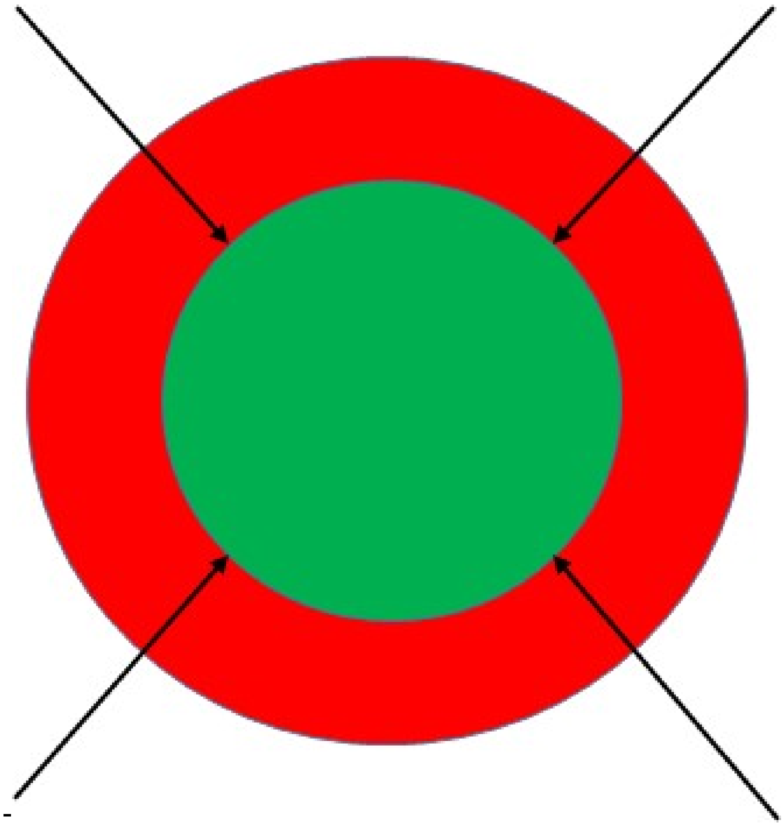


Figure 20.3: Example of equal and opposite deflection

Figure 20 shows this visually. In this case angles of contact would need to be found where the deflection is equal. However even with this in mind the prototype produced in testing still had a larger amount of deflection then was desirable. It was identified that the problem was the method of joint attachment and therefore this was what team 19 focused on in redesign. As described in Section 16 the joints of the manipulator and the motors used were both reconsidered for future builds. It was deemed that the prototype produced was insufficient for testing to this degree of accuracy without implementation of professional, high precision machining of the new designs. However, the 1 N probing force was given as the largest possible force on a CMM which does not accurately represent the forces encountered on the smaller sized CMM which was the focus for the design and prototyping. These machines, along with all laser measurement, non-contact machines will not produce forces large dynamic forces in which case the unmodified design is acceptable.

Hexagon produces many different versions and sizes of CMM's and therefore the design must be scalable. In this case there was no metric in order to measure this by so the practice of design for X was employed as consideration throughout the process.

Although the design and prototype focused on the A frame CMM. Scalability was achieved by using engineering tools to aid in design while also employing a "modular" design technique. The general design of the manipulator consists of a simple three linkage system with bar attachment. A MatLab script was written to aid in determining the optimal lengths of each of these linkages for any specific size of CMM. Therefore for any amount of scaling up can be achieved by selecting larger parts; ie larger motors with more powerful drivers, thicker linkages and a larger Bar Ball. All the rest of the practices remain the same for the manufacture of a larger manipulator including all control logic.

This was a second generation design with the basis taken off work done previously. However with the information provided from the prior design team 19 decided to start from white sheet and go a different direction. So as is always the case with a first generation product there is still room from iteration and improvement. As stated in section 16, team 19 began the redesign process with several additions to the design in order to fix problems that were presented over the design and testing process. The final design of the Bar Ball Manipulator presented by team 19 performs its intended functions and meets design specifications.

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A Appendix - Finite Element Analysis

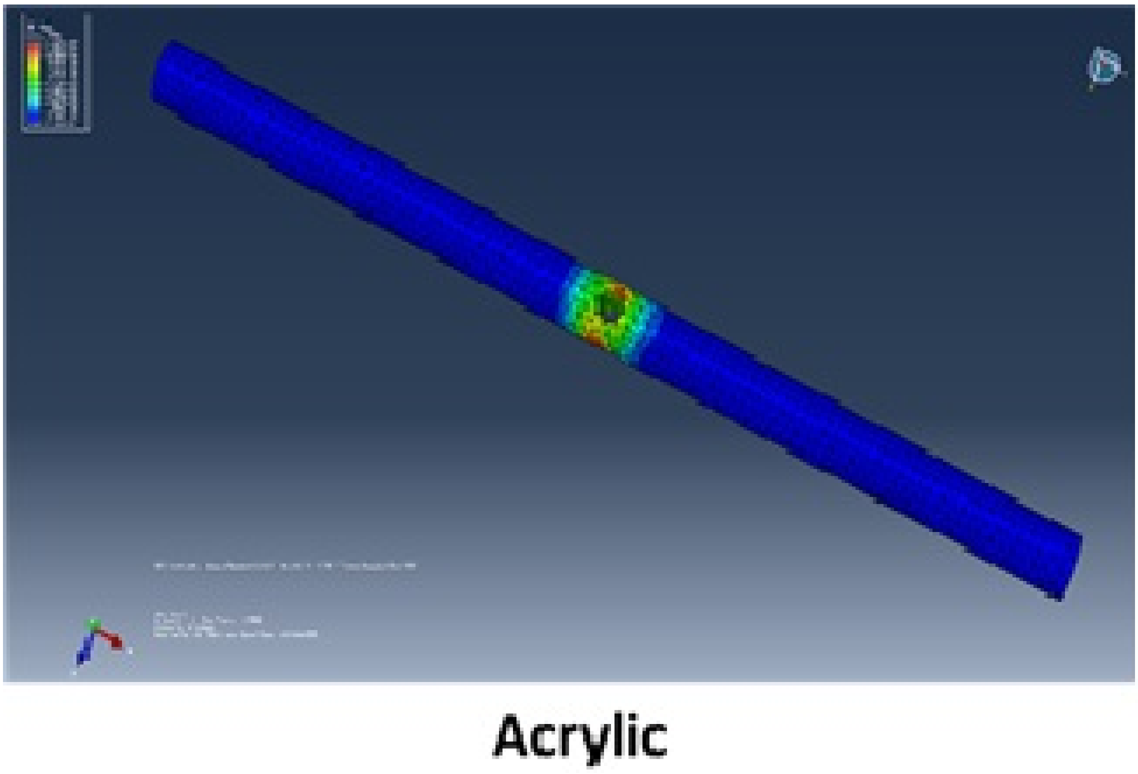


Figure A.1: Acrylic Heat Transfer

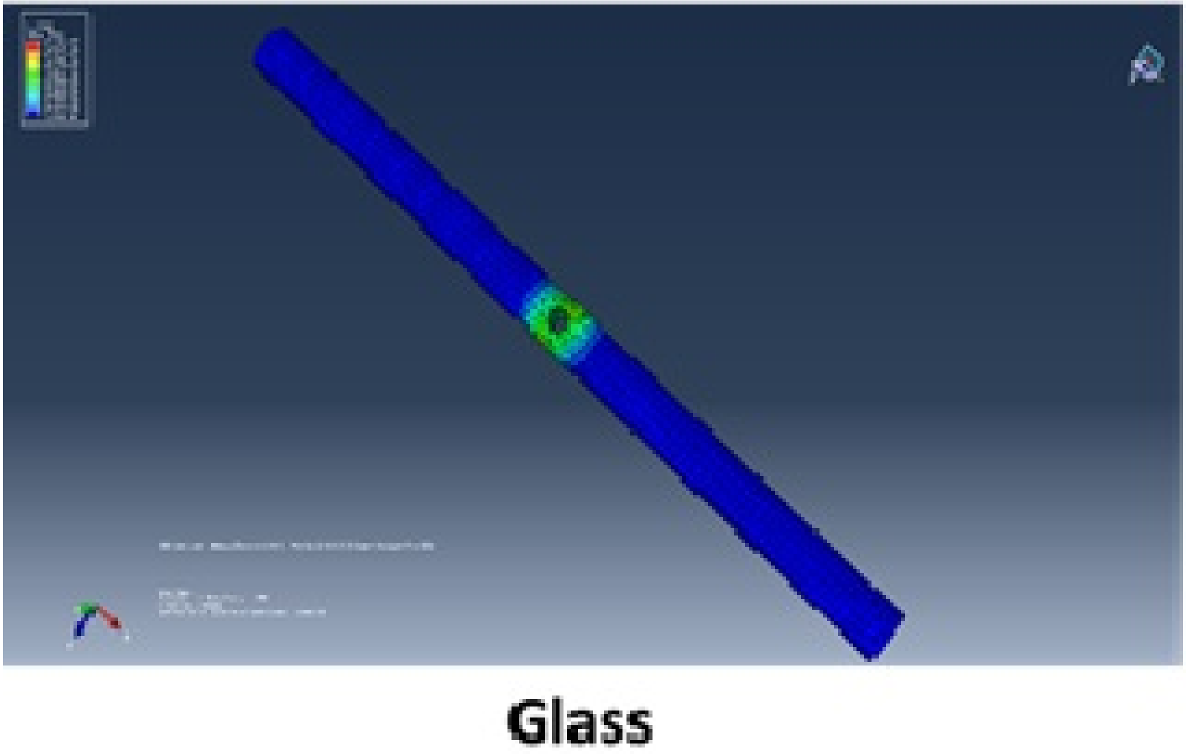


Figure A.2: Glass Heat Transfer

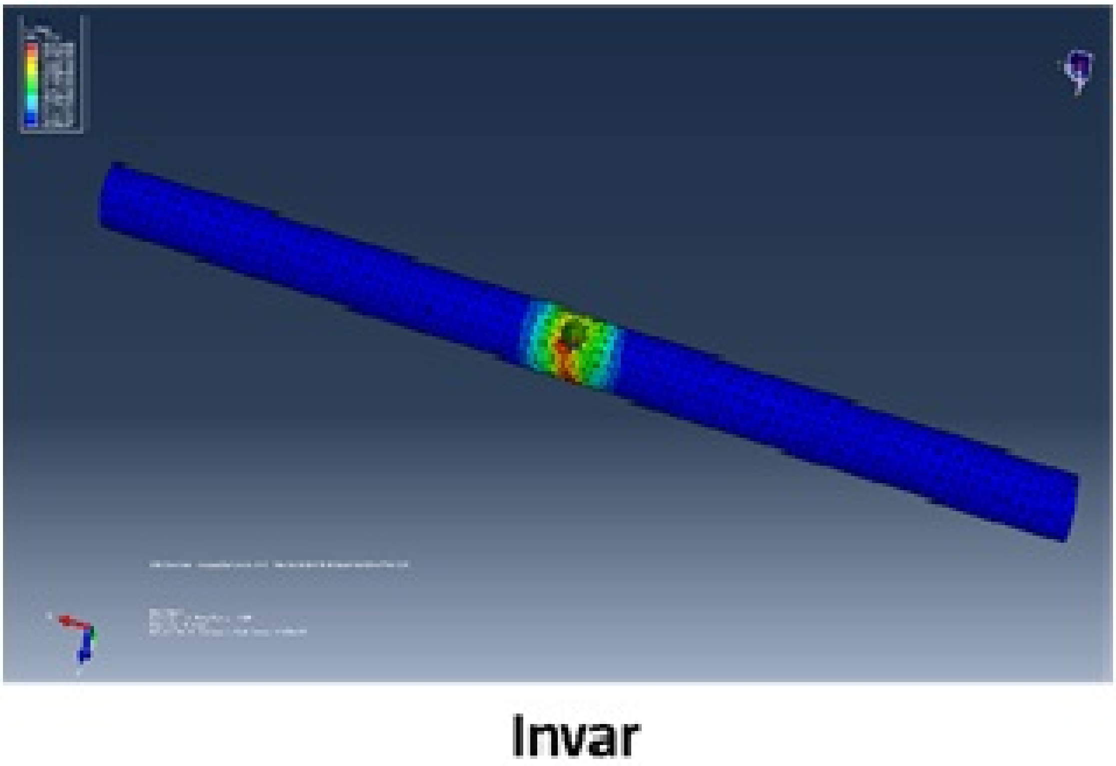


Figure A.3: Invar Heat Transfer

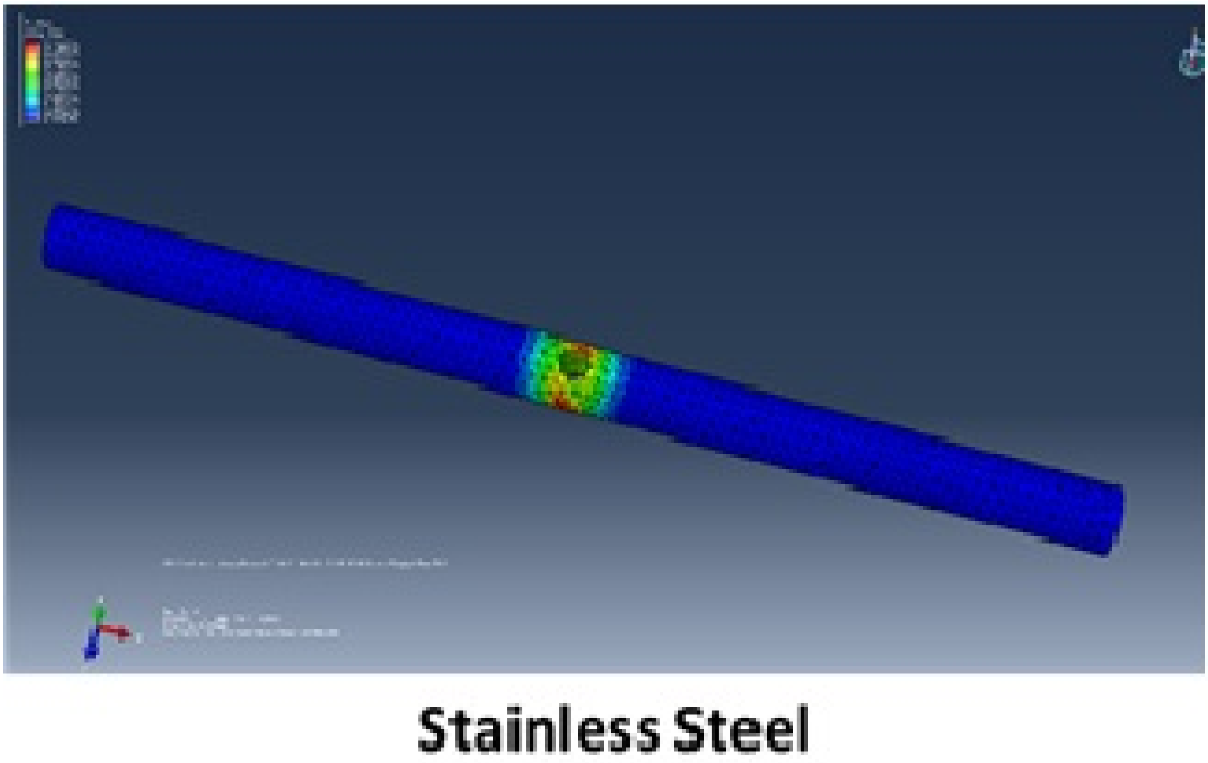
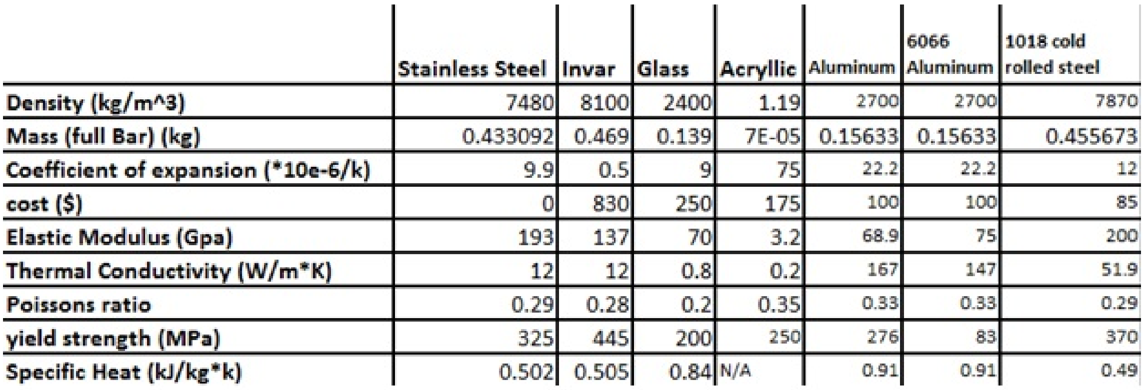


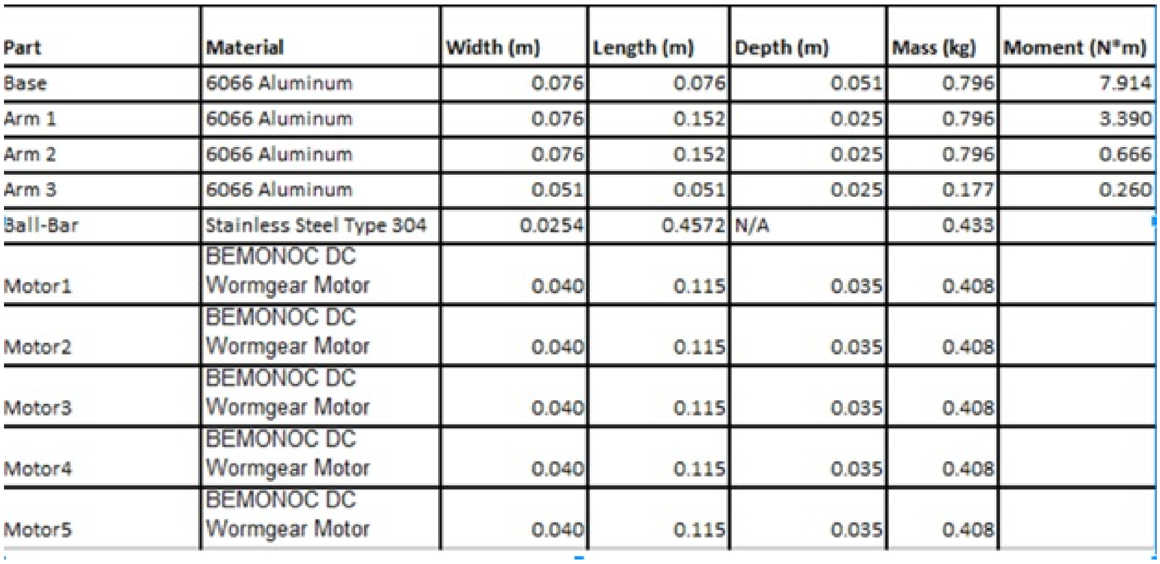
Figure A.4: Stainless Steel Heat Transfer

Table A.1: Material Selection



	Stainless Steel	Invar	Glass	Acryllic	Aluminum	6066 Aluminum	1018 cold rolled steel
Density (kg/m^3)	7480	8100	2400	1.19	2700	2700	7870
Mass (full Bar) (kg)	0.433092	0.469	0.139	7E-05	0.15633	0.15633	0.455673
Coefficient of expansion (*10e-6/k)	9.9	0.5	9	75	22.2	22.2	12
cost ($)	0	830	250	175	100	100	85
Elastic Modulus (Gpa)	193	137	70	3.2	68.9	75	200
Thermal Conductivity (W/m*K)	12	12	0.8	0.2	167	147	51.9
Poissons ratio	0.29	0.28	0.2	0.35	0.33	0.33	0.29
yield strength (MPa)	325	445	200	250	276	83	370
Specific Heat (kJ/kg*k)	0.502	0.505	0.84	N/A	0.91	0.91	0.49

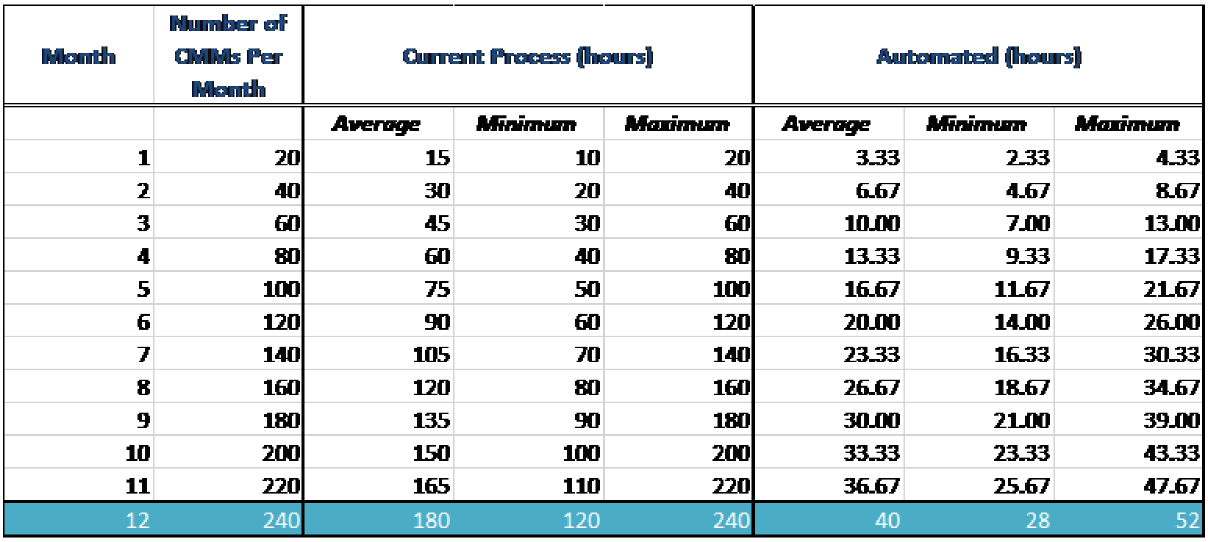
Table A.2: Moment Chart



Part	Material	Width (m)	Length (m)	Depth (m)	Mass (kg)	Moment (N*m)
Base	6066 Aluminum	0.076	0.076	0.051	0.796	7.914
Arm 1	6066 Aluminum	0.076	0.152	0.025	0.796	3.390
Arm 2	6066 Aluminum	0.076	0.152	0.025	0.796	0.666
Arm 3	6066 Aluminum	0.051	0.051	0.025	0.177	0.260
Ball-Bar	Stainless Steel Type 304	0.0254	0.4572	N/A	0.433	
Motor1	BEMONOC DC Wormgear Motor	0.040	0.115	0.035	0.408	
Motor2	BEMONOC DC Wormgear Motor	0.040	0.115	0.035	0.408	
Motor3	BEMONOC DC Wormgear Motor	0.040	0.115	0.035	0.408	
Motor4	BEMONOC DC Wormgear Motor	0.040	0.115	0.035	0.408	
Motor5	BEMONOC DC Wormgear Motor	0.040	0.115	0.035	0.408	

B Appendix - Cost Analysis

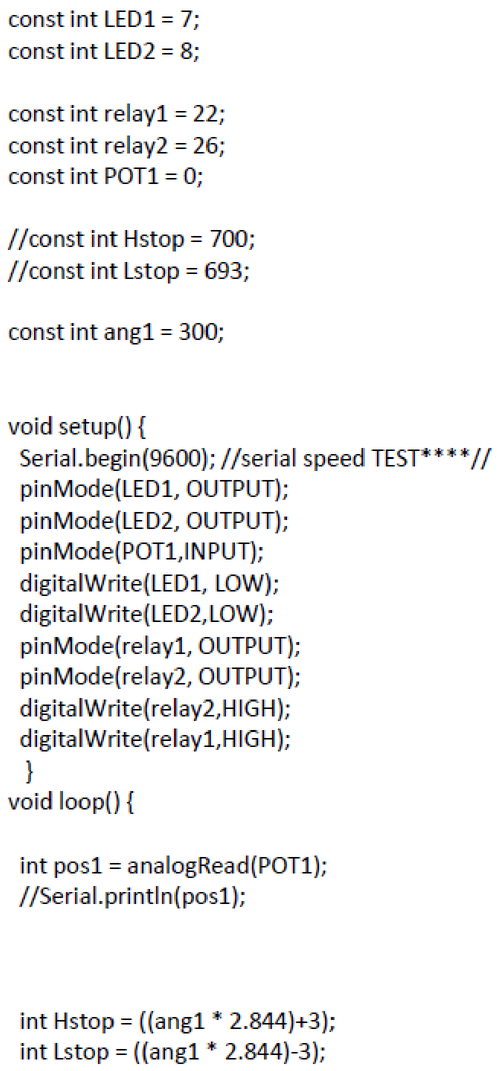
Table B.1: Time Analysis



Month	Number of CMMs Per Month	Current Process (hours)			Automated (hours)		
		Average	*Minimum*	*Maximum*	*Average*	*Minimum*	*Maximum*
1	20	15	10	20	3.33	2.33	4.33
2	40	30	20	40	6.67	4.67	8.67
3	60	45	30	60	10.00	7.00	13.00
4	80	60	40	80	13.33	9.33	17.33
5	100	75	50	100	16.67	11.67	21.67
6	120	90	60	120	20.00	14.00	26.00
7	140	105	70	140	23.33	16.33	30.33
8	160	120	80	160	26.67	18.67	34.67
9	180	135	90	180	30.00	21.00	39.00
10	200	150	100	200	33.33	23.33	43.33
11	220	165	110	220	36.67	25.67	47.67
12	240	180	120	240	40	28	52

C Appendix -Arduino Code

C.0.1 Proof of Concept Code



```
const int LED1 = 7;
const int LED2 = 8;

const int relay1 = 22;
const int relay2 = 26;
const int POT1 = 0;

//const int Hstop = 700;
//const int Lstop = 693;

const int ang1 = 300;


void setup() {
 Serial.begin(9600); //serial speed TEST****//
 pinMode(LED1, OUTPUT);
 pinMode(LED2, OUTPUT);
 pinMode(POT1,INPUT);
 digitalWrite(LED1, LOW);
 digitalWrite(LED2,LOW);
 pinMode(relay1, OUTPUT);
 pinMode(relay2, OUTPUT);
 digitalWrite(relay2,HIGH);
 digitalWrite(relay1,HIGH);
  }
void loop() {

 int pos1 = analogRead(POT1);
 //Serial.println(pos1);



 int Hstop = ((ang1 * 2.844)+3);
 int Lstop = ((ang1 * 2.844)-3);
```

Figure C.1: Arduino code used for proof of concept

C.0.2 Code for Final

`4 Arm Motion`

```
/////////////////////////////Pin definitions///////////////////////////////////
const int POT1 = A0;
```

```
const int POT2 = A1;
const int POT3 = A2;
const int POT4 = A3;

const int DIR1 = 2;
const int DIR2 = 3;
const int DIR3 = 4;
const int DIR4 = 5;

const int PWM1 = 6;
const int PWM2 = 7;
const int PWM3 = 8;
const int PWM4 = 9;

const int BTN1 = 10;

////////////////////////////// Program Variables ///////////////////////////////

int INPOS1 = 0;
int INPOS2 = 0;
int INPOS3 = 0;
int INPOS4 = 0;

int POS1;
int POS2;
int POS3;
int POS4;

int DesPOS1;
int DesPOS2;
int DesPOS3;
int DesPOS4;

const int play = 1;
const int stopPOS = 5;

int STAGE=1;

///////////////////////////////////// Voltage Control //////////////
```

```
const int highDelay1 = 2000; ////// 600 is about 6 volt output, 3000 is 11.5V
const int lowDelay1 = 100;

const int highDelay2 = 2000; ////// 600 is about 6 volt output, 3000 is 11.5V
const int lowDelay2 = 100;

const int highDelay3 = 1800; ////// 600 is about 6 volt output, 3000 is 11.5V
const int lowDelay3 = 100;

const int highDelay4 = 2500; ////// 600 is about 6 volt output, 3000 is 11.5V
const int lowDelay4 = 100;

int Hstop1;
int Lstop1;
int Hstop2;
int Lstop2;
int Hstop3;
int Lstop3;
int Hstop4;
int Lstop4;

void setup() {
  Serial.begin(9600);
pinMode(POT1,INPUT);
pinMode(POT2,INPUT);
pinMode(POT3,INPUT);
pinMode(POT4,INPUT);

pinMode(BTN1,INPUT);

pinMode(DIR1,OUTPUT);
pinMode(DIR2,OUTPUT);
pinMode(DIR3,OUTPUT);
pinMode(DIR4,OUTPUT);

pinMode(PWM1,OUTPUT);
pinMode(PWM2,OUTPUT);
pinMode(PWM3,OUTPUT);
```

```
pinMode(PWM4,OUTPUT);
}
void loop() {
//  if (digitalRead(BTN1)==HIGH){
//      checkALLpositions();
//      assignSTAGE();
//      moveONE();
//      moveTWO();
//      moveTHREE();
//      moveFOUR();
//      STAGE++;
//  }
  if (Serial.read()>5){
    Serial.println(STAGE);
    checkALLpositions();
      assignSTAGE();
      moveONE();
      moveTWO();
      moveTHREE();
      moveFOUR();
      Serial.print("In Position at STAGE ");
      Serial.println(STAGE);
      STAGE++;
      INPOS1=1;
      INPOS2=1;
      INPOS3=1;
      INPOS4=1;

  }
  //Serial.println("Waiting");
}
```

```
Check Position
void checkALLpositions(){
  Serial.println("Testing Positions");
  POS1 = analogRead(POT1);
  POS2 = analogRead(POT2);
  POS3 = analogRead(POT3);
```

```
  POS4 = analogRead(POT4);
}

Motion one
////////////////////////////////////////// MOTOR ONE ////////////////////////
void moveONE(){
  Serial.println("Moving Motor 1");
  Hstop1 = ((DesPOS1) + play);
  Lstop1 = ((DesPOS1) - play);

  Serial.println(DesPOS1);

  while (INPOS1<stopPOS){ // decrease stopPOS if voltage/speed is slower
    POS1 = analogRead(POT1);
    Serial.println(POS1);
    if (POS1>Lstop1 && POS1<Hstop1){
      digitalWrite(DIR1,HIGH);
      digitalWrite(PWM1,LOW); //Low cuts Movement, direction is irrelevant
      INPOS1++; //debouncing with stopPOS
      }

      else if (POS1>Hstop1){
        digitalWrite(DIR1,LOW);
        pulseMOVE1();
      }
      else if (POS1<Lstop1){
        digitalWrite(DIR1,HIGH);
        pulseMOVE1();
      }
}
}

void pulseMOVE1(){
digitalWrite(PWM1,HIGH);
delayMicroseconds(highDelay1);
digitalWrite(PWM1,LOW);
delayMicroseconds(lowDelay1);
}
Motion two
```

```
///////////////////////////////////////// MOTOR TWO ////////////////////////
void moveTWO(){
  Hstop2 = ((DesPOS2) + play);
  Lstop2 = ((DesPOS2) - play);
  Serial.println(DesPOS2);
  while (INPOS2<stopPOS){ // decrease stopPOS if voltage/speed is slower
    POS2 = analogRead(POT2);
    Serial.println(POS2);

    if (POS2>Lstop2 && POS2<Hstop2){
      digitalWrite(DIR2,HIGH);
      digitalWrite(PWM2,LOW); //Low cuts Movement, direction is irrelevant
      INPOS2++; //debouncing with stopPOS
      }

      else if (POS2>Hstop2){
        digitalWrite(DIR2,LOW);
        pulseMOVE2();
      }
      else if (POS2<Lstop2){
        digitalWrite(DIR2,HIGH);
        pulseMOVE2();
      }
}
}

void pulseMOVE2(){
digitalWrite(PWM2,HIGH);
delayMicroseconds(highDelay2);
digitalWrite(PWM2,LOW);
delayMicroseconds(lowDelay2);
}
Motion three
///////////////////////////////////////// MOTOR THREE ////////////////////////
void moveTHREE(){
  Hstop3 = ((DesPOS3) + play);
  Lstop3 = ((DesPOS3) - play);

  while (INPOS3<stopPOS){ // decrease stopPOS if voltage/speed is slower
```

```
    POS3 = analogRead(POT3);
    Serial.println(POS3);

    if (POS3>Lstop3 && POS3<Hstop3){
      digitalWrite(DIR3,HIGH);
      digitalWrite(PWM3,LOW); //Low cuts Movement, direction is irrelevant
      INPOS3++; //debouncing with stopPOS
      }

      else if (POS3>Hstop3){
        digitalWrite(DIR3,LOW);
        pulseMOVE3();
      }
      else if (POS3<Lstop3){
        digitalWrite(DIR3,HIGH);
        pulseMOVE3();
      }
}
}

void pulseMOVE3(){
digitalWrite(PWM3,HIGH);
delayMicroseconds(highDelay3);
digitalWrite(PWM3,LOW);
delayMicroseconds(lowDelay3);
}
```

Motion four

```
///////////////////////////////////////// MOTOR FOUR ////////////////////////
void moveFOUR(){
  Hstop4 = ((DesPOS4) + play);
  Lstop4 = ((DesPOS4) - play);

  while (INPOS4<stopPOS){ // decrease stopPOS if voltage/speed is slower
    POS4 = analogRead(POT4);
    Serial.println(POS4);

    if (POS4>Lstop4 && POS4<Hstop4){
      digitalWrite(DIR4,HIGH);
      digitalWrite(PWM4,LOW); //Low cuts Movement, direction is irrelevant
```

```
      INPOS4++; //debouncing with stopPOS
      }

      else if (POS4>Hstop4){
        digitalWrite(DIR4,LOW);
        pulseMOVE4();
      }
      else if (POS4<Lstop4){
        digitalWrite(DIR4,HIGH);
        pulseMOVE4();
      }
}
}

void pulseMOVE4(){
digitalWrite(PWM4,HIGH);
delayMicroseconds(highDelay4);
digitalWrite(PWM4,LOW);
delayMicroseconds(lowDelay4);
}
Stages
void assignSTAGE(){
  if (STAGE==1){
    DesPOS1 = 850;
    DesPOS2 = 480;
    DesPOS3 = 180;
    DesPOS4 = 530;
  }
  else if (STAGE==2){
    DesPOS1 = 700;
    DesPOS2 = 480;
    DesPOS3 = 660;
    DesPOS4 = 530;
  }
  else if (STAGE==3){
    DesPOS1 = 700;
    DesPOS2 = 700;
    DesPOS3 = 540;
    DesPOS4 = 1000;
```

```
}

else if (STAGE==4){
  DesPOS1 = 700;
  DesPOS2 = 700;
  DesPOS3 = 540;
  DesPOS4 = 530;
}

else if (STAGE==5){
  DesPOS1 = 700;
  DesPOS2 = 480;
  DesPOS3 = 180;
  DesPOS4 = 530;
}
else if (STAGE==6){
  DesPOS1 = 850;
  DesPOS2 = 480;
  DesPOS3 = 180;
  DesPOS4 = 530;
  STAGE=0;
}
else if (STAGE==7){
  DesPOS1 = 700;
  DesPOS2 = 700;
  DesPOS3 = 880;
  DesPOS4 = 150;
}
else if (STAGE==8){
  DesPOS1 = 700;
  DesPOS2 = 700;
  DesPOS3 = 540;
  DesPOS4 = 150;
}
else if (STAGE==9){
  DesPOS1 = 700;
  DesPOS2 = 700;
  DesPOS3 = 540;
  DesPOS4 = 1000;
```

```
  }
  else if (STAGE==10){
    DesPOS1 = 700;
    DesPOS2 = 700;
    DesPOS3 = 540;
    DesPOS4 = 530;
  }
  else if (STAGE==11){
    DesPOS1 = 700;
    DesPOS2 = 480;
    DesPOS3 = 660;
    DesPOS4 = 530;
  }
  else if (STAGE==12){
    DesPOS1 = 700;
    DesPOS2 = 480;
    DesPOS3 = 180;
    DesPOS4 = 530;
  }
  else if (STAGE==13){
    DesPOS1 = 850;
    DesPOS2 = 480;
    DesPOS3 = 180;
    DesPOS4 = 530;
  }


}
```

D Appendix D - Geometric Analysis

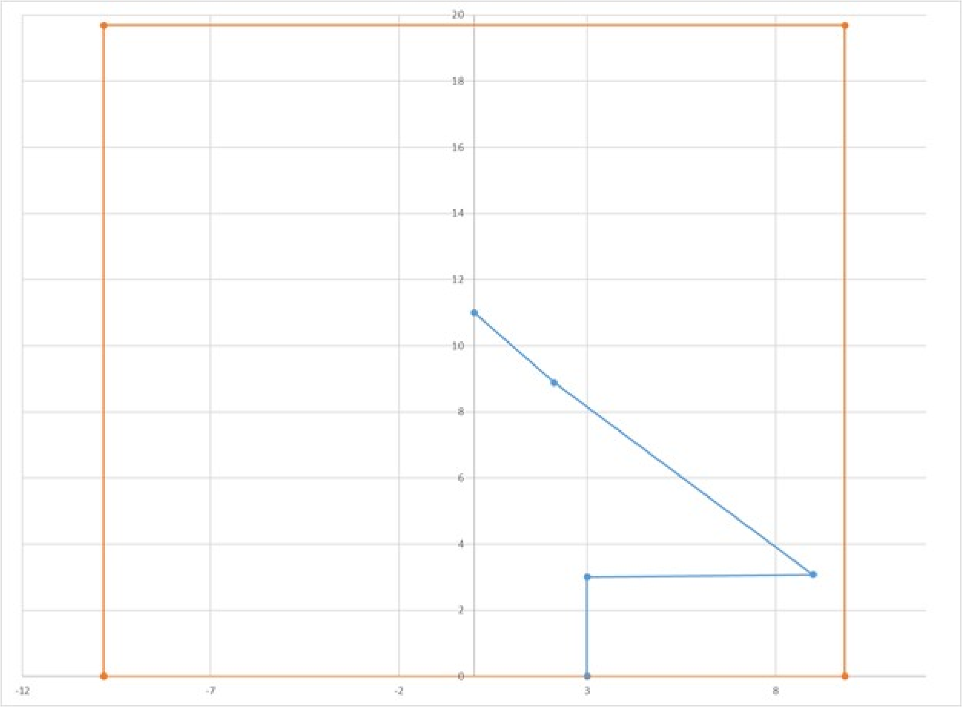


Figure D.1: Position one sample

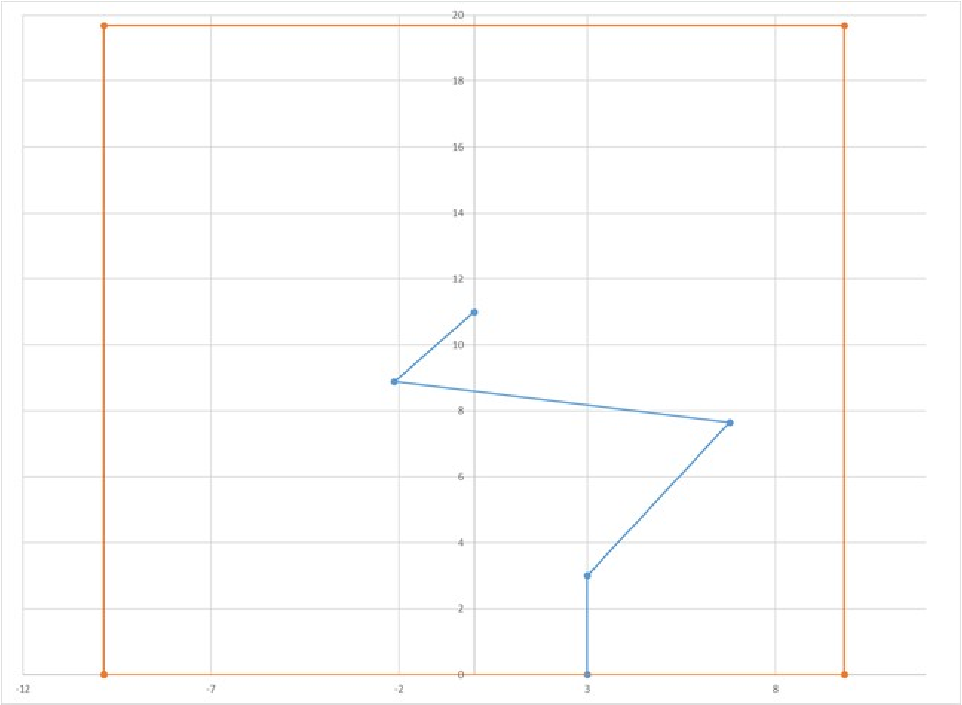


Figure D.2: Position two sample

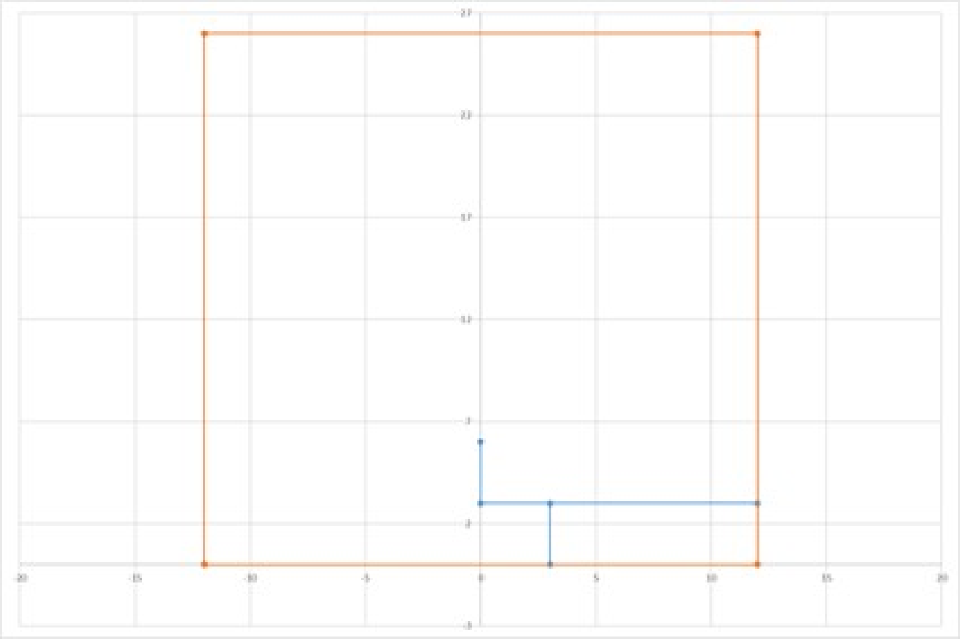


Figure D.3: Position three and four sample

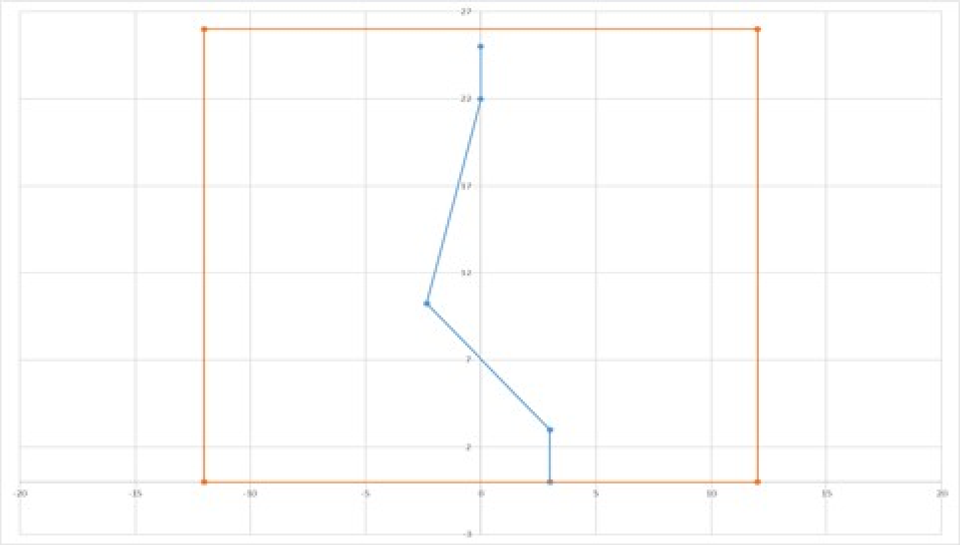


Figure D.4: Position five and six sample

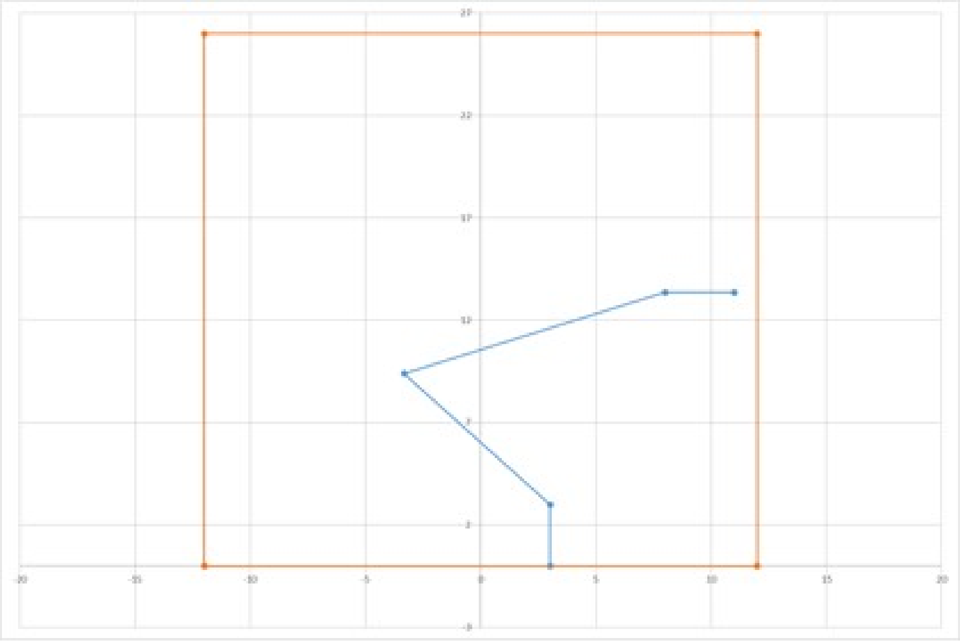


Figure D.5: Position seven and eight sample

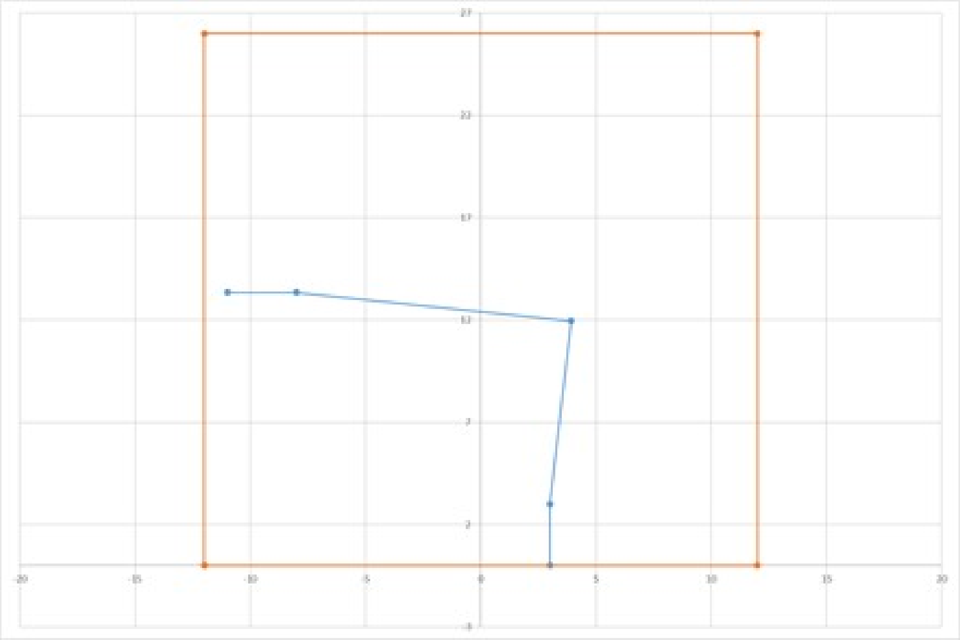


Figure D.6: Position nine and ten sample

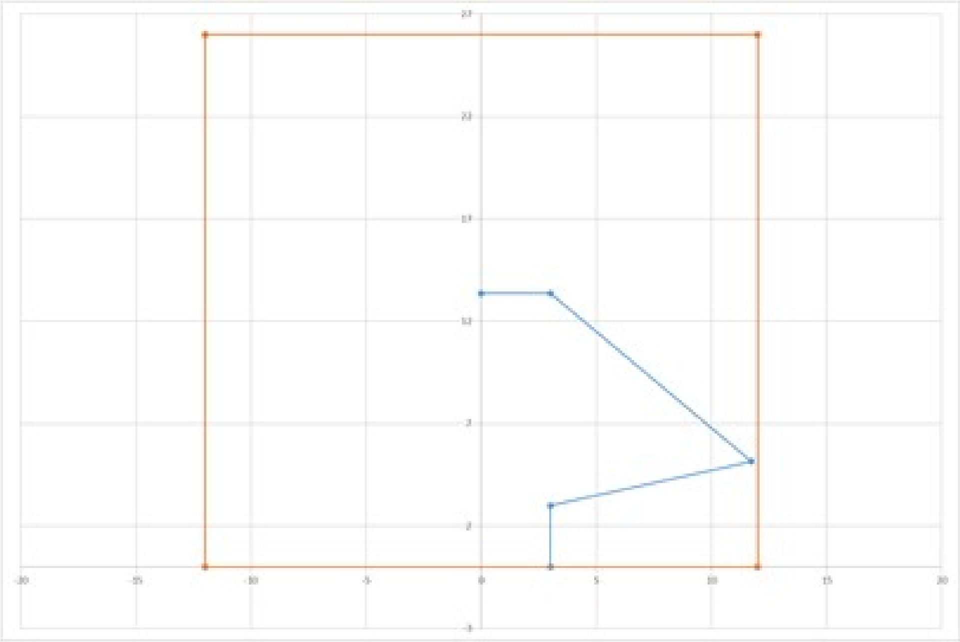


Figure D.7: Position eleven and twelve sample