Project B8 – Universal Dome Standoff Bonding

Final Report

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NORTHROP GRUMMAN

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1 DISCLAIMER

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2 EXECUTIVE SUMMARY

The Northrop Grumman Standoff Project team was tasked with designing and manufacturing an articulating arm that will effectively hold standoff mounting templates in position for the duration of the adhesive cure process. The team's design looks to replace the current taping method used by Northrop Grumman technicians when mounting avionics electronics to the forward and aft domes of various rocket motors. To achieve a suitable final design to manufacture, the team followed Northern Arizona University Engineering Capstone processes to fully understand, analyze and evaluate all potential concepts and manufacture the final design. With the completion of the first semester of the project, the team had a suitable design that would be manufactured. Utilizing the vast assortment of tools and machines in the 98C machine shop, the team was able to build the various components of the final design. A few clarifications during manufacturing from the client led to small design changes to optimize performance and meet all the customer needs. Although not 100% completed due to the Covid-19 pandemic, the most up to date version of the design can be seen in figure 1 below.

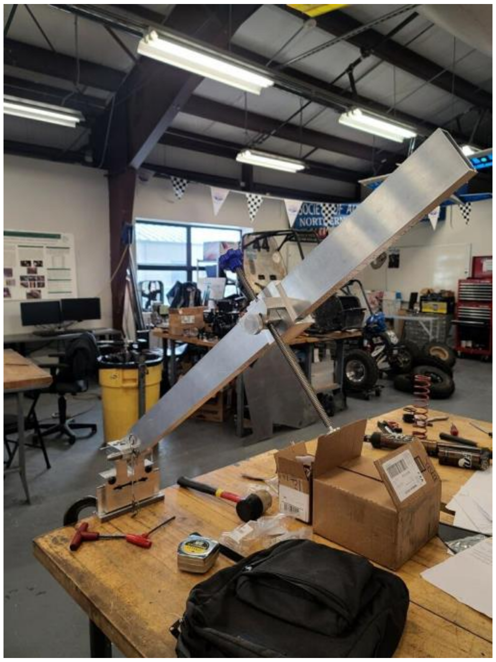

Figure 1: Final Device

With the final design as complete as currently possible, the remaining work done for the team is finishing the written work assignments. These final assignments include the future work that would have been applied to the design to reach the final idea the team designed. If the team hadn't had in person activities halted due to the pandemic, the final design would have been able to be powder coated, teflon lined and physically tested to ensure all customer requirements were met. Ultimately the final device seen in figure 1 is a great representation of the teams work over the course of the project and gives a good basis for how the completed device would function.

3 ACKNOWLEDGEMENTS

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5 BACKGROUND

5.1 Introduction

Rocket motor integration activities at Northrop Grumman field sites currently bond standoffs (threaded mounting devices that are used for avionic electrical components) to rocket motor domes using adhesives and tape. The standoffs are mounted to metal brackets, which are taped to the motor dome for between 24 to 72 hours in order for the adhesive to cure. This method is unreliable and fails roughly 5% of the time causing the brackets to either slip or fall off the motor domes. When the taping fails, an increase in man hours is required; this costs time and money when installing these standoffs. For this reason, Northrop Grumman's Flight Systems Group has requested for a team to design, analyze, and build a prototype universal dome standoff bonding tool that can be mounted to the attach rings of several variations of rocket motors (Castor 38, 30XL, and Orion 50XL) seen in Appendix A, that will hold standoff brackets in place while the adhesive cures.

5.2 Project Description

The following is the original project description provided by Northrop Grumman:

During rocket motor integration activities at Northrop Grumman field sites, many standoffs (threaded mounting devices for avionics) are bonded to motor domes using adhesives. The current method of operations uses a bracket or template, to which the standoffs are mounted. The adhesive is applied, then the bracket is taped to the motor dome to hold the bracket in place for the 24 hour or longer cure period. The tape method is unreliable and occasionally allows the brackets to slip or fall off of the domes. A waste of time and labor hours are incurred when the taping method fails. NGC is requesting that NAU select one team to design, analyze and build a prototype articulating arm that can be mounted to the attach rings of several different motor types that will firmly hold the standoff template brackets in place during adhesive cure.

Requirements:

1. The mounting arm shall be able to support brackets bonded at a range of four inches to 36 inches inboard from the motor circumferential ring.
2. The mounting arm shall have six degrees of freedom to allow the standoff templates to be held in place at the proper location and angle on the motor domes.
3. The handling arm shall be mountable to the forward and aft attach rings of several rocket motors (details to be supplied by NGC).
4. The handling arm must be ESD (electro static discharge) compliant.
5. The handling arm shall be adaptable to several different mounting bracket templates via adapters or another method of re-configuration.
6. The handling arm shall be able to hold an adapter and standoffs of total mass up to 10 lbs.
7. The handling arm shall have the ability to be locked into place and apply a force of at least 20 lbs. on the adapter pushing it onto the motor dome.
8. Safety factors for all components must be 3.0 based upon the maximum expected loads. The arm is to be load tested to 125% to demonstrate structural integrity.
9. The handling arm must be easily manipulated by hand.

Additional Information:

For design purposes, the following assumptions may be made:

1. The standoff templates are flat aluminum plates of sizes 6.0" x 6.0" up to 10.0" x 16.0"
2. The arm will be attached to the standoff templates by clamping, not by bolting, bonding, or any other method.
3. The height of the standoffs (distance between motor dome and bottom of template) will be at l

east 0.5 inches.

Specific interface requirements will be provided upon selection. Other considerations students should take into account are: Life cycle evaluation for service life prediction, service and periodic maintenance, ease of handling and transportation.

Since the beginning of the project, changes to the project requirements have occurred. It is now expected that the mounting arm shall be able to perform a pull test of 50 lbs at 45 degrees from the centerline of the bracket. The pull test is required due to Northrop Grumman's current process of applying a pull test with a fish scale after the adhesive cures to verify that the mounting bracket will not fall off during flight. The client also now expects to be able to use multiple mounting arms at a time. This is not a requirement for the project, however, this is something the client wants the team to consider for the design. Currently, the technicians secures multiple mounting brackets at a time with the taping method, so this expectation was added to the project description in order to match the efficiency of the current tapping method. The budget for this project is set at $10,000.

6 REQUIREMENTS

In order to fully understand the goal of the project, an in depth analysis of the requirements requested by the customer and requirements that must be met by the design team was performed. These were listed as customer requirements (CRs) and engineering requirements (ERs). After these requirements were listed, a quality function deployment (QFD), which can be seen in Appendix B, was created in order to compare the engineering requirements to the requests of the client and quantify the impact of each on the final design. An in depth description and analysis of these requirements can be read below

6.1 Customer Requirements (CRs)

As discussed in section 1.2, the articulating arm must be able to meet the requirements listed by Northrop Grumman. The client requires that the final design be electrostatic discharge (ESD) compliant. If the design were not ESD compliant, the final design could transmit static electricity to the electrical components on the rocket motor dome, which could burn out the circuit. In order to prevent this from happening, ESD standards must be considered during the design process. Along with this material property, the articulating arm must be able to support brackets bonded at a range of 4 to 36 inches inboard from the motor circumferential ring. This will allow standoffs close and far from the rocket motor ring to be bonded to the motor dome.

Additionally, the design should have six degrees of freedom to allow the standoff templates to be held in place at the proper location and angle on the motor dome. This will allow the device to reach all directions to bond the standoffs. The arm should also be mountable to the forward and aft attach rings of several rocket motors. This will allow Northrop Grumman to use the articulating arm on multiple rocket motors instead of creating separate designs for each. The handling arm should be adaptable to several different mounting bracket templates. This is due to there being a large number of standoff templates that are used in these applications. The design should be able to apply to flat aluminum plates of sizes 6.0” x 6.0” up to 10.0” x 16.0”. Because of these sizes, the weight of each standoff varies. However, the design should be expected to hold an adapter and standoff up to a total mass of 10lbs.

To secure the standoffs in place on the rocket motor dome, the design should be able to lock in place and apply a push force of 20 lbs. on the adapter pushing it onto the motor dome. To test if the adhesive has cured, the articulating arm should be able to perform a 50 lb. pull force normal to the rocket motor dome surface, at 45 degrees from the centerline. These axial force tests can be combined into a singular customer requirement that meets both statements discussed by Northrop Grumman. The client also requires that safety factors for all components must be 3.0 based upon the maximum expected loads. The arm is to be load tested to 125% to demonstrate structural integrity. This will verify that the device will be both durable and robust for future use.

Along with these requirements, the design team is requiring that the device be within the $10,000 budget provided by Northrop Grumman. The handling arm shall also be a reliable design and safe for the operators to use. The client also wants the team to consider having a design that allows for the use of multiple mounting arms at a time. Since Northrop Grumman currently tapes multiple standoffs in place at a time, this was added in order to match the efficiency of the current tapping method. Since the plan is for only one operator to use this device, the final design should also be easy to use and transportable for the technicians. Table 1, as shown below, displays the current customer requirements and their weights.

Table 1: Weighted Customer Requirements

	Customer Requirements	Weight
1	ESD Compliance	0.09
2	Apply Axial Forces	0.09
3	Six Degrees of Freedom in Movement	0.09
4	Usable 4”-36” Inboard of Ring	0.09
5	Adjustable Interfaces	0.09
6	Support 10 lbs. in Locked Position	0.09
7	Durability	0.08
8	Reliability	0.08
9	Ease of Operation	0.07
10	Minimum 3.0 Factor of Safety	0.06
11	Use of Multiple Mounting Arms at a Time	0.05
12	Safe Operation	0.05
13	Transportability	0.04
14	Cost Within Budget	0.03

As shown in Table 1, each customer requirement has a corresponding weight. The weights allow the team to show the significance of each customer requirement related to the project. ESD compliance, apply axial forces, six degrees of freedom, usable 4”-36” inboard of the ring, adjustable interfaces, and support 10 b in a locked position are equally the highest rated customer requirements due to Northrop Grumman requiring these in the original project description. Furthermore, durability and reliability are the next highest customer requirements at a weight of 0.08. If the device is not designed to run effectively multiple times, then it will not meet the expectations of the client. While durability and reliability are important for the overall design, the other customer requirements listed by the client in the project description are ranked higher. If none of the 0.09 customer requirements are met, then the design is inadequate and will not be implemented into their applications. Ease of operation is ranked 0.07 because the client asked this to be considered in the design process. Although this is not a set requirement, it is still ranked highly since it was specifically asked for by the client.

The minimum factor of safety is ranked as 0.06. Usually, systems used in flights are set to a factor of safety of 1.5. This is because usually the higher the factor of safety, the more weight is added to the rocket. Since the articulating device will not be used in flight, there can be a higher factor of safety that is usually set to 3.0. For this reason, the factor of safety, while important, is ranked lower than the other customer requirements. Furthermore, the use of multiple mounting arms at a time and safe operations are ranked at 0.05. The multiple mounting arm requirements is a late consideration the customer added to the project. While this is a requirement that will be designed around by the team, the client has specified that this is a requirement that should not be a main priority. Safe operation is weighted less than the other requirements due to many of them being directly correlated to safe operation, such as ease of operation, reliability, and the functionality of the device. Since it is not expected to use the entirety of the $10,000 budget, the cost within budget is ranked the lowest at 0.03

6.2 Engineering Requirements (ERs)

In accordance with section 2.1, verifiable engineering requirements were created to assign measurable parameters or conditions to each customer requirement. This allowed the project team to evaluate if the generated concepts would meet the client’s expectations for the final design. The device should be evaluated if it is electrically conductive (Y or N). This is an essential engineering requirement because the design needs to be ESD compliant to protect the circuitry mounted to the motor dome. For this reason, the material of the device will be evaluated to verify that it will not carry static electricity into any of the electrical components of the rocket motor. Additionally, the mass (lbm) of the device is another value that will affect the transportability, durability, reliability, factor of safety, usability, and ease of operation. The articulating arm will need to have enough mass from the material thickness to work effectively and reliably, but also have a minimum amount of mass to make sure the device does not damage any of the existing equipment.

The device must also be operable by one or two people. The mass will be affected by the principal dimensions (in.) of the device. This will alter the customer requirements associated with mass such as effect whether the device is usable 4"-36" inboard of the ring, and determine if the device is usable for adjustable interfaces. These requirements will also be affected by the working length of the device (in.). The working length is one of the most important parts of the articulating arm, because if the device can not reach the standoff location, it is useless. In order to verify if the device can reach anywhere in the rocket motor dome, the working angle of the device (degrees) will be evaluated throughout the concept generation section. The modulus of elasticity is the final engineering requirement that will be directly related to the reliability and durability of the device to verify that it will not break. This will also correlate with the electrically conductive evaluation in order to make sure that the materials that work best for reliability and durability will be ESD compliant. Below is a table of each engineering requirement as well as a design-to value for each.

Table 2: Engineering Requirements with Design-to Values

	Engineering Requirements	Units	Design-to Values
1	Electrically Conductive	Y or N	Yes
2	Mass	lbm	25 ± 5
3	Principal Dimensions	in	8"W x 40"L x 6" H (±2")
4	Working Length	in	32"
5	Working Angle	Degrees	360^0
6	Modulus of Elasticity	lbf/in^2	$< 10.4 \times 10^6$ Psi [2]

As seen in Table 2 above, each engineering requirement has a corresponding design-to value as determined by the design team. The device should be electrically conductive so that it can be grounded and carry less of a charge. The mass of the device should be no larger than what one person can carry and operate. For this reason, the design-to value is estimated to be 25 lbs with a ± 5 lb range. The device will clamp on the rocket motor ring with an estimated 8" width along with a 40" length reach out from the rocket ring and an estimated 6" height. The device is expected to reach 4-36" inboard from the motor circumferential ring, which makes the working length 32". The entirety of the rocket motor dome should be reached with the final device, which means the working angle needs to be 360^0around the rocket motor dome. It can be assumed at this point in the project that the material used for the final device will be somewhat similar to the material the rocket motor dome ring which is constructed from 7075 Aluminum. 7075 Aluminum has a modulus of elasticity of 10.4×10^6Psi. As the rocket motor ring cannot be damaged during installation, the team has specified the modulus of elasticity to be less than that of the ring material. This is to ensure that the articulating arm fails before any damage can be caused to the motor ring.

6.3 Functional Decomposition

The functional decomposition serves to provide a visual representation and understanding of the flows and sub-functions of our project. This process includes the functional model as well as the black box model. The black box model represents the expected energy, material, and signal flows into and out of the design as well as the overall function. The flows that are addressed in the black box model include the human hand and aluminum bracket which represent material flow, human power which is an energy flow, and device position which is a signal flow. The overall function of the design is to hold the bracket in place which considers the customer requirements of the 20lb push force and 50lb pull test. The flows represent a material, energy, or signal that is used by or that affects the product. The creation of the functional model followed a reverse engineering and redesign methodology that places an emphasis on what is being accomplished by the design rather than how. Using the ideas and information gathered during the creation of the black box model and evaluation of the customer needs the team could determine the sub-functions required of the design. The sub-functions identified during this process would allow the team to begin the concept generation stage with the creation of a morph matrix. The sub-functions that are identified within the functional model include import bracket, press bracket, transmit M.E., and position bracket which represent operations performed on a flow or multiple flows to transform it from its input to its output. The flows and sub-functions correspond to customer needs and ensure their presence within the model. The functional model and black box model were performed concurrently with the subsystem benchmark which explains the discussion of those topics in this section.

6.3.1 Black Box Model

This section outlines the team's process of creating and finalizing the black box model. Figure 1, as shown below, shows the team's final Black Box Model. The purpose of creating the Black Box Model was for the team to understand the overall function of the product that will be designed and realize its appropriate inputs and outputs. Simplifying the design problem into the product's functionality, inputs, and outputs, helped the team gain a better understanding on the type of product that must be designed. There are three categories of inputs and outputs, also known as flows, which includes material(s), energy, and signals. These flows provided the team with information on what the product will use and what it will be affected by. The product's overall function was based on the project's requirements which was to "hold standoff in place". Materials inputted into the design include the human hand and bracket. A bracket will be mounted to/held in the device, utilizing human energy, and positioned in place to push onto the standoffs while the adhesive cures. Human energy is converted into mechanical energy through the positioning of the device. To know whether the product is pushing the standoffs in place, the product will signal through a click or snap noise.

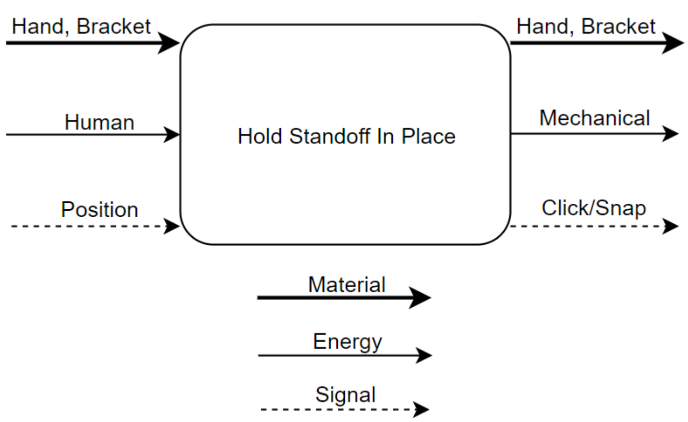


Figure 1: Black Box Model

6.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

This section discusses a more in-depth functional decomposition model derived from the black box model found in figure 1. The black box model was used to understand the overall function of the proposed design and how it converts inputs to outputs. By taking the material, energy and signal flows that will ultimately be transmitted through the design, and understanding how they are manipulated and used will ensure a deep understanding of the overall functions and working of the design. The functional decomposition model presented in figure 2 is an expanded view on the black box model in section 2.3.1. This model follows each material, energy and signal flow within the design to observe what is happening to each flow throughout the design. The overall purpose of the project design is to orient and secure a bracket in place while the adhesive cures which requires a lot more flow manipulation than it seems.

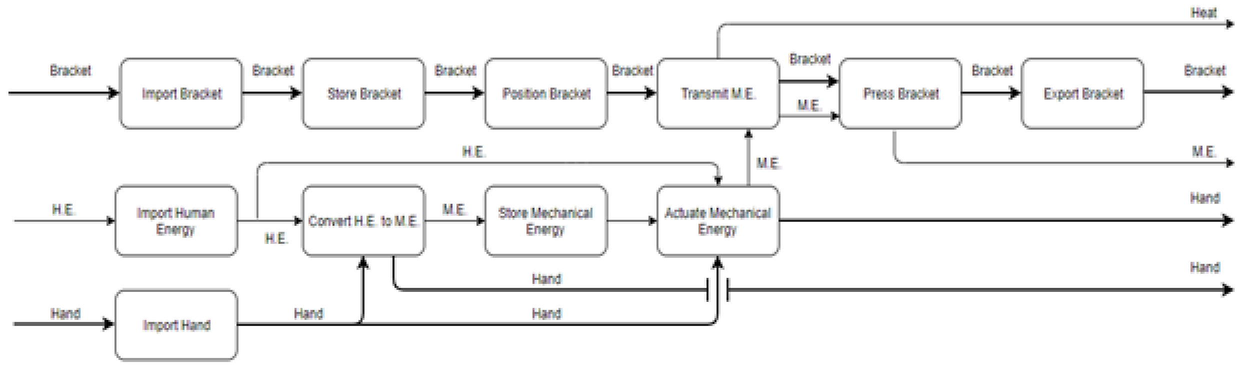


Figure 2: Functional Decomposition Model

In figure 2 above, it can be observed where each material, energy and signal flow interacts with the sub-functions of the design. The bracket is imported into the machine, stored, positioned and then pressed onto the dome for the curing process before being removed. The human energy (H.E) is imported into the system from the human hand which is then converted to mechanical energy to move the design and bracket into place. This mechanical energy is stored within the system and actuated to transmit the mechanical energy into the pressing of the bracket (i.e. 20lb push test, 50lb pull test). This functional model helped the team understand what each sub-function of the design was supposed to do to achieve the desired outcome. From this model, concept generations for each sub-function and subsystem of the design could be proposed to create various concepts that fit the overall functions from the black box model and functional decomposition model. The design being created must import and store a bracket, position that bracket, and apply an axial force to the bracket during the curing process all by human power. As shown in Table 3, these derived Sub-Functions of the design are what will be used to ensure the customer needs (Design Functions) gathered from Northrop Grumman are satisfied.

Table 3: System Sub-Functions

	Sub-Functions	Design Functions
1	Import Bracket	Mount to Ring
2	Press Bracket	Hold Bracket
3	Transmit M.E	Apply Axial Force
4	Position Bracket	Angle Bracket
5	Position Bracket	Translate Bracket
6	Position Bracket	Locking

6.4 House of Quality (HoQ)

This section discusses the team's house of quality and how this has helped the team in the design process. The quality function deployment (QFD) model used to evaluate the customer and engineering requirements for this project can be seen in figure 3 at the end of this section.The purpose of this QFD was to relate the requirements given by the client to a set of engineering parameters derived by the team. The customer requirements outlined the need for a universally positionable handling arm that is capable of mounting to the outer ring of a rocket motor and apply axial forces to the standoff bracket. From these given needs, the team was able to generate a list of engineering requirements, which centered around the ability to service as much area as possible while maintaining ESD compliance and having minimal weight.

The development of the QFD for this design project gave a chance to compare the engineering requirements to the requests of the client and quantify the impact of each on the final design. From these calculations, the team was able to visualize the importance of different aspects of the design given the various effects on customer requirements. The modulus of elasticity of the material ranked the most important, as a failure of the device could damage the expensive components handled by the arm or the dome of the motor itself. At the other end of the spectrum, the strength of components in contact with the motor ring should not exceed that of the ring itself, as the ring should not be damaged in the event of a handling error. While geometry will also factor in to the strength of the part, this is only a starting point given that the final dimensions are currently unknown.

The mass of the ring also stood out to the team as an especially important engineering requirement, as a large mass would add to the stress applied to ring mount while also making the device more cumbersome to use. Given that the current method of standoff application, while prone to failure, requires little handling effort, additional setup time of the teams design should be minimized. The tolerance for the mass of the final design was set to encompass reasonable weights which may be supported by a single operator.

The next two highest weighted engineering requirements, working length and working angle, combine to describe the serviceable area on the rocket motor dome. These relate directly to the customer requirements, as the design must reach predefined inward distances around the entirety of the motor ring. If the final design does not meet these requirements, it will not be usable for the intended purpose.

While weighted as the least important requirements in the QFD, electrical conductivity and limited principle dimensions are still necessary to produce a device that is up to the standard the team would like to achieve. As grounding connections will be accessible when the device is used, and each component can be individually ground, it is not necessary for all parts to be conductive as a single unit. This will factor more into material selection than design choice, but is still an important consideration. Limiting the principle dimensions has a similar weight, as it is not necessary to perform the basic functions required. However, as this handling arm may be used by different operators at multiple facilities, a smaller total size would allow for easier relocation and general use.

Customer Need	Weight	Engineering Requirements	Electrically Conductive (Y or N)	Mass (slugs)	Principal Dimensions (in)	Working Length (in)	Working Angle (Degrees)	Modulus of Elasticity (lbf/in2)
1. ESD compliance	0.10		9	0	0	0	0	0
2. Apply axial forces	0.10		0	1	0	3	3	9
3. Six degrees of freedom in movement	0.10		0	0	0	9	9	0
4. Usable 4" - 36" inboard of ring	0.10		0	1	9	9	3	1
5. Transportability	0.07		0	9	9	3	3	0
6. Ease of operation	0.08		3	9	3	9	9	0
7. Durability	0.09		0	3	0	0	0	9
8. Reliability	0.09		0	3	0	0	0	9
9. Adjustable Interfaces	0.10		0	3	0	3	3	0
10. Support 10lbs in locked position	0.10		0	3	0	3	3	9
11. Minimum 3.0 Factor of Safety	0.07		0	3	0	0	0	9
Absolute Technical Importance (ATI)			1.14	2.9	1.77	3.63	3.03	4.15
Relative Technical Importance (RTI)			0.27	0.70	0.43	0.87	0.73	1
Target ER values			(Reference Table 2)					
Tolerances of ERs								
Testing Procedure (TP#)			3.1	3.3	3.3	3.2, 3.3	3.2, 3.3	3.3

Figure 3: House of Quality

6.5 Standards, Codes, and Regulations

The purpose of this section is to discuss the standards and regulations that are relevant to the project and how they would be applied in industry. The function of standards and regulations within manufacturing and design processes is to ensure safety, reliability, and efficiency. Most standards are promoted and maintained by engineering societies and regulatory agencies such as the Institute of Electrical and Electronics Engineers (IEEE) or the American Society of Mechanical Engineers (ASME) [1]. The codes and standards included within this section were procured from the ASME standards catalog. The standards that were chosen for this section include ASME Y14.5-2009 Dimensioning and Tolerancing, B30.2-2009 Overhead and Gantry, B18.29.1-2010 Helical Coil Thread Inserts, B5.48-1977 Ball Screws, B1.5-1997 Acme Screw Threads, P30.1-2014 Planning for Load Handling Activities, B107.3000-210 Torque Instruments, and B46.1-2009 Surface Texture.

This section will go over each individual standard that may be applied to this project in detail. The codes that were considered for the final design of the device were found using the American Society for Mechanical Engineers (ASME) codes and standards database. The codes and standards that were considered for this project can be referred to below in Table 4.

Table 4:. Codes and Standards

Standard Number or Code	Title of Standard	Application to the Project
ASME Y14.5-2009	Dimensioning and Tolerancing	This standard could help facilitate the creation of engineering drawings that effectively communicate design intent.
ASME B30.2-2009	Overhead and Cantilevered Gantry Cranes	Applies the operation and safety procedures associated with cantilevered gantry cranes which can be related to our product.
ASME B18.29.1 - 2010	Helical Coil Screw Thread Inserts--Free Running and Screw Locking	This standard relates to our project by providing information on threaded hole helical screw inserts which are included within the power screw assembly.
ASME B1.5 - 1997	Acme Screw Threads	This resource gives information related to acme screw threads which is the thread form which will be used for the power screw.
ASME P30.1 - 2014	Planning for Load Handling Activities	This standard establishes planning considerations and practices that apply to Load Handling Equipment (LHE), other associated equipment and activities when moving loads vertically or horizontally.
ASME B107.3000 - 2010	Torque Instruments	This Standard provides performance and safety requirements for manually operated torque instruments, commonly used for mechanical measurement of torque for control of the tightness of threaded fasteners.
ASME B46.1 - 2009	Surface Texture	This Standard is concerned with the geometric irregularities of surfaces. It defines surface texture and its constituents: roughness, waviness, and lay.

As seen in Table 4 above, the first standard to be considered for this project was related to the aspect of dimensioning and tolerancing with respect to engineering drawings. The resource from which this standard originated from the AMSE and is denoted as Y.14.5-2009. This standard will help facilitate the creation and review of the engineering drawings in order to ensure their readability and design intent. The project includes the creation of an in depth CAD package which in order to be effectively communicated to the client must be transferred into drawing format. This standard will affect the project by influencing this process and changing the methods of dimensioning and tolerancing of these engineering drawings.

The next standard to be considered will be the ASME B30.2-2009 Overhead and Gantry standard which relates to the cantilevered gantry design of the device. This standard applies to the installation, operation, and maintenance of hand-operated gantry cranes. While the device is not a gantry crane it does share similarities, which include the bracket delivery system and the overhead rail design. This standard also applies to special circumstances such as non-vertical force delivery and guided loads which are consistent with the current design. This standard will help the project by allowing the team to comply with regulations of the industry while maintaining operational efficiency and safety.

The current design utilizes a power screw system to deliver pull and push forces at the appropriate angles to the brackets. This standard is denoted as ASME B18.29.1-2010 within the table above. This assembly will include components such as helical coil screws (lead screws) and screw locking mechanisms. This standard will help with the facilitation of the design of this assembly by providing information on the proper selection of Screw thread insert (STI) taps, installation, and dimensional data. This standard could influence the team's decision on the power screw that is chosen for the device as it would adhere to standards used in industry.

The thread form of the power screw is an important consideration to be had for the design of the rail cart assembly. This standard is denoted as ASME B1.5-1997. This standard will give information on the applications and general limits and tolerances of acme threaded screws. Due to the prolific occurrence of acme threaded power screws within force delivery systems, the team will heavily consider its use within the device. This resource will provide information on the three classes of general purpose acme threads as well as their alignment, clearances, major and minor diameters, and appropriate alignment. This will influence the team's discussion of the correct power screw to be utilized within the design due to the information provided within the standard.

The nature of the device as it was originally envisioned was to act as a force applicator to achieve specific conditions to aid in the curing of the adhesive on the bracket templates. There is a standard within the ASME database which focuses on load handling activities which is denoted as ASME P30.1-2014 which focuses on the preparations and practices which apply to load handling equipment such as our device. This resource will aid in the completion of the project by providing information regarding the device which can be included in the operation manual which will be created in the coming weeks. Other than benefiting the creation of the operation manual, this standard will also ensure that our device adheres to any regulations defined by this standard.

For the force application of the device, a torque instrument will be used to transfer axial loads through the power screw assembly onto the bracket template. A standard that can be applied to this procedure would be the ASME B107.3000-2010 standard which focuses on torque instruments and any performance or safety requirements that may be associated with them. For our device, the input torques required to achieve the expected axials loads were very minimal in comparison to the critical torque of the power screw. Other topics that this standard applies to would be mechanical measurement of torque loads which is a procedure that will be used on the power screw assembly.

The final standard included on the list would apply to the surface texture of the device which is significant to its proper operation. This standard is denoted as ASME B46.1-2009 and deals with geometric irregularities regarding surfaces. This applies to our device because the rail cart assembly must glide over the rails with little friction to allow for ease of operation by technicians. This standard could help identify surface irregularities which may affect the interfaces between components of the assembly. Using the standards and codes presented in this section, the team will be more knowledgeable in future endeavors on the applications and importance of codes and standards in industry.

8 3 Testing Procedures (TPs)

This section discusses the testing procedures developed by the team to prove that all components of the design meets each engineering requirement. Additionally, the purpose of these test procedures is to prove that the team's final solution meets all engineering requirements. To reiterate, the engineering requirements are electrically conductive, mass, working length, working angle, and modulus of elasticity. The team plans to conduct a total of three test procedures which are "ESD Compliance", "Torque Wrench", and "Working Angle and Length". Based on these test procedures, the team was required to purchase $441.26 worth of testing equipment prior to conducting these tests. All tests were planned to be conducted after spring break, during the week of March 23, on a Thursday or Friday at noon in 98C. However, due to the COVID-19 pandemic, these tests were unable to be performed due to the team being unable to meet. For this reason, the justification for the design is solely calculation based, which will be discussed further in this report. This section will discuss each test, and what would have been done if they were completed.

8.1 Testing Procedure 1: ESD Compliance

This section outlines the ESD Compliance testing procedure which works to prove that the team's design meets the electrically conductive engineering requirement. The primary objective of this test procedure is to verify that the product will not carry static electricity into any of the electrical components of the rocket motor. This test requires the entire team, an anti-static table mat with a common ground cord, anti-static mat, a digital static field generator and a multimeter. Upon retrieving all necessary equipment, the team was planning on meeting during the week of March 23 on a Thursday or Friday at noon in 98C for approximately 30 minutes to conduct the test.

8.1.1 Testing Procedure 1: Objective

The purpose of this test procedure is to verify that the team's device is electrically conductive which is an engineering requirement. The team will test this particular aspect of the project because it is important that the final device, when functioning, will not carry static electricity into any of the electrical components of the rocket motor. How this test procedure will run is that the entire device will be placed on an anti-static table mat which would be grounded by a common ground cord. An anti-static mat will be placed on the floor to ground the user. A multimeter would be used between a team member (red wire) and the device (black wire) and is expected to read 0V to prove ESD compliance. To further verify that the device meets this engineering requirement, the team will use a digital static field generator on the device to provide the same expected 0V.

8.1.2 Testing Procedure 1: Resources Required

For this test, the entire team would be involved and the necessary equipment included an anti-static table mat, common ground cord, a multimeter, and the completed device. All equipment necessary for this test procedure would have been purchased by the team, but was not purchased due to the COVID-19 pandemic. The Anti-Static table mat, anti-static mat, and the common ground cord will be ordered online at uline.com. the multimeter will be purchased at Home Depot. These items will cost a total of $826.81. Since the ESD compliance requirement is weighted heavily by the customer, it is imperative that the team invests in the appropriate equipment to follow the ANSI/ESD 6.1 standard.

Table 5: ESD Resources Needed

Index	Tool	Dimensions	Reference	Price ($)
1	Anti-Static Table Mat	2'x4'	https://www.uline.co	85.00
2	Common Ground Cord	15'	https://www.uline.co	17.00
3	Multimeter	n/a	https://www.homedep	40.00
4	Anti-Static Mat	2'x3'	https://www.uline.co	50.00
				192.00

The resources required to carry out the ESD compliance testing are presented in Table 5 above. The total cost of these materials is shown on the right side of the table along with the website where they were located.

8.1.3 Testing Procedure 1: Schedule

This test would have likely occurred on the week of March 23.The team will likely meet on a Thursday or Friday at noon in 98C to conduct this test. This test was estimated to take approximately 30 minutes. Additionally, before the test can be conducted all equipment must be ordered prior to testing. Shipping of the anti-static table mat, anti-static mat, and common ground cord is estimated to take 1-2 business days.

8.2 Testing Procedure 2: Torque Wrench

This section discusses the second test procedure which works to evaluate the actual torque input to obtain a 20lb push and a 50lb pull. This procedure would test the functionality of the entire device under the pull and push test conditions. This test would have been repeated 15 times to test the reliability and robustness of the device. The entire team would have been involved in this test procedure and would have utilized a protractor, mock motor ring, and the complete device. This test would have occurred during the week of March 23 on a Thursday or Friday at noon in 98C and will approximately take 1 hour.

8.2.1 Testing Procedure 2: Objective

The purpose of this test is to evaluate the actual torque input to obtain a 20lb push and a 50lb pull. Additionally, this test will also prove the functionality and reliability of the angling mechanisms of both the ring clamp and bracket holder while applying the incremental forces to achieve the push and pull test conditions. This test will prove that the team's design meets both the working angle and working length engineering requirements. This test will require the entire team, complete device, a mock motor ring, a protractor, and torque wrench. The procedure requires that the team places a spring scale at the end of the device and applies torque to the wrench at incremental forces to obtain the 20lb push and a 50lb pull. This will be tested at 45 degrees normal to the surface, and the data will be plotted in excel comparing the applied torque and corresponding forces.

8.2.2 Testing Procedure 2: Resources Required

The entire team was going to be involved in this test procedure. Additionally, the equipment required includes a protractor, a 0.19" aluminum 7075 sheet cut into the appropriate dimensions of the ring, the completed device, and torque wrench. In order to create a mock motor ring, the team was going to purchase a 0.19" aluminum 7075 sheet online at onlinemetals.com and submit a work order to 98C in order for them to cut the sheet and round it. The protractor would have been purchased in store at Target. The total cost of the testing equipment is $89.27 and the team will allocate an additional $200 for the work order. The resources needed are presented in Table 6 below.

Table 6: Working Angle Resources

Index	Tool	Dimensions	Reference	Price ($)
1	Protractor	n/a	https://www.target.co	3.39
2	Aluminum 7075 Sheet (0.19" THK)	12"x24"	https://www.onlinemet	85.88
3	Torque Wrench	n/a	https://www.harborfrei	159.99
				249.26

The resources required to carry out the working angle testing are presented in Table 6 above. The total cost of these materials is shown on the right side of the table along with the website where they were located.

8.2.3 Testing Procedure 2: Schedule

The test would have occurred during the week of March 23, most likely on a Thursday or Friday at noon in 98C, and is estimated to take 1 hour. Prior to testing, the team submitted a work order for the mock motor ring to 98C three weeks before the test. Additionally, the 7075 aluminum sheet was to be purchased and received prior to placing the work order, however this was delayed due to COVID-19 restrictions that were implemented before the shutdown of the manufacturing lab. Onlinemetals.com provides 1-2 ground day shipping, so the team was going to factor this in when preparing for this test procedure.

8.3 Testing Procedure 3: Working Angle and Length

This section discusses the test procedure required to prove the functionality, reliability of the angling mechanisms of both the ring clamp and bracket holder, and that the device meets the required mass and working length applying a maximum force of 50 lbf. The resources required include a digital scale, ruler, measuring tape, calipers, meter stick, and a laptop. The team would have used the scale in the Soil Lab classroom, a meter stick would have been purchased online, and the rest of the measuring devices would have been borrowed from 98C. This test procedure required the entire team and would have been conducted during the week of March 23 on a Thursday or Friday at noon at 98C.

8.3.1 Testing Procedure 3: Objective

The objective of this test is to verify that the device meets the mass, working length, principal dimensions, working angle, and modulus elasticity engineering requirements. The test will require the measurement of all device components using either a ruler, measuring tape, calipers, or a meter stick. Additionally, each component will also be weighed using a digital scale. In order to achieve this, the device will be completely unassembled to weigh each component. Through this test, the physical measurements should closely match the final CAD which would verify that the device meets the principal dimensions and mass engineering requirements. The reason why this test is important is because the team must meet specific dimensions in order to ensure that the device will be able to function on various types of rocket motor domes with varying diameters. Upon completing the measurements, the device will be mounted on the mock motor ring and will test the device at various angles while applying the 50lbf. This test will be repeated at least 20 times to verify durability and robustness of the device.

8.3.2 Testing Procedure 3: Resources Required

In order to be able to conduct this test, the team will need to acquire a digital scale, torque wrench, ruler, measuring tape, calipers, and a meter stick. To weigh the device, the team will use the digital scale found in the soils lab room. Additionally, the ruler, measuring tape, and calipers will be found in 98C and the team will check these equipment out on the day of the test. The meter stick will be purchased online. All team members will be present and will record the measurements on a shared google document or spreadsheet.

Table 7: Mass and Working Length Resources

Index	Tool	Dimensions	Source	Price ($)
1	Torque Wrench	n/a	https://www.onlineme	159.99
2	Digital Scale	n/a	NAU	0
3	Ruler	n/a	NAU	0
4	Measuring Tape	n/a	NAU	0
5	Calipers	n/a	NAU	0
				159.99

The resources required to carry out the mass and working length testing are presented in Table 7 above. The total cost of these materials is shown on the right side of the table along with the website where they were located.

8.3.3 Testing Procedure 3: Schedule

This test would have been conducted on the week of March 23, when the device was required to be completed. The team was planning on meeting on that Thursday or Friday to measure each component. Prior to conducting the test, the team was planning to check when the Soils lab was available or schedule to use the digital scales and check 98C to verify that it has a ruler, measuring tape, and calipers.

9 DESIGN SPACE RESEARCH

This section discusses the design research that the team has undergone to better understand the scope of the required design. The team has conducted a literature review, system benchmarking, and subsystem benchmarking. The literature review encompassed research on ESD compliance, clamping methods, ways to apply axial forces, methods to lock joints, and rocket motor basics and components. The system benchmarking takes three existing full-system designs that aligns with some customer needs, and the subsystem benchmarking takes three sub-system designs that fulfills the design's sub-functions derived from the functional decomposition model.

9.1 Literature Review

In order for the design team to have a better understanding of the project, a literature review was conducted for five main topics. ESD compliance was researched further since many members of the design team have never heard of electrostatic discharge before the project began. Methods into mounting the articulating arm were also looked into to find common clamping methods used, and to find ways to implement them into the final design. Ways to apply axial forces were reviewed to find methods of securing the brackets onto the standoff while the adhesive cures. Methods to lock joints in an articulating arm were researched in order to make sure the device locks in place while applying the axial force. Lastly, an overview of rocket motor basics and components was made to allow the design team to get an understanding of what the final device will affect and be applied to.

Of these literature review topics, the main topics that the team used for benchmarking and design research were clamping methods, ways to apply axial forces, and methods to lock joints. ESD compliance was utilized later in the project toward the testing portion of the project, however as long as the material used to create the bonding arm was conductive, the device would likely be conductive so this was not influenced too much in the design space research portion of the project. In regards to rocket motor basics and components, while this is important to understand as the final design will be mounted to this system, for design research it would not prove to be helpful to providing solutions. Specifically during the subsystems section 4.2.2, research on the motor ring clamp, axial force application, and the locking methods were all helpful as each of them were subassemblies. While looking over these subassemblies, various types of sources were found which were helpful. Each source looked into patents that the team could refer to for design ideas, engineering textbooks which utilized analyses that the team could use to determine if their design would operate as expected, and engineering conferences which discussed each topic in greater detail on a broader scope.

9.2 Benchmarking

The benchmarking section addresses both full-system and subsystem level existing designs related to the project requirements. The purpose of this section is to identify fully working systems that meet major design requirements including 6 degrees of freedom, application of axial forces, usable 4”-36” inboard of the ring, support 10lbs in a locked position, ESD compliant, and adjustable interfaces. In addition to this, the purpose of identifying the subsystem level existing designs was to ensure that the smaller components of the device would meet its respective engineering requirements. Based on both systems, the team would have a deeper understanding of the complexity and would be able to identify necessary design aspects to consider for the concept generation portion of the design process.

9.2.1 4.2.1 System Level Benchmarking

This section outlines the system level benchmarking process, how they were chosen, and what products were selected. The benchmarking process was based on the major design requirements of the project which included safety, reliability, articulating arms with 6 degrees of freedom, reach, gripping mechanisms, and load capacity. The purpose of this section was to determine the three major benchmarking products that would be used to inform the team on potential design ideas that meet the project criteria. Since the project proposed that the team design an articulating arm that clamped onto the outer ring of the motor dome while holding the standoffs in place, the first two benchmark products modeled this requirement. The first design modeled the use of one arm while the second design utilized two arms. The third benchmarking product chosen was a rail system which offers a unique solution to the project.

9.2.1.1 *4.2.1.1 Existing Design #1: 6 DOF Robot Arm*

This system-level existing design is a six degree of freedom robotic arm that has a repeat location accuracy of ±0.1mm and a maximum load of 2kg [2]. The design has a 650mm arm length and is electrically powered. Furthermore, this was specifically chosen because it meets the six degree of freedom requirement. The cons of this design include its maximum load capacity and its reach. The pros of using this design as a benchmark is that it meets the articulating arm requirement which is a good basis to the design process. This arm models potential joints and structure that the team can use during the concept generation portion of the project. As shown in figure 4 as shown below, the robotic arm has a component at the end of the arm that allows users to mount claws or any clamping devices which is a design aspect that can be considered when brainstorming ideas of attaching the clamps for brackets to the arm.

Figure 4: 6 DOF Robot Arm [2]

9.2.1.2 *4.2.1.2 Existing Design #2: Dual Arm*

The second existing system-level design is a dual robotic arm that has enhanced functional dexterity. This device can lift over 110lbs and can be driven joint-by-joint to perform tasks such as picking up boxes, opening containers, and using tools [3]. Figure 5, as shown below, is a visual of the dual arm system. This design meets the six degrees of freedom, potential to add a clamp at the bottom of the system, and gripping mechanism for the brackets. The use of hands as a gripping method is a unique solution to holding the brackets as well as the use of two arms. This design serves as a notable benchmark product because it meets major project requirements and provides feasible design solutions.

Figure 5: Dual Arm [3]

9.2.1.3 ***4.2.1.3 Existing Design #3: Aluminum Rail Workstation Cranes***

As shown in figure 6, the third existing system-design for benchmarking is the aluminum rail workstation crane that has the capability to meet the six degree of freedom requirement with design modifications, and lifts loads as light as 35lbs [4]. This design offers a unique solution to the design problem by utilizing rails rather than multiple joints and arms. While this is a complete system, this benchmark can best be used once additional designs are added to this later in the design process. However, this benchmark provides a more secure base structure than the articulating arms which is an aspect to consider when the safety and reliability of the team's product are a priority.

Figure 6: Aluminum Workstation Cranes [4]

9.2.2 4.2.2 Subsystem Level Benchmarking

This section addresses the six subsystems and considers three existing designs per subsystem which will serve as references for the concept generation portion of the design process. The subsystems were determined from the functional decomposition model and allowed the team to identify the necessary objectives that the device must meet to accomplish its overall function. Existing designs were then chosen to further develop an understanding of each subsystem's function and to ensure that each system would meet the project's requirements.

9.2.2.1 *4.2.2.1 Subsystem #1: Hold Bracket ("Press Bracket")*

Holding the bracket for this design is crucial for the overall functionality of the device. It is one of the main customer needs provided by Norhtrop Grumman that is the "press bracket" section of the functional decomposition model provided in figure 2. This is an important aspect of the project that needs to be rigid and adaptable, to fit different standoff brackets ranging from 6"x"6 up to a maximum of 10"x16". This subsystem will guarantee that the brackets are held in the correct place during the entirety of the curing process to ensure proper functionality of the rocket components. The three proposed designs that are relevant to this specific subsystem that were discussed by the team include the spring loaded clamp, the C-clamp, and the claw.

9.2.2.1.1 **4.2.2.1.1 Existing Design #1: Spring Loaded Clamp**

The spring loaded clamp is one of the most common types of clamps seen on a day to day basis. By utilizing a wound spring, applying radial force will rotate the spring, opening the clamp, and when released the stored energy in the spring will be used to hold the bracket in place within the clamp arms. A simple wooden clothes pin is an excellent example of this concept. By pinching the back of the two clamp arms, the arm rotates around the wound spring opening up the front end of the arms. Releasing the back end of the two arms will close the front, latching onto anything within the working range of the arms. For the project design a much stronger, better manufactured spring loaded clamp would have to be designed for durability and reliability purposes related to our engineering requirements and customer needs.

9.2.2.1.2 **4.2.2.1.2 Existing Design #2: C-Clamp**

The C-clamp is also a viable existing design that can be used to hold the standoff bracket in place during the curing process. The clamp arms are on a sliding cylinder horizontally that is also set inside a power screw (i.e. Threaded Rod) that when spun will slide one of the clamp arms either inward or outward to account for different size brackets. Once open to a large enough working area, the threaded screw can be turned in to apply a clamping force on the bracket to keep it in place. Utilizing a self locking power screw will ensure the bracket doesn't slip or move during the curing process. An example of this clamp is the very woodworking C-clamp that helps mount wood or other material to tables. This design would likely be more secure and solid than the spring loaded clamp but also requires more set up time and device manipulation relating to the ease of use and durability in the customer needs.

9.2.2.1.3 **4.2.2.1.3 Existing Design #3: The No Law Claw**

The third existing design that was analyzed was the claw machine design that can be observed in numerous arcades and game stores across the world. A design containing three jointed arms are all connected at a center point at the top. These arms sit inside joints that allow for internal and external movement of the arms that when actuated all arms move together to provide a clamping force on an object. This design would be more space efficient than the above spring loaded and threaded clamp designs as the arms all move together rather than independently, but the three points of contact would make it difficult to hold the rectangular shaped 10"x16" brackets in place during the curing process.

9.2.2.2 *4.2.2.2 Subsystem #2: Apply Axial Force ("Transmit M.E.")*

The transmit mechanical energy subsystem originates from the customer need requirement of performing a 20lb push force as well as 50lb pull test onto the bracket/template. This is an important aspect of the design because Northrop Grumman's system of verifying proper adhesive curing is by application of a 20lb push force for up to 72 hours as well as a pull test of 30 minutes afterwards. These processes ensure the safety and functionality of the mounted components during the operation of the rocket. The proposed designs that will be considered in the benchmarking of this subsystem include the lead screw, scissor jack, and variable spring stiffness as discussed in the literature review.

9.2.2.2.1 **4.2.2.2.1 Existing Design #1: Lead Screw**

The lead screw is the most promising mode of force transmission being considered for the project. The simplistic and efficient nature of the mechanical functions of the power screw serve to decrease costs and increase reliability. The advantages of the power screw includes its ability to translate rotational motion to linear motion which allows ease of operation. The ability of the power screw to transmit force onto the bracket/template while also being irreversible due to its self locking properties represents a major potential for the transmit mechanical energy subsystem. This method of force application provides an easily manageable system which closely correlates to the engineering requirements of the project and is the main proposed solution for this subsystem.

9.2.2.2.2 **4.2.2.2.2 Existing Design #2: Scissor Jack**

The scissor jack is a design that we are considering for the application of the axial force onto the bracket/template or as seen in the functional model below, transmit mechanical energy. This design covers the engineering requirements of the project due to its ability to apply axial force through transmission of power through an integrated lead screw. This mechanism would be mounted to the rail cart and be the main mode of securing the bracket to the standoff. The minimal manual input required to produce a 20lb and 50lb force is a major advantage of this system. Due to the ease of operation and simplicity of this mechanism, it is a major consideration for this aspect of the project.

9.2.2.2.3 4.2.2.2.3 Existing Design #3: Variable Spring Stiffness

The variable spring stiffness patent that was analyzed in the literature review offers a different type of force application method that may prove useful for this subsystem. The implementation of this system could decrease overall weight and increase the ease of operation. The disadvantages associated with this system include the inability to reverse force direction which would require further complexity to meet the 50lb pull test requirement. This mechanism could be operated by a drive knob mounted to the rail cart that would vary the spring force acting on the bracket. Some reservations about this design include frequency of spring replacement, maintenance, and degradation.

9.2.2.3 ***4.2.2.3 Subsystem #3: Angle Bracket ("Position Bracket")***

The ability to angle the bracket originates from the customer needs of six degrees of freedom and ease of use. The standoff brackets mentioned throughout the project are to be mounted on both the forward and aft ends of the rocket motors which are dome shaped. Being able to apply these standoffs securely to the dome during the curing process requires that the bracket be able to rotate and adjust to the surface of the dome to ensure that each standoff is firmly attached to the dome. In order to achieve this customer need, an angling system must be applied to the end of our design to react to the surface of the rocket motor dome that is easy to use and effective in its purpose. The three proposed designs to accomplish this requirement include a ball and socket joint, a universal joint, and a parallel plates design.

9.2.2.3.1 **4.2.2.3.1 Existing Design #1: Ball & Socket**

The first design that was proposed and analyzed by the team was the ball and socket joint. This design is a spherical "ball" component that fits inside a spherical cavity "socket" that allows the ball to rotate freely across a wide working angle. This type of joint is found within the human body in both the hip and shoulder joints that allow for a very large range of motion. Another example is the ball joint in a vehicle that allows the front tire to stay aligned while the body moves up and down with the driving conditions. This design directly relates to the six degrees of freedom requirement needed by Norhtrop Grumman that would be adaptable to all surface conditions of the rocket dome.

9.2.2.3.2 **4.2.2.3.2 Existing Design #2: Universal Joint**

The second proposed design was another concept taken from mechanical joints, the universal joint. This joint is found along the drive shaft of most vehicles and ultimately connects two shafts that aren't aligned axially and still allows for transmission of power and torque between the two shafts. This U-joint as it is commonly called has two U shaped pieces that fit together with an X shaped centerpiece connecting the two U's. This allows for a very wide range of motion from one shaft to the other and would work well when trying to angle the bracket for this project design.

9.2.2.3.3 **4.2.2.3.3 Existing Design #3: Parallel Plates**

Parallel plates was a proposed design that the team discovered that was quite interesting. Two parallel plates were separated by six pistons that allowed the top plate to be angled in a wide array of orientations. The pistons would slide in and out to account for the top plates movement and assumedly would lock in place when done transitioning. This design is very creative and quite unique but when being analyzed for the team's design, it seems to over complicate the task at hand. Although useful in achieving the wide angle distribution needed for the brackets, the pistons and plates would add extra weight and decrease the ease of use on the design.

9.2.2.4 ***4.2.2.4 Subsystem #4: Translate Bracket ("Transmit M.E")***

In order to meet the customer requirement for the device to be usable 4"-36" inboard of the rocket motor ring, a description of possible ways to translate the bracket across the rocket motor dome was created. As described in the project description, the device must be able to be applied to multiple rocket motors (Castor 38, 50XL, and Orion 30XL), so this translation must reach across each rocket motor dome. The translation must also be easy to operate and allow for easy transportability of the device by one individual. The proposed designs to meet this subsystem design is a sleeve, telescope, and rail. The description of these existing designs can be seen below.

9.2.2.4.1 **4.2.2.4.1 Existing Design #1: Sleeve**

The first proposed design for translating the bracket was a mechanical sleeve. The design has four main pieces, two metal plates, a screw, and a nut to tighten the screw to the metal plate on the other end (and possibly two washers). This design has two metal plates connected that can be moved axially along the surface direction. The sliding allows a device to extend outward to reach a further distance. The metal plates are locked in place by a screw that tightens through two oval holes through the two metal plates. Then a nut is tightened on the other end of the screw to lock the two metal plates in place. This design has been used in household parts such as ikea furniture to allow for the extension of a part. This design is a simple device that could be created, however for the team's design, this would make the device multiple pieces which would need to be assembled on site by operators. If this design was implemented into the final full system, a solution would need to be found on how to allow for easy assembly.

9.2.2.4.2 **4.2.2.4.2 Existing Design #2: Telescope**

The next existing design that is used to translate a system outwards is a telescoping feature. Seen commonly on canopy tents to allow the legs to extend upwards, telescoping consists of a large circular or rectangular piece that contains smaller pieces inside the larger base. These smaller parts can extend outward to create a large translation. These could be locked by a pin such as in a canopy tent, or friction locked after a certain distance outward. This design could be implemented into the final articulating arm design, however it would need to have a FEA done to see if it would not deform under the loads described in the project description. This could occur since telescoping parts are hollow and tin to allow for more smaller components to fit inside the larger piece.

9.2.2.4.3 **4.2.2.4.3 Existing Design #3: Rail**

The final existing way for the translation of the bracket is to create a rail system for the force block to move across. A rail just refers to a railroad system where two metal bars extend to the full length the device needs to be (36") to allow the axial force to reach all distances. In this design's case, the force block would also be on a rail system to allow for six degrees of freedom specified in the project description. This design would allow for a simpler design that allows for less points of failure, however it could be a problem if any part of the dome protrudes above the rocket motor ring. There would need to then be a way to angle the device upward from the clamped portion with a device similar to a hinge. This existing design would also be harder to transport due to not being able to collapse on itself (such as the telescope).

9.2.2.5 *4.2.2.5 Subsystem #5: Locking*

While the locking subsystem varies with the chosen design and physical motion that is occurring, it is a necessary function for nearly every component in all proposed designs. Without locking mechanisms, the device would not be able to position the bracket accurately and maintain this location. The ability to provide an axial force is also dependent on the locking subfunction, as the components must transfer the load as a single rigid body during operation. Various methods exist to lock parts into a set position, three of which are outlined below.

9.2.2.5.1 **4.2.2.5.1 Existing Design #1: Locking Lead Screw**

A lead screw, or power screw, operates by converting a twisting motion into a linear actuation, which can be used to position the bracket on the surface of the rocket motor dome. It is necessary for this position to be held throughout the curing of the adhesive and the pull test, as motion may cause the adhesive to cure incorrectly or an improper pull test. The lead screw, if correctly designed, will be able to lock into place automatically from the thread friction when a force is applied. This design cannot be used to change the angle of the part, but is useful in locking the axial position.

9.2.2.5.2 **4.2.2.5.2 Existing Design #2: Camera Tripod Head**

Another existing locking method for a movable component is the universal tripod head, which is used with many camera systems. The purpose of the tripod head is to set the angle of the camera to any position specified by the user and maintain this angle for the duration of the use. This would help to satisfy the need for six degrees of freedom in design while also ensuring that the bracket is held in the correct position, which is normal to the surface of the rocket motor dome. A design similar to the camera tripod head would be able to compensate for the lack of angle changing ability in the power screw, effectively locking the bracket position.

9.2.2.5.3 **4.2.2.5.3 Existing Design #3: Friction Locking Baton**

In order to position the force block, or cart, above the application point on the dome, a system must be employed to translate it inward from the ring. In the case of a rail, which is not limited to discrete positions, a friction lock may be employed. A similar design can be seen in the friction locking baton, which utilizes the coefficient of friction between materials to hold a component in place. This type of baton can be extended into position without keying, and maintains locking under significant loads. While the positioning is not universal as needed in handling arm design, a similar form of friction locking may still be useful in a rail type translation system.

9.2.2.6 *4.2.2.6 Subsystem #6: Mount to Ring ("Position Bracket")*

The sixth subsystem is to mount the device to the outer ring of the rocket motor dome. This subsystem is derived from the “position bracket” portion of the functional decomposition model because it ensures that the device is secured and is able to reliably position the bracket. This subsystem meets the requirement of safe and ease of operation as well as the need to clamp onto the ring. In addition to these requirements, the designs that were considered and chosen as the subsystem-level existing products needed to be adjustable to different ring sizes and curvature and not deform the ring’s material.

9.2.2.6.1 **4.2.2.6.1 Existing Design #1: Miter Clamp**

The first subsystem-level existing design is the miter clamp that is typically used to hold two objects together at 90 degrees. Typically, miter clamps come in spring or clam clamp varieties with both varieties being able to clamp materials such as wood without deformation. In addition to this, miter clamps are adjustable to various angles and thicknesses of materials which meets the clamping requirements of this project. This design may not provide enough clamping force as it is used mostly for woodworking, but its mechanism is an aspect to consider since the rings’ thickness values are low.

9.2.2.6.2 **4.2.2.6.2 Existing Design #2: Hose Clamp**

The next existing design is the hose clamp which works well in applications such as securing fittings. This design is adjustable to different sized rings but would not be flexible to different angles of curvature. Although it is not adjustable to different angles of curvature, this design offers the mechanisms necessary to clamp the device to the ring given its flexibility. This design was chosen because of the flexibility of the design. At a design point of view, the hose clamp can potentially be redesigned for the project by adding additional components.

9.2.2.6.3 **4.2.2.6.3 Existing Design #3: Spring Clamp**

The final existing design is the spring clamp which is ideal for clamping objects that are delicate. Spring clamps are typically designed with adjustable jaws that have soft plastic or rubber pads to protect the material being clamped. A spring clamp provides large amounts of clamping force while protecting the material being clamped which meets an important design requirement. Additionally, a spring clamp design is versatile and can be redesigned to meet the required adjustability aspect to this subsystem.

11 **5 CONCEPT GENERATION**

The concept generation portion of the project utilized information from the literature review, benchmarking, and functional and black box models to aid in the brainstorming of design solutions. The concept generation methods that were used included the gallery and morph matrix. The gallery method provides a great environment for creativity as the various design iterations can be easily understood and expanded upon by the team. The morph matrix facilitates the execution of systematic concept generation based on the ideas presented for each of the individual subsystems. This section will include the proposed final full system design solutions as well as for the individual subsystems. The advantages, disadvantages, and technical analysis of the design concepts will also be addressed.

11.1 5.1 Full System Concepts

The below sections include detailed descriptions and design figures for the full system and subsystem concepts developed by the team. A morph matrix was utilized to construct various concepts for each subsystem and then built different design concepts based on the different sub functions. Three of the most promising full system designs are detailed below.

11.1.1 5.1.1 Full System Design #1: Rail Crane

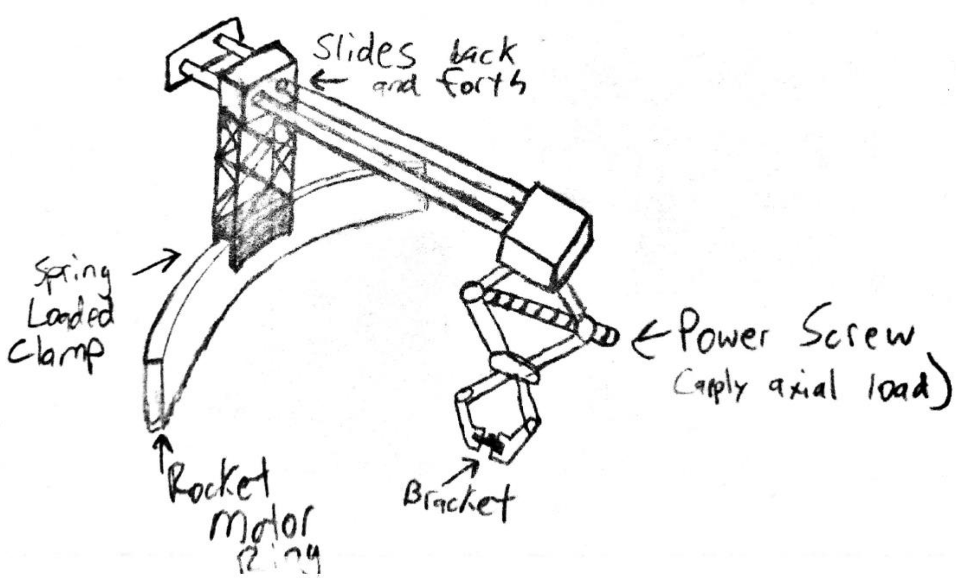
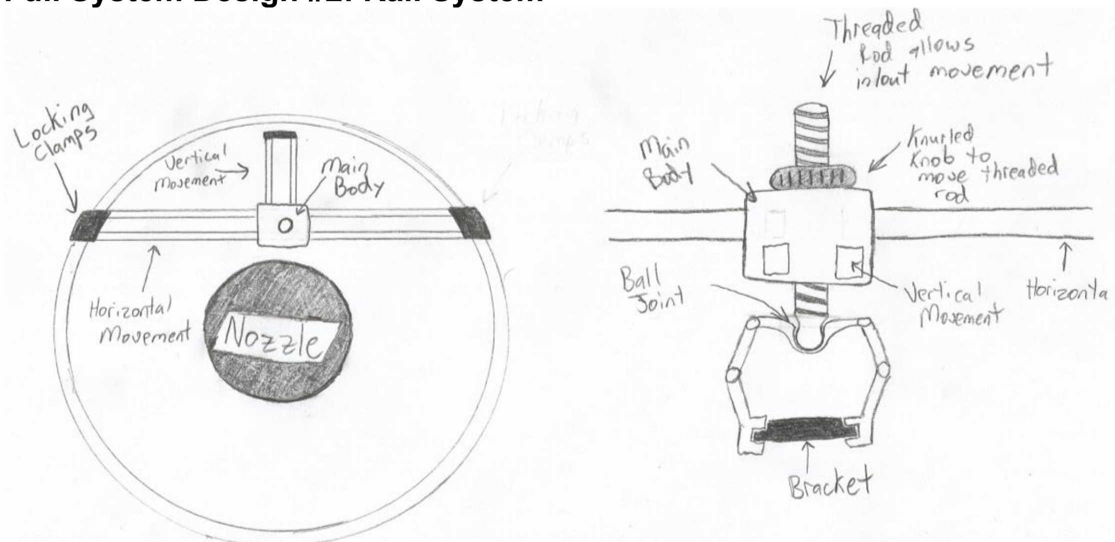


Figure 7: Rail Crane Design

Figure 7 as shown above, shows a fairly detailed drawing of the first full system concept developed. This design is loosely based on a construction crane that slides back and forth through the vertical portion of the frame. This feature allows the bracket to be positioned at various distances inward of the ring, which from the customer requirements needs to be between 4”-36”. The rail crane is attached to the ring of the rocket motor using a spring loaded clamp as well as a spring loaded clamp to hold the bracket. To apply the axial forces needed to supply the 20lbs on the bracket, a scissor jack variant is implemented. A horizontal power screw will force the scissors open to apply the 20 lb push and 50 lb pull test needed.

This design works in a linear motion so the base of it won’t be able to turn, leading to a very strong and rigid product. However, due to the design being elevated like a crane, and only clamping to the motor ring in one place, the crane will impart a large moment to the very expensive rocket motor ring which should be avoided at all costs.

11.1.2 5.1.2 Full System Design #2: Rail System



11.1.3

Figure 8: Rail System Concept

The rail system concept depicted in figure 8, won't be an articulating arm at all but more related to a mobile cart system. The device will mount in two points along the motor ring with one set of rails. Riding on these rails is a cart that has another set of rails going perpendicular to the first. This will allow the device to move both side to side and up and down covering the entire working surface of the dome. To apply the forces needed on the bracket, an axially oriented power screw can be threaded in or out to either push or pull on the rocket dome. Utilizing a ball joint on the bottom end of the power screw, the bracket will be able to orient with the surface of the dome ensuring proper contact between the standoffs and the dome for curing.

This device greatly reduces the moment on the motor ring by attaching in two places which greatly reduces the fear of bending the ring. However, Northrop Grumman wants numerous standoffs mounted at the same time so this device takes up a substantial amount of area thus reducing the amount of standoffs that can be mounted simultaneously.

11.1.4 5.1.3 Full System Design #3: Computer Articulating Arm

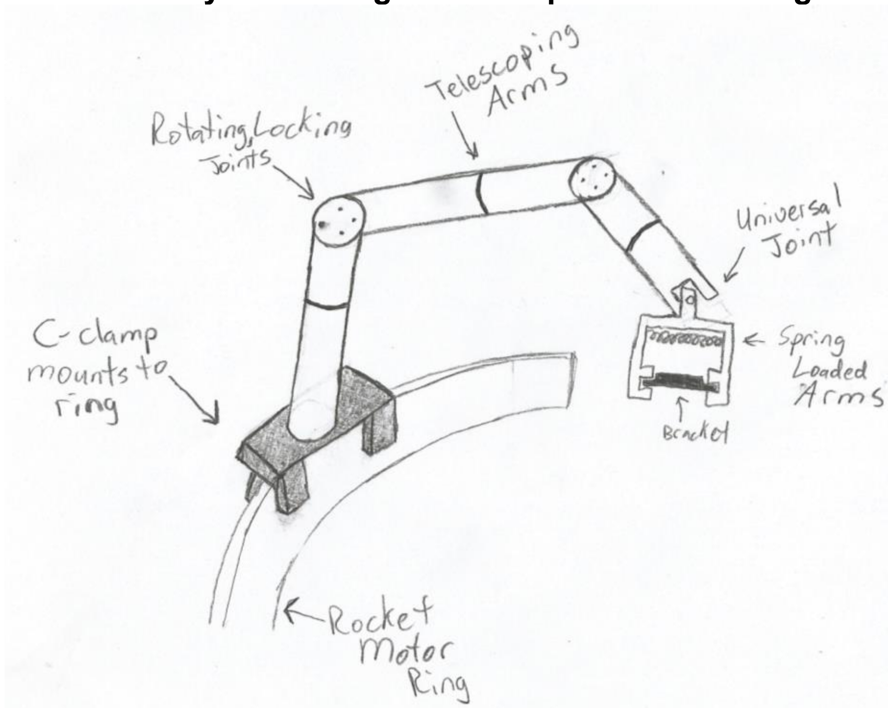


Figure 9: General Articulating Arm

The final full concept system that the team generated is a general articulating arm which is presented above in figure 9. This design utilizes three locking joints to allow the bracket to be positioned anywhere it needs to go. Similar to a computer articulating arm, the device is very maneuverable and would cover the entire range needed for the rocket motor domes. Like the rail crane design, the articulating arm would mount to the rocket motor ring in a single point utilizing a self locking power screw like the C-clamp. To service the full angle range needed to accommodate the dome profile, a universal joint like the ones found in vehicle drive shafts would be utilized. From this a spring loaded clamp would be attached to the end of the universal joint to hold the bracket template.

This design is very space efficient like the rail crane system. It would allow for numerous standoffs to be mounted at the same time while locking in place to ensure a proper cure process. However, this design utilizes multidirectional joints which complicates the overall mechanics and could lead to more failure points.

11.2 5.2 Subsystem Concepts

The six subsystem functions that will be discussed in this section include hold bracket, apply axial force, angle bracket, translate bracket, lock, and mount to ring, all of which can be viewed in the functional model and black box model. The designs for these subsystems were generated using the gallery and morph matrix methods. These subsystems represent the proposed solutions to the functions discussed in the functional decomposition section above. Each subsystem section is composed of three designs as well as a discussion on its relevance and contributions to filling the requirements of the project.

11.2.1 5.2.1 Subsystem #1: Hold Bracket ("Press Bracket")

The following designs are the proposed concepts that the team generated to hold the bracket. Based on section 4.2.2, the existing designs for these sub-functions, the team generated variations of these to implement on the project.

11.2.1.1 5.2.1.1 Design #1: Spring Clamp
Figure 10 below shows the team's variation of the modern spring clamp (clothes pin). The bracket will fit inside the arms of the clamp with a loaded spring at the top. This spring would apply an inward force to the bracket, keeping it in place with a firm grip during the curing process. The spring would have to be variable enough in length to account for the 6 in. x 6 in. bracket up to the 10 in. x 16 in. bracket. The top corners of the clamp would have to be on a pin so that they could expand outward to account for the brackets. The negative aspect of this design is the spring itself because if the spring isn't strong enough to hold the bracket from moving, it could cure the bracket in the wrong position ultimately wasting time. However the clamp would be extremely easy to import and hold the bracket, it just might not be strong enough.

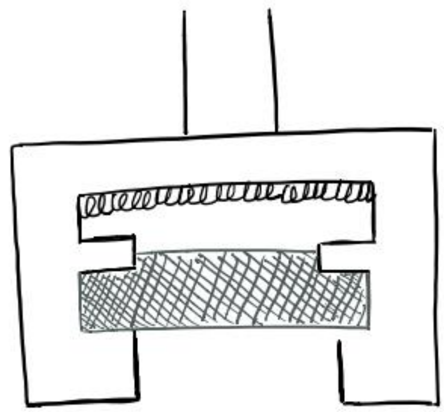


Figure 10: Spring Clamp Concept

11.2.1.2 5.2.1.2 Design #2: Threaded Clamp
The threaded clamp shown in figure 11 is a variation of the C-clamp design that is used in carpentry shops. This device would work similar to the spring loaded clamp above except it would utilize a threaded screw that would pull the clamp arms closer together exerting an inward force on the bracket. This device would not be as easy to adjust as the spring is quicker to adjust, but the threaded clamp would ensure that a more consistent and stronger force is applied to the bracket to keep it in place. This design would ensure that the bracket doesn't move in the clamp during the curing process but might be difficult to expand to account for the 10 in. x 16 in. bracket.

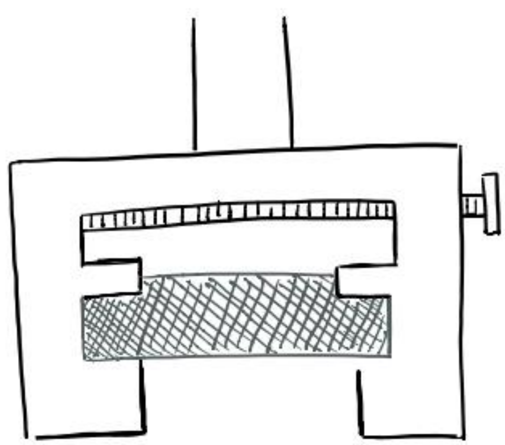


Figure 11: Threaded Clamp Concept

11.2.1.3 5.2.1.3 Design #3: Claw

The final design concept for holding the bracket is the Claw design that resembles a claw machine that could be found in an arcade. The design shown in figure 12 has a multiple jointed arm that moves together with the other arms. At the top of the design a sliding sleeve will move upward which in turn pulls all the arms toward the center grasping the bracket. This design works really well as it doesn't take up much space and all the arms move together, but it wouldn't be very useful grasping the square 6 in. x 6 in. bracket then grasping the 10 in. x 16 in. rectangular bracket.

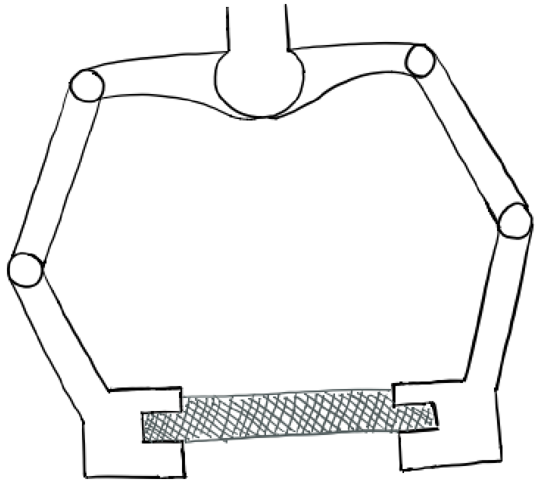


Figure 12: Claw Concept

11.2.2 5.2.2 Subsystem #2: Apply Axial Force ("Transmit M.E.")

The application of the axial force to the bracket is a hard requirement for this project. In order to facilitate the curing process of the adhesive a push force of 20lbs is required for up to 72 hours. The concepts that were proposed for this subsystem were derived from the information gathered during the benchmarking and literature review. The methods of push force applications that are considered for this subsystem include the telescoping system which is derived from the variable spring, the lead screw, and the scissor jack. These subsystem designs will be discussed in the corresponding sections below.

11.2.2.1 5.2.2.1 Design #1: Telescope

The telescoping method utilizes locking positions along concentric sections to lock in place once a desired force is applied. This subsystem is a derivation of the variable spring system that was discussed in the literature review section above. This system could be promising due to the limited size and complexity of its design. The subsystem can be referred to in figure 13 below.

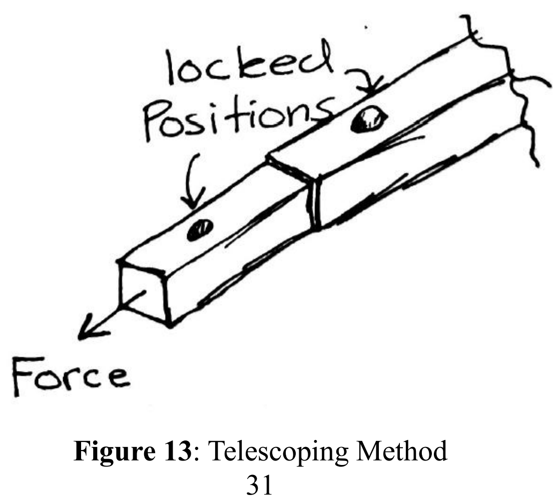


Figure 13: Telescoping Method

As seen above in figure 13, the telescoping arm locks its concentric segments into place using the spring loaded pins in line with the holes. Using a system of force measurement, the desired force could be locked in using these preset positions. The disadvantages of this system are going to be designing a system that works in this fashion as well as accounting for the added size that this would add to the overall design.

11.2.2.2 5.2.2.2 Design #2: Lead Screw

The lead screw provides a simple and easily operable mechanism of applying a push force onto the bracket. The translation of rotational motion into linear motion allows the technicians to operate this device with ease. The minimal input force allows for this device to be used by the desired two or less technicians. The self-locking features of the lead screw assure that during the push operation, there is no reverse in the direction of the force. The lead screw can be referenced to in figure 14 below.

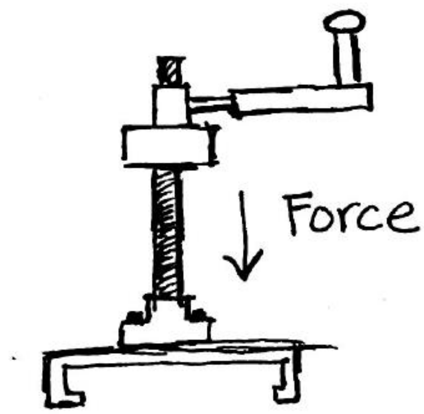


Figure 14: Lead Screw

The disadvantages of this design are going to be the size that it adds and weight that it adds onto the arm. With the existing concerns for the bending of the rocket motor rings, the added weight would add another moment that we would need to consider.

11.2.2.3 5.2.2.3 Design #3: Jack

The jack design was derived from the scissor jack which was discussed in the literature review above. The scissor jack provides a mechanical system for performing a push test of 20lb and pull test of 50lb. The advantages of the jack are that it requires minimal input force to gain the aforementioned output forces. The disadvantages of the jack are that it requires a lot of space to function as well as adds a lot of weight to the design. These disadvantages could be accounted for if we were to go further into the design of this subsystem. The jack design can be referenced to in figure 15 below.

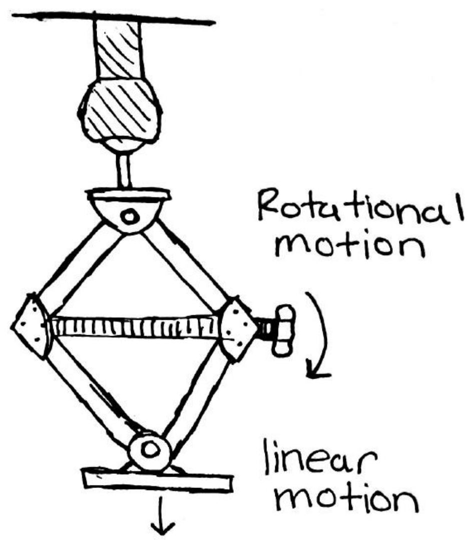


Figure 15: Scissor Jack

While the jack design provides the same functionality as the lead screw it also adds complexity and weight. This issue is important to consider when weighing these two subsystems against each other. The selection of the final design for this subsystem will be discussed in more detail in the technical selection criteria section.

11.2.3 5.2.3 Subsystem #3: Angle Bracket

The rocket motor dome has a rounded profile and thus being able to apply the standoff to it at any angle is critical to a complete curing process. In order to achieve this aspect, the device must have a method to vary the angle of attachment for the bracket. If the device only actuates straight down without being able to account for the dome profile, the standoffs would not be applied where they were intended which could affect the functionality of the rocket motor.

11.2.3.1 5.2.3.1 Design #1: Locking Ball and Socket Joint

Figure 16 below is the ball and socket joint that is being considered for the varying angle aspect of the project. This ball and socket has the ability to add a "locking lever" that will allow the joint to move freely when open, then lock at a specific angle when closed. This design provides a wide working angle for the bracket to be positioned and then locked into place. The negative aspect that could arise is the locking component adds complication to the system that could potentially fatigue or move with the 20lb push test.

Figure 16: Ball and Socket Concept

11.2.3.2 5.2.3.2 Design #2: Universal Joint
The universal ball joint design is another method to manipulate the bracket to any angle needed on the dome profile. This device utilizes two interlocked U joints with a cross section piece connecting them. This allows the U's to rotate around one another similar to the ball joint and adhere to the profile needed. Figure 17 below demonstrates the general look of the universal joint. This design adds a lot of mobility to the working angle but does not have an easy method to lock the angle in place.

Figure 17: Universal Joint Concept

11.2.3.3 5.2.3.3 Design #3: Parallel Plates
The final concept generated was a system of parallel plates connected by six hydraulic pistons. These pistons allow the top plate to move and adjust to any angle by elongating or compressing different pistons as seen in Figure 18. This device adds a lot of complexity to the entire system and would likely increase price and weight of the overall design. This parallel plate subsystem would work very well to adhere to the profile of the dome but the added complexity negates the benefits.


Figure 18: Parallel Plate Concept

11.2.4 5.2.4 Subsystem #4: Translate Bracket

Applying a translation for the bracket of the articulating arm is one of the strongest customer requirements. The design must reach 4-36" inboard from the rocket motor ring. This will be done by creating a translation design that will allow the force block to apply axial forces normal to the rocket motor dome. These concepts were initially discussed during benchmarking in section 4.2.2.4. During the benchmarking stage, three main concepts were brought up as possible methods to translating the bracket that are being used currently as existing designs. The methods of translating the bracket are a telescope, sleeve, and rail system. These designs are discussed in further detail below.

11.2.4.1 5.2.4.1 Design #1: Telescope

The telescope design as seen in figure 19 is a retracting design. A large body with a hollow interior is the base of the design, and smaller dimensioned bodies are placed inside the large base. The telescope then translates by extending these smaller bodies out from the base, which allows translation outward.

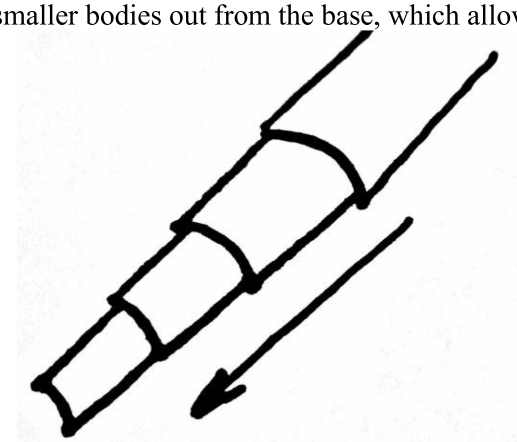


Figure 19: Telescope Translation

An advantage to the telescope design is that it is easily transportable. This allows operators to collapse the design upon itself, and less material to be used in the extension as opposed to a long bar that could be used in the rail design below. Less material however has drawbacks in functionality as a solid metal bar is less likely to break under the axial load that will be applied to this design. This design will also need to be locked with a pin or by friction, which will create a point of failure if the pin were to break under the load, or if the friction lock would work reliably.

11.2.4.2 5.2.4.2 Design #2: Sleeve

The second design is called the "sleeve". This design contains four parts: two metal plates, a screw, and a nut (and possibly two washers). The two metal plates have an oval hole to allow the screw to be placed into. The plates can adjust position, and the screw and nut would lock the position of the plates where the operator would need them. This can be seen in a top and side view in figure 20 below.

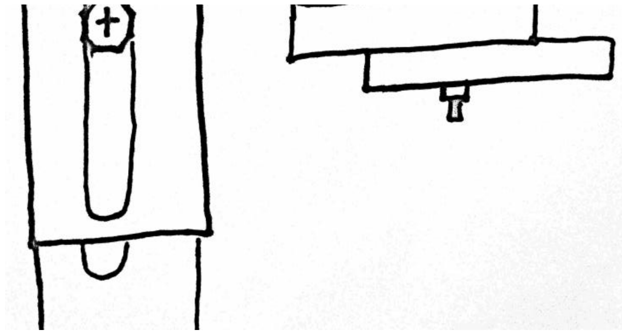


Figure 20: Sleeve Translation

The sleeve would work well with position accuracy as opposed to the telescope design above. The operator could pick exactly where the design would need to be, and lock it in place. This design however has many drawbacks. Since the design would need to be held in place while locking, the articulating arm would be in multiple pieces that the operator would need to assemble on site. This would affect transportability and ease of operation due to the fact that the sleeve would need to be held in place while locking. This would likely require two people to set up the device. The design would also have to have multiple sleeves to reach the distance required by the project, which would cause more points of failure due to the multi screw attachments. This would likely add a bow to the arm when the axial force test was applied, causing the design to push away from the standoff rather than push the standoff to the rocket motor dome.

11.2.4.3 5.2.4.3 Design #3: Rail

The rail design function is similar to a railroad. Two rails are clamped onto the rocket motor ring that moves inboard of the ring. The device that would apply a force could then move to the location required, lock onto the rails, and then lower to apply the axial load. In order to meet the six degrees of freedom design requirement, a second rail system would be added to the force block to allow the block to move in the opposite direction of the main rail system. This design can be seen clearly in figure 21 below.

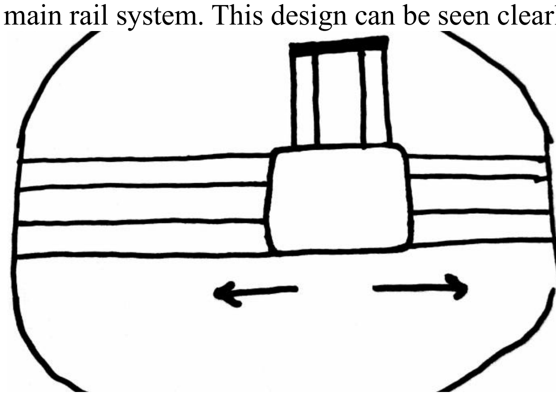


Figure 21: Rail Translation

This design allows for operators to easily move the force block to the standoff location, allowing for the easiest use for operators of the three designs discussed. The design also allows for less points of failure across the translation, since the rail is only two parts opposed to the previous designs discussed. The rail system would also be very easy to use and reliable due to two solid metal rods being extended outward of the ring; as opposed to the sleeve, which would have multiple attachments, and telescope, which would consist of multiple hollow pieces. This would allow the design to be more durable and meet the factor of safety requirements more effectively than the other two designs. Since the rail would be at a set length, unless a foldable rail design was created, the final device would be long and bulky. This would make the transportability harder than the other two designs. The device would also be more difficult to use multiple designs at a time, and would cost more to make since the metal rails would be entirely made of material similar to the rocket motor ring (Aluminum).

11.2.5 5.2.5 Subsystem #5: Locking

The locking subsystem works in conjunction with the requirements to translate and angle the bracket, as it allows for the positions set by these subsystems to be maintained. Locking mechanisms not only make the device as a whole easier to handle, but allow for axial forces to be applied without sacrificing the accuracy of the position. Below are three potential subsystems which were considered for the final design. Unlike other subfunctions, locking of components occurs at multiple points in the handling arm, which means that these subsystem designs may be used in conjunction with one another.

11.2.5.1 5.2.5.1 Design #1: Threaded Joint

The threaded joint allows the user to change the angle of approach relative to the surface of the rocket motor dome. The design has an arm on either side, which can be rotated relative to one another. When the nut and bolt at the center of the joint is tightened, the load creates a frictional force between the two and which locks the angular position. The threaded joint can be seen in figure 22 below.

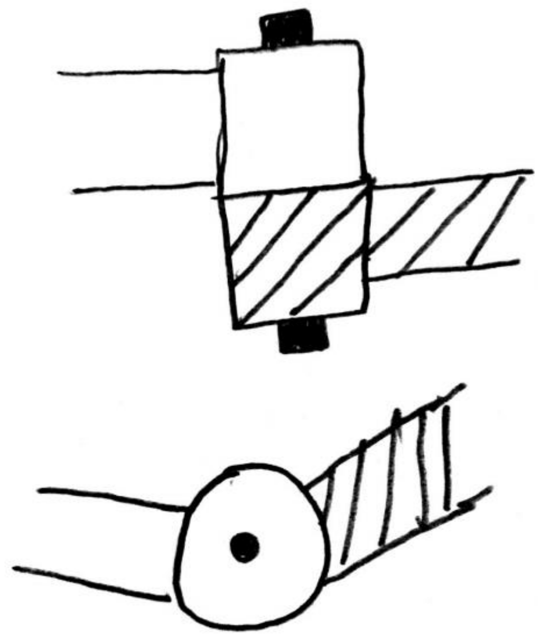


Figure 22: Threaded Joint

The threaded joint provides a rigid solution for angling the bracket, creating a strong joint with low complexity. There are downsides to this design, however, including the need for a tool to provide enough load for the joint to remain rigid during the pull test. This type of joint also only allows for the angle to change in one direction, which means that multiple may be needed to accurately position the bracket for installation.

11.2.5.2 5.2.5.2 Design #2: Self-Locking Screw

The self-locking screw provides a method of linear positioning for the bracket. With this method, a user would provide a torque at the end of the screw, which would then be translated into the motion of the bracket towards the rocket motor dome. A depiction of the self-locking screw can be seen in figure 23 below.

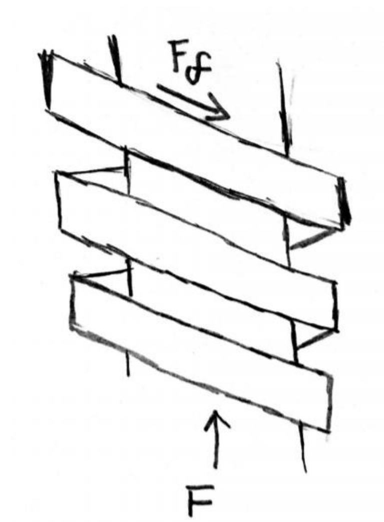


Figure 23: Self-Locking Screw

The self-locking screw is a convenient method of fixing the final position of the bracket, as a correctly designed screw will not move without an input from the user of the device. If a large handle is fixed to the end of the power screw, little force is required to apply a necessary load at the bracket, which adds an element of convenience for handling the device. A drawback to the lead screw is the time that must be taken to cover a significant distance. Tre translation of the bracket for each turn of the locking screw is relatively low, which means that moving the bracket a significant distance with this method may not be as quick as desired. Another disadvantage of the power screw is the rotational motion, which could change the orientation of the bracket as it extends toward the motor dome. Another part would be needed to eliminate this rotation, which would increase the weight and complexity of the design.

11.2.5.3 5.2.5.3 Design #3: Spring Lock

The purpose of the spring lock is to set the position of a force block on a sliding rail. This design could be useful to set the location on the rails without having discrete stopping points, which improves the accuracy when positioning the bracket. The spring lock design can be seen in figure 24 below.

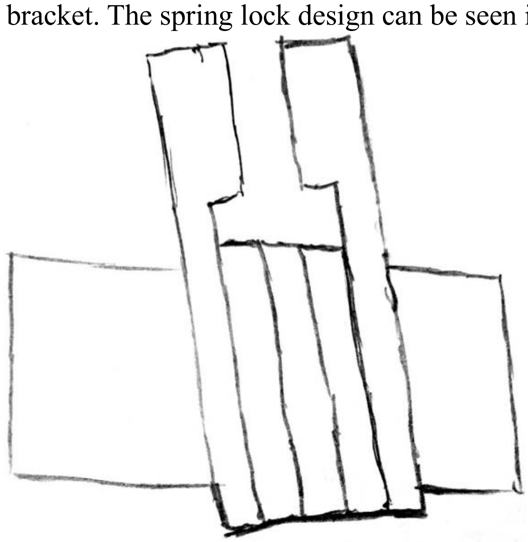


Figure 24: Spring Lock

The spring lock design operates similarly to the springs used in a gym to keep weights on a bar. This design would make setting the force block location simple, but would certainly have drawbacks. The handles for clamps like these are generally large, to provide leverage for the user and a large friction force on the rail. These handles could prove to be cumbersome in an already busy section of the design, and could provide inadequate leverage if downsized. The fatigue on the spring over time could also be an issue, and would potentially render the clamps useless.

11.2.6 5.2.6 Subsystem #6: Mount to Ring

The subsystem “mount to ring” is related to the “position bracket” sub-function in the functional decomposition model. Mounting the device to the ring is a crucial component for the overall functionality of the device. Without a strong and secure clamping system, the structural integrity of the entire device would falter. In addition to ensuring that the device is secure, it must also be adjustable to different sized rings and curvatures without deforming the ring.

11.2.6.1 5.2.6.1 Design #1: C-Clamp

The implementation of a c-clamp, shown in figure 25, as the means to secure the product to the rings would likely require the use of multiple clamps attached to the arms. Rather than directly attaching the arm to the c-clamps, the clamps would most likely be attached to a base similar to the 6 DOF arm or the dual arm shown in the benchmarking section. This method would provide ease of operation and the ability to adjust the positions between the two clamps depending on the size and flexibility of the base of the device. Although this design provides flexibility, it is restrained by its inability to conform to the various curvatures which would be a problem when attempting to mount the device to different sized rings.

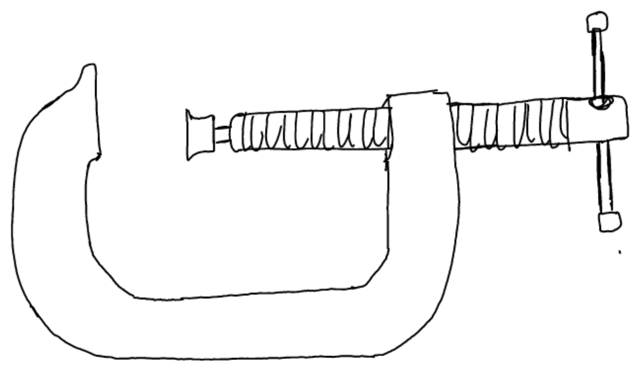


Figure 25: C-Clamp

11.2.6.2 5.2.6.2 Design #2: Hose Clamp

The hose clamp is a viable solution that provides flexibility around the entire ring while also providing security. Rather than closing the entire loop, the team can take the hose clamp mechanism and alter it so it can conform to the curvature of the ring. To achieve this design, the clamp would be cut and would be threaded to allow the ring to adjust in curvature. The design shown in figure 26, can be designed to universally fit the various sized rings or be an interchangeable part of the device. It meets the adjustability requirement but may not be as secure as other designs. Another design aspect to consider and can also be considered a con, is how the hose clamp will be attached to the arms. The hose clamp at its current state is best suited to secure fittings and would require design modifications to meet the clamping requirements of the project.

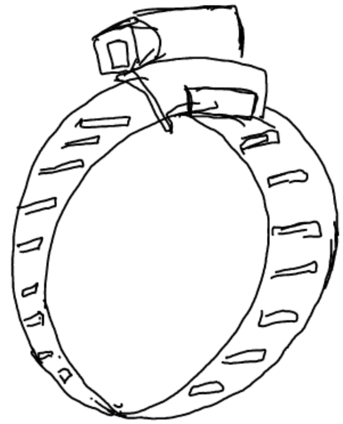


Figure 26: Hose Clamp

11.2.6.3 5.2.6.3 Design #3: Spring Clamp

The use of a spring clamp as a means to mount the device to the outer rings would provide ample clamping force without deforming the ring's material. Figure 27, as shown below, is a representation of a common spring clamp with paddings where the object will be clamped. When considering the use of a spring clamp, it is important to note that the team would not necessarily use this classic design and would utilize the clamp mechanism. This design, when modified to be adjustable to the ring motor, would provide security of the device and maintain the ring's current state proving that it would be one of the more safe and realistic options.

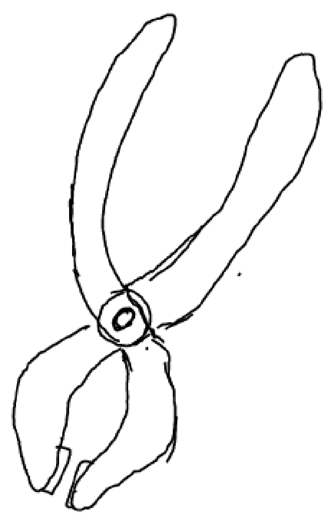


Figure 27: Spring Clamp

12 6 DESIGN SELECTED – First Semester

Given the complexities involved with both the engineering requirements and goals of this project, many considerations had to be made to ensure that the overall function was as expected when implementing this design. This chapter contains the considerations made in the design process, including the final choices that the team proceeded with in manufacturing. Also described is the plan for the physical construction of the device, including processes and material choices. The entire CAD model is shown as well, which serves to provide a visual of the design as a whole and communicate design intent.

12.1 *6.1 Design Description – First Semester*

The nature of this design project calls for a design that can move and lock in all degrees of freedom, while maintaining a rigid platform for the transmission of a load. This set of requirements created a modular design process in which certain design decisions could be made independently of one another. The final choices that were made for each of the primary subfunctions are discussed in the subsections below, working from the rocket motor inward.

12.1.1 6.1.1 Motor Ring Clamp

The clamping system for the rocket motor ring involves attaching the entire design to a thin piece of aluminum surrounding the circumference of the motor , which will then be used as an anchoring point during operation. This has the potential to create a large moment about the motor ring when the pull test is performed with a long lever arm, which must not damage the aluminum ring.

In order to provide a simple method for engagement of the clamp, the team opted to utilize an aluminum rail with a single attached screw system. This decision allows for a large amount of force to be applied across a section of the ring, while positioning the movable components outside of the motor itself where they can be easily accessed. A simplified version of this system is shown in figure 28 below, which is subject to change based on the machinability of the components.

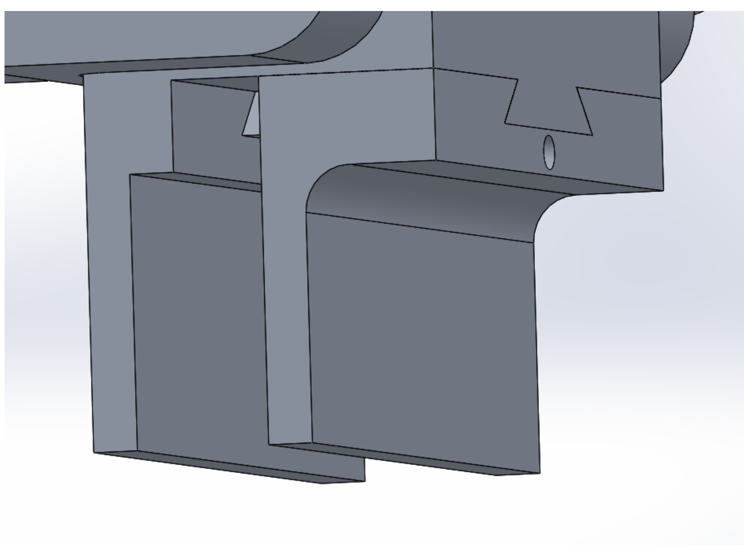


Figure 28: Clamping Mechanism for Attachment to Motor Rings

This design was derived from the large clamping force that may be exerted by a standard vice with little relative input from the user. This is to ensure that the device will not slip from the ring during operation, as such a failure could cause damage to nearby componentry. The width of the clamp was decided with a Solidworks FEA analysis using the large load from the pull test combined with the maximum lever arm;

creating the worst case scenario. The resulting factor of safety for the ring in the most vulnerable location was 3.3 with a clamp contact width of 8 inches, which exceeded the 3.0 necessary for the design. The resulting stress distribution is shown in figure 29 below.

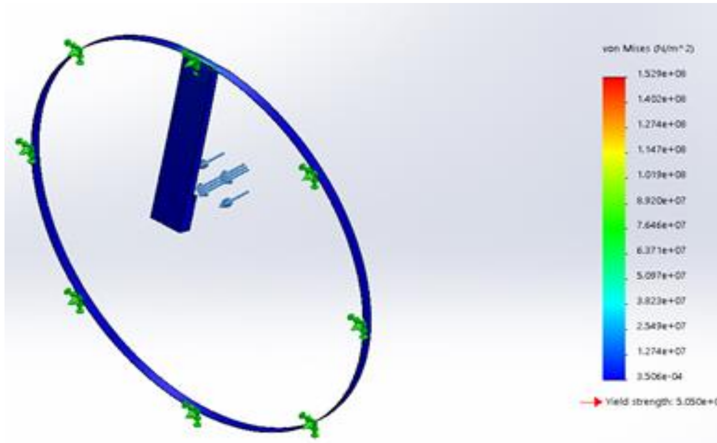


Figure 29: FEA Analysis of Moment Arm on Motor Ring

The only location on the ring which experiences significant stress is near to the fixed edge in the FEA simulation, which is partly due to the unrealistic nature of a fully fixed surface. This would be far less in practice, given that the material that the ring attaches to would be allowed to elastically deform slightly. Combined with the positioning of this test at the worst case scenario, the team felt confident in allocating an 8 inch clamp width for the ring attachment.

Because the rotor motor rings have fairly minimal principle dimensions, and given the potential for a large moment about them, it was desirable for the team to maximize the distribution of load across as much of the surface as possible. For this to happen, individual clamp jaws must be utilized for each of the two ring geometries that this device is to be used with. A potential jaw for the Orion 50 motor ring is shown in figure 30 below.

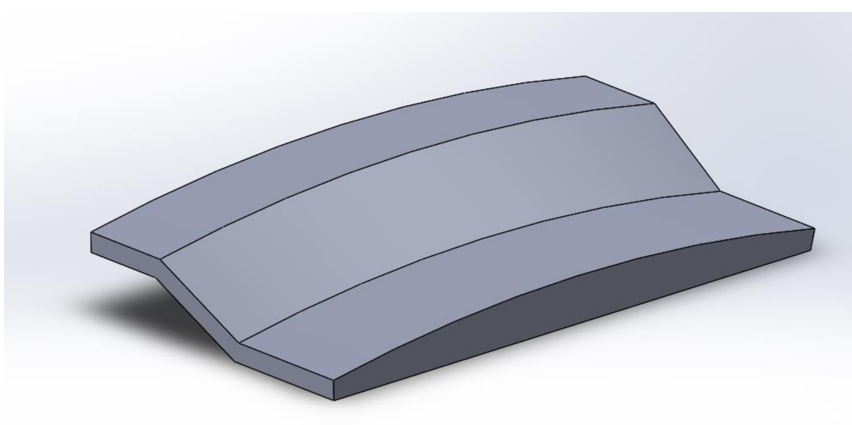


Figure 30: Custom Clamp Jaw for Orion 50 Motor Rings

This clamp jaw was designed to conform to the precise geometry of the Orion 50 motor ring, which allows for a more even stress distribution as well as an increase in clamp area for frictional purposes. While it would not propose an issue for the team, it should be noted that a CNC machine will be required for the manufacturing of these custom clamp jaws.

12.1.2 6.1.2 Spline Shaft for Rail Angle

As shown in figure 31, the Castor 30 series of motors features a dome which protrudes beyond the mounting ring. This variance will require the ability to angle the device above the raised surface, allowing for installation at any point on the dome.

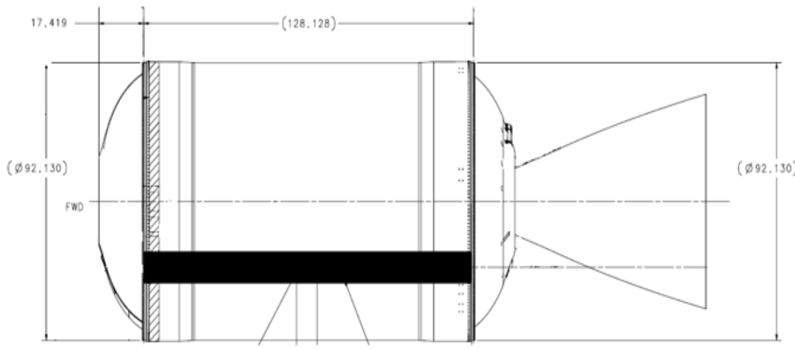


Figure 31: Castor 30 Engineering Drawing

The solution for this angle change needed to be both easily manipulable by hand and provide the necessary strength to withstand a large moment. The team decided to use a spline shaft to accomplish this goal, which would accommodate the change in angle with a set of teeth on both halves of the rotational system. The integration of the spline shaft into the design can be seen in figure 32 below.

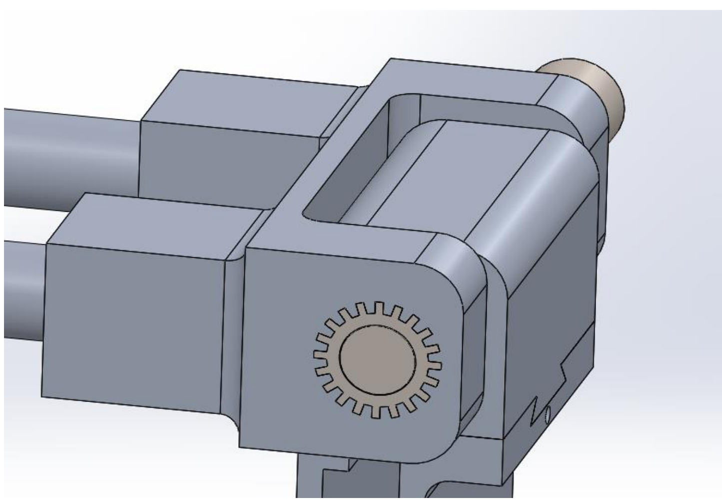


Figure 32: Spline Shaft used to Adjust Rail Angle

Unless complicated tool paths are used to create a spline shaft with a CNC machine, these components will likely be outsourced for production. The depiction in figure 32 will adjust based on the components purchased, but would optimally contain as many teeth as possible for positioning of the rail system near to the dome surface.

This system is to be accompanied by an alignment feature that will keep the two components together while the angle of the rails is changed. Two options are present to ensure that this can be done, with the final decision depending on what spline shafts and hubs are available from suppliers. One option is to remove the splines from portions of the shaft, allowing for the shaft to be translated for tooth disengagement while the inner diameter keeps the rail and clamp systems together. Another option involves sleeving centralized hubs into the outer portion of the clamp, which would maintain the location of the components when the shaft was removed.

12.1.3 6.1.3 Rail System

The need to translate the standoff brackets to various distances inward from the rocket motor ring required a subsystem that was either extendable or could otherwise position the bracket. Due to low weight and simplicity, as well as the ability to position at any point inward from the ring, a rail system was chosen to serve this purpose. The rail set width was set to distribute the load evenly across the ring clamp while maintaining a small form factor with high maneuverability. The width also allowed for sufficient area to mount the central components, such as the lead screw and nut, between them. A depiction of the rails extending from the ring clamp is shown in figure 33 below.

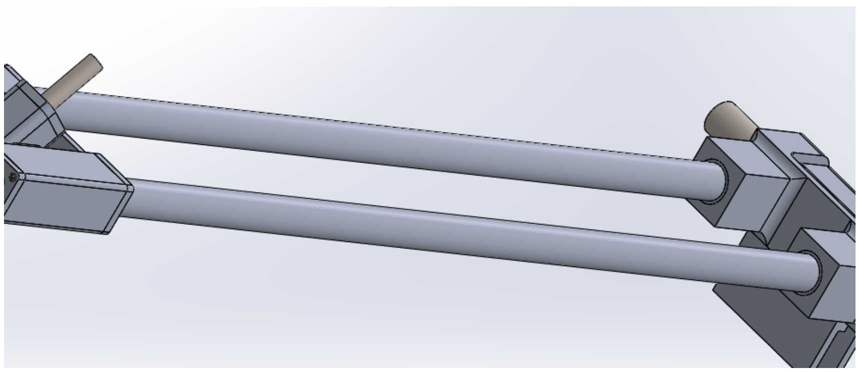


Figure 33: Rail System

As with the ring clamp system, the diameter of the rails was determined based upon the deflection and factor of safety in the worst case scenario for the device. With a 36 inch rail length, the maximum deflection from a 50 pound load can be found using equation (1), where I is the moment of inertia for the rail cross section. To minimize the deflection while maintaining a high factor of safety, low weight and high corrosion resistance, 7075 aluminum was chosen for this application.

$$\delta = \frac{PL^3}{3EI} \qquad [1]$$

Considering an elastic modulus of 10400ksi and an even distribution of the load between the rails, the maximum expected deflection is 0.83 inches with a rail diameter of 0.98 inches. This diameter was chosen to accommodate drilling a 1 inch hole in the cart, while the rail would be made on a lathe and could facilitate a sliding fit [4]. While more calculations will be made in the analytical reports to ensure that this material and geometrical choice was optimal, early FEA provides a factor of safety much larger than the minimum requirement for this project.

12.1.4 6.1.4 Rail Cart and Lead Screw

With the rail system already chosen, the design decisions for the cart revolved around maintaining the required feature set and strength while minimizing weight. As the stresses on this material were lower due to the axial, non-moment-inducing loads, cheaper 6061 aluminum with high machinability, low weight and the same corrosion resistance was selected. This system is shown in figure 34 below, and was set up to allow for the angling of standoff brackets normal to the rocket motor dome. This was implemented to ensure that the force was evenly distributed across the standoffs and that the pull test could be performed at the specified 45 degrees.

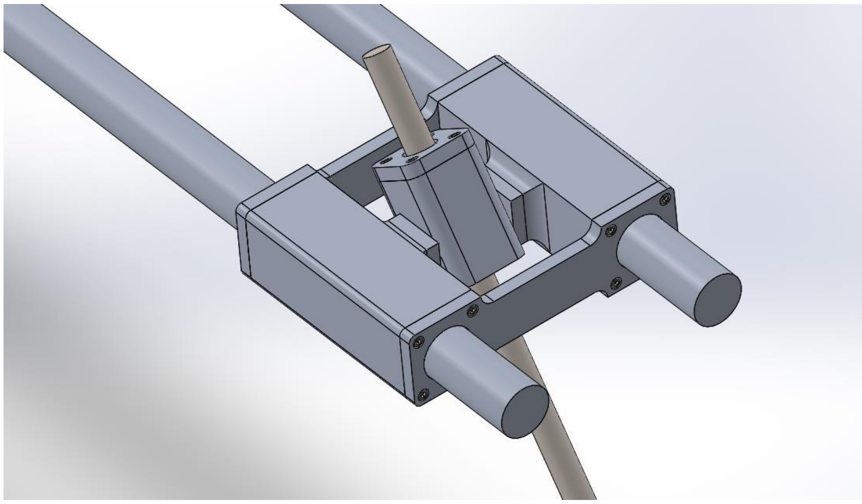


Figure 34: Rail Cart and Angleable Lead Screw

The rail cart itself is braced by plates at the front and rear, which maintains subsystem rigidity when a load is applied through the lead screw. The changes in angle are facilitated through cylindrical rods, which are part of the centerpiece and insert into the sections which lie directly on the rails.

The total weight of the aluminum cart pieces is less than 3 pounds, while the use of a plastic lead screw nut also serves to decrease weight. The total weight of the stainless steel lead screw, which was chosen for corrosion resistance properties, will depend on the length needed for the application. However, less than 1 pound for this component is expected when considering the given rocket motor geometries. More calculations will be performed in a future analytical report to verify the dimensions and locking ability of the lead screw. The addition of a knurled nut at the top of the screw will facilitate extension and force application to occur during the use of the device.

The component strength is far beyond what is required to withstand the load from the 50 pound pull test, but still manages to provide a low total weight that can be easily manipulated by hand. The dimensions of the cart were set to distribute load at the base of the rails, but the maximum principle dimension of 5 inches ensures that it will not be cumbersome in use.

12.1.5 6.1.5 Measuring the Applied Force

The given tolerances of ±2 pounds allow for the force to be measured with low resolution instrumentation. An issue faced by the team, however, is that the force gauge must be integrated into the design and must therefore align axially with the lead screw. The proposed solution to this issue placed a spring usable for extension and compression between the lead screw and standoff bracket. This would allow for the change in length of the spring to be observed and reported as a force, assuming that an accurate spring constant could be determined. The current housing design for this gauge can be seen in figure 35 below.

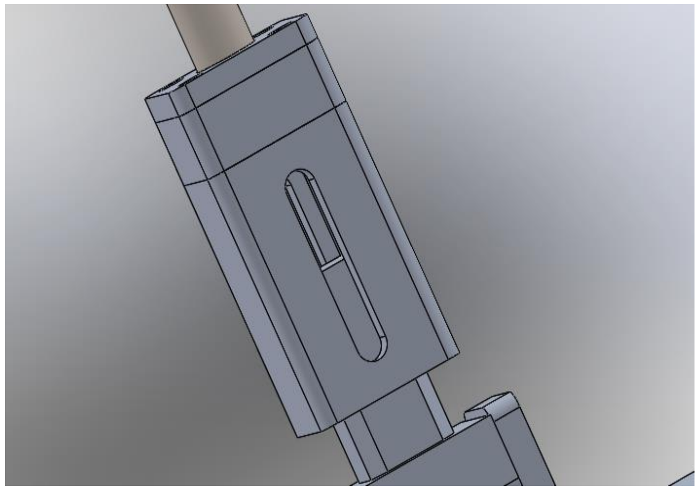


Figure 35: Force Gauge Spring Housing

The optimal spring constant for this device will be determined during testing, which will then allow for marks to be made on the housing with the desired loads applied. This method allows for a lightweight piece of custom instrumentation with the desired accuracy that, aside from the spring itself, can be machined in-house.

12.1.6 6.1.6 Setting the Cure and Pull Test Angles

For this device to operate as intended, the application of a force normal to the surface must be made to cure the adhesive at the base of the standoffs. After this is completed, the angle relative to the bracket must be set to 45 degrees to proceed with the pull test. A joint with pin holes drilled at the necessary locations for these settings is to be positioned at the end of the lead screw assembly. This joint can be seen in figure 36 below.

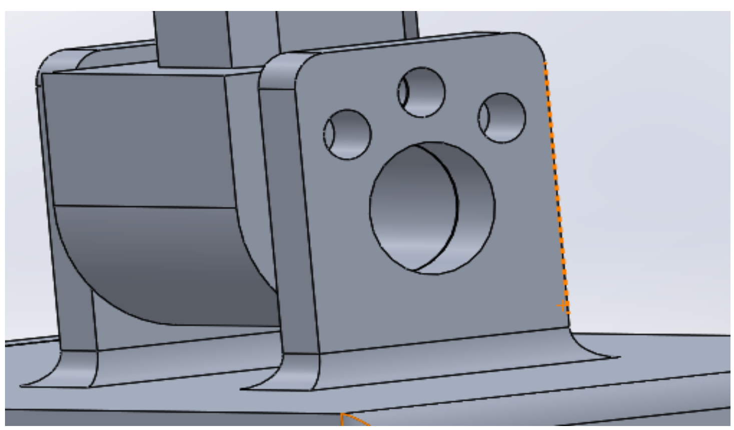


Figure 36: Joint for Setting Angle Relative to the Dome

The larger hole shown in this design carries the bulk of the load created by the lead screw, ensuring that the junction remains rigid. The smaller holes will house a pin that will set the angle of the applied force relative to the surface. This pin is small relative to the center pin, as it is only used to verify that the testing is performed at the correct angle.

12.1.7 6.1.7 Retaining the Bracket

Standoff brackets of varying sizes will be used in conjunction with this device, which will require a subsystem that can accomodate all of them and transmit the load to the surface of the motor dome. The current design for this subsystem is shown in figure 37 below.

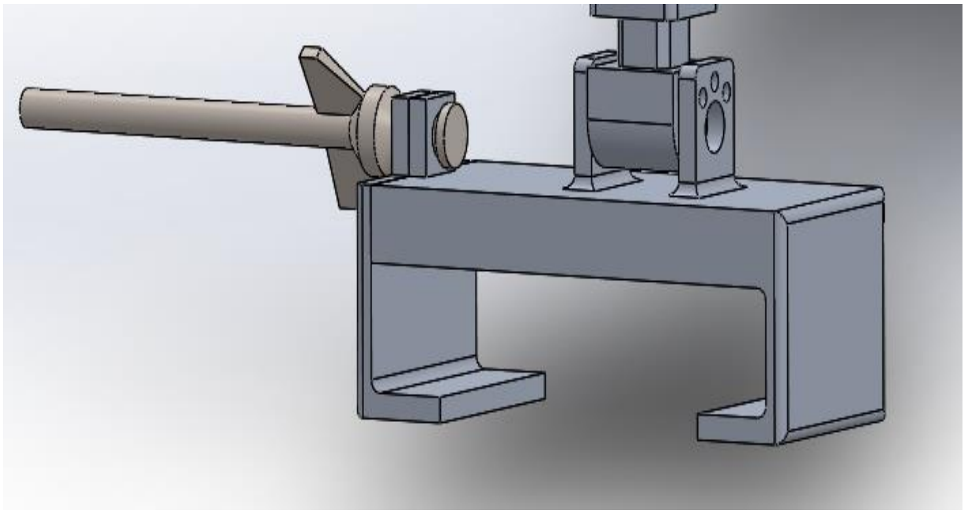


Figure 37: Bracket Retention Subsystem

This design utilizes a rail, similar to those seen in the tool holder of a lathe, to slide two halves of the clamp relative to one another and change the system size. A simple wing nut and stud combination will make using the clamp easy for any operator while ensuring that a force can be applied to keep the standoff bracket in place.

12.1.8 6.1.8 Initial Prototype

Prototyping for this design allowed for physical interaction with the geometry of the design, using different materials of course. The majority was 3D printed, while PVC piping was used to simulate the rail system. This initial design iteration can be seen in figure 38 below.

Figure 38: Initial Prototype

From interacting with the prototype, the team was able to verify that the bulk of the final design could be easily manipulated by hand, although certain components were not present. While the coefficient of friction for these materials differs from the final materials, this prototype still provided an idea of what the sliding fit on the rails will feel like when in use. The design behind the spline shaft was greatly simplified for this prototype, but still was able to show the team that a looser fit would allow for better manipulation of the rail angle, which will be a factor if this component is machined in-house. Based on the feel of this design, an end cap may also be added to the end of the rails for better parallel alignment.

12.2 *6.2 Implementation Plan – First Semester*

The following section of the report details the processes that will be performed in the future to convert this conceptual design into a physical product. This includes how the components will be manufactured or procured, the materials and other resources that will be required, as well as a general schedule of future events and depictions of the final assembly.

12.2.1 6.2.1 Component Machining and Procurement

In order to maximize the learning potential of this project for all members of the team while also positively impacting the budget, as many components as possible will be machined in the NAU machine shop. This will of course increase the required workload during the manufacturing phase, but will undoubtedly benefit all involved in this project.

While the entire team has completed or will soon complete mill and lathe training, some of the more complex parts of this design will require the use of CNC machining. If at all possible, the entire team plans on receiving this training as well so that all aluminum components may be machined without outsourcing. Some parts, however, such as the lead screw, spline shaft, nuts for both of these and all other screws, will be purchased from a vendor due to the complex geometries presented.

12.2.2 6.2.2 Expected Materials Overview

The majority of the material used in this design is 6061 aluminum, with 7075 aluminum also included for the construction of the rails. All of this will be purchased as a large piece of aluminum stock, which will then be segmented for the machining of the individual components. This will save the team a significant amount of money while also providing valuable machining experience and the ability to alter finished parts if needed.

The finalized budget for the project can be seen in Appendix C. Many of the materials purchased in Appendix C's table were manufactured by the team using raw aluminum blocks. This plays a large part in why the budget used by the design team was far less than what was given by Nothrop Grumman. The overall bill of materials can be seen in Appendix D.

12.2.3 6.2.3 Schedule

The schedule of remaining deliverables for this design project is shown in figure 39 below, with due dates to the right and personal goals for finalizations to the left.

Fall Semester				
Final Report	Everyone	0%	11/6/19	11/15/19
Final BOM/CAD Package	Sage, Dakota	0%	10/14/19	11/20/19
PDR Presentation	Everyone	0%	10/28/19	11/18/19
Individual Analytical Report	Everyone	0%	10/14/19	11/28/19
Final Prototype	Everyone	0%	11/20/19	12/4/19
Website Check 2	Tyler, Brandon, Elaine	0%	11/6/19	12/9/19
Spring Semester				
Post Mortem	Everyone	0%	1/6/20	1/15/20
Self-Learning	Everyone	0%	1/6/20	1/24/20
Hardware Review	Everyone	0%	1/15/20	2/14/20
Website Check 3	Tyler, Brandon, Elaine	0%	2/1/20	2/21/20
Midpoint Presentation	Everyone	0%	2/17/20	3/4/20
Midpoint Report	Everyone	0%	2/17/20	3/6/20
Individual Analysis II	Everyone	0%	2/1/20	3/13/20
Final Product Finished & Device Summary	Everyone	0%	1/15/20	3/25/20
Drafts of Posters	Everyone	0%	3/1/20	4/1/20
Testing Proof	Everyone	0%	3/25/20	4/8/20
Final Poster and Operation Manual	Everyone	0%	4/1/20	4/15/20
Final Presentation (UGRADS)	Everyone	0%	4/1/20	4/24/20
Final Report and CAD Package	Everyone	0%	4/6/20	4/29/20
Website Check 4	Tyler, Brandon, Elaine	0%	4/29/20	5/4/20

Figure 39: Schedule

This schedule is tentative, and will be updated with changes as time progresses. Some events, such as days to be spent machining, will be added during the spring when this is sorted out more accurately.

12.2.4 6.3 Final CAD Assembly

Shown in figure 40 below is the CAD representation of the final design that is being proposed by the team. All subfunctions of this design have been covered at earlier points in the report, but the final model serves both as a visual aide and to communicate design intent as a whole.

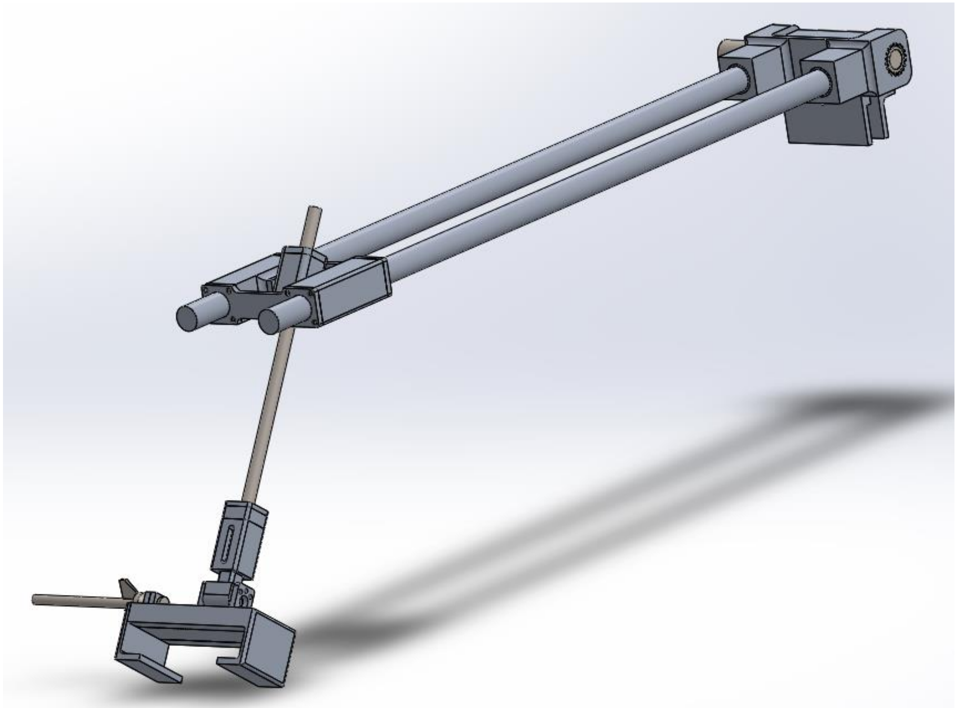


Figure 40: CAD Assembly

To provide a sense for the assembly process, as well as to clarify how the components come together as a whole, an exploded view of the design can be seen in figure 41 below. The cart portion of the design is greatly clarified by this exploded view, as many different components merge to create this subsystem.

Figure 41: Exploded View

The complexity of this design is more easily communicated through the exploded view, as many components must be put together to successfully meet all of the customer requirements. Machining all of these components will require a lot of planning and preparation from the team, but will also provide a very rewarding experience.

13 **7 IMPLEMENTATION – Second Semester**

This section will go into detail on the steps taken to ensure that the device meets the engineering requirements and what types of manufacturing was implemented to complete the final product. The types of manufacturing methods used to create the final product include the CNC mill, vertical mill, and lathes located in the NAU Machine Shop. Design changes made to the device to ensure the functionality of the device have been justified through calculations and inspection.

13.1 ***7.1 Manufacturing***

This section will focus on the manufacturing implemented for the production of the final product. This will include the machines utilized to fabricate the sub-assemblies as well as the methodologies utilized to ensure the quality of those parts. As of now the team has strictly machined on the vertical mills and lathes that are located in the 98C machine shop. After the preliminary design presentation at the Northrop Grumman headquarters, the senior engineers that work there informed the team that the assembly of the design should minimize the usage of the CNC parts to reduce cost and complexity of the design.

The majority of the design has been machined on the vertical mills as the product was created in Solidworks with simplicity in mind. The design minimizes curved edges as they are almost impossible to create on a vertical mill and would need to be placed in a CNC to accurately mill out of raw material. Straight edges, square bodies, and tight tolerances ensure that the fitments of all the pieces are accurate and move together as the team intended. The current rail cart is composed of a milled C-channel with a flat plate completing the rectangular cart. Tight and accurate tolerances in the parts resulted in a very nice fit to the teams selected rectangular rails that translate the cart across the motor dome. The mill has also helped the team drill counterbores, counter sinks, and cut threads where needed.

The other major machining done on the device has been on the machine shop lathes. The team has constructed the large threaded knobs, axles, and bolts that are critical components of the design on the lathe. The lathe also makes it possible to add chamfers to axles to allow them to fit into slots easier and ensure proper fitments. The other large piece of machinery in the machine shop that hasn't been implemented yet is the CNC mill. This is a computer controlled mill that takes an inputted code and cuts accurate complex shapes into the stock material.

Moving forward with the project, the team will continue to use both the vertical mill and the lathe to machine the majority of the final product. More straight edges and square bodies will be machined as well as pins and thumb screws for the design. However, the CNC will be required as precise curves will need to be cut for the pieces that clamp to the motor ring. The motors that are used by Northrop Grumman have various diameters and the clamps that the team is going to use have to match the diameters exactly to ensure a proper fit and the surface area is maximized. To achieve the proper fitment, the large CNC has to be used and since only one member of the team has CNC experience on the small mills, work orders will have to be placed so the shop managers can construct the parts needed.

Before final parts were created by the team, test samples were created to test fitments between parts of various sizes. For the axles that allow the brackets to rotate, the team began with a twenty thousandths fitment and analyzed the performance. It was clear that the fit was too large and the axle wiggled more than it rotated. The second test was done with a ten thousandths fit which was noticeably better but still allowed for some rocking between the parts. Lastly, a five thousandths fit was created and tested which resulted in a near perfect fit where the axle rotated nicely with extremely minimal rocking. For the rail cart and the rail system, a first test of twenty thousandths resulted in a nearly optimal fit that the team was satisfied with. These machined test fits helped the team explore and understand what fitments to implement for the rest of the product.

In the previous report, the design team had received an engineering requirement change which resulted in a change in the overall design. Since those changes were implemented, the team has been primarily focused on machining the entirety of the design. The team started with the rail cart as seen in figure 42 below.

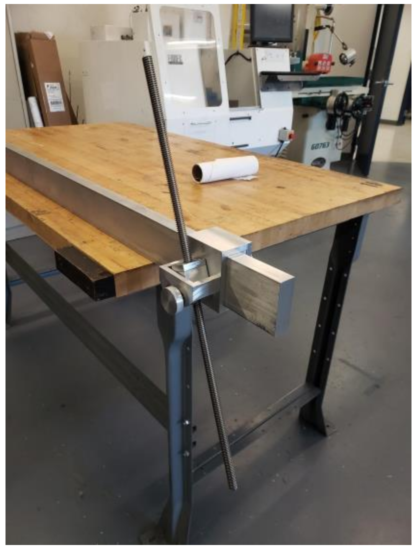


Figure 42: Manufactured Rail Cart

All of the design changes, discussed in the previous report, were implemented into the manufacturing of the rail cart system in figure 42. The only aspect of the design that is displayed in figure 41 that is not currently being used in the final product is the rectangular rail. The rail is solid in figure 41, however it is actually hollow in the final design as seen in figure 43 below.

Figure 43: Final Product

Seen in figure 43, many of the other components of the design are completed. The rail system is now a hollow tube that is 3”x1”x1/8” thick. The rail cart slides onto the rail and is able to lock in place with a pressure plate that utilizes a capped screw which was created on the lathe. Two holes are drilled into the other end of the rail to lock the rails to the angling mechanism. The components on the left side of figure 42 are now fully manufactured and can be seen as CAD parts in figure 44 below.

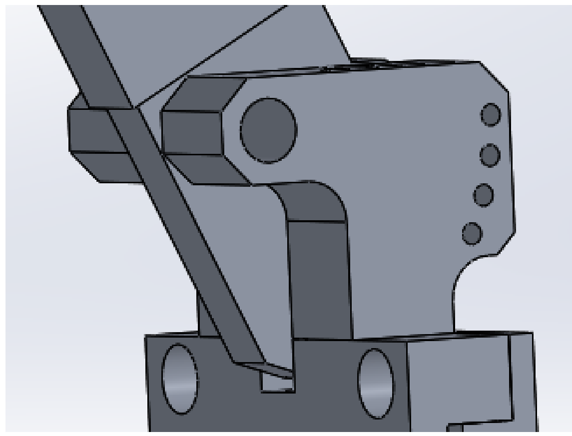


Figure 44: Angling Mechanism

The rail mount is inserted into the rail which locks the rail in place with two ¼” pins. The device is then able to angle as needed with 5 positioning holes placed 9 degrees offset from one another. Two p-pieces are then able to lock the angle with two pins that are inserted through the p-pieces and the rail mount. The ¾” hole works as the rotation axle while the smaller ¼” holes allow for the device to angle as needed and locked in place with a pin. There are four holes on the p-pieces to allow for additional angling positions for operators as needed. The p-pieces are then bolted onto the clamping mechanism that can be seen clearer in figure 45 below.

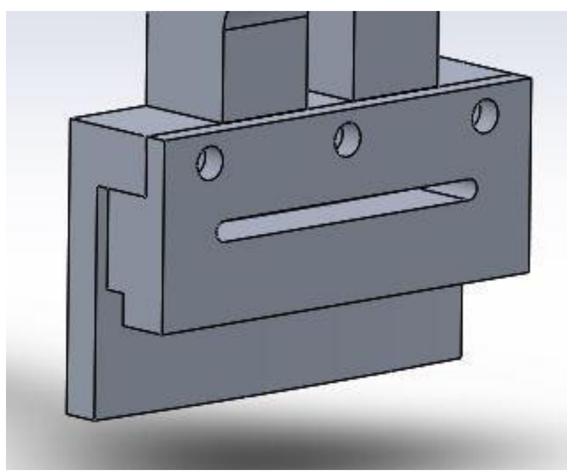


Figure 45: Clamping Mechanism

The inner and outer clamp pieces were created with a curvature that would match the 92” diameter rocket motor ring of the Castor 30XL which were created using the CNC to get accurate dimensions and proper fitment. The team also created a mock motor ring to rig the device to for testing procedures. The mock ring and clamp can be seen together in figure 46 below.

Figure 46: Mock Motor Ring and Clamp

The mock ring was also created using the CNC to allow for the correct curvature of the Castor 30XL. The holes however were created using a 3D printed hole template that fit the dimensions and curvature of the Castor 30XL. This was built as the CNC in the machine shop is a 3-axis and wouldn't be able to rotate the piece to drill the holes in the correct placements. The team then drilled holes into the mock ring as seen in figure 47.

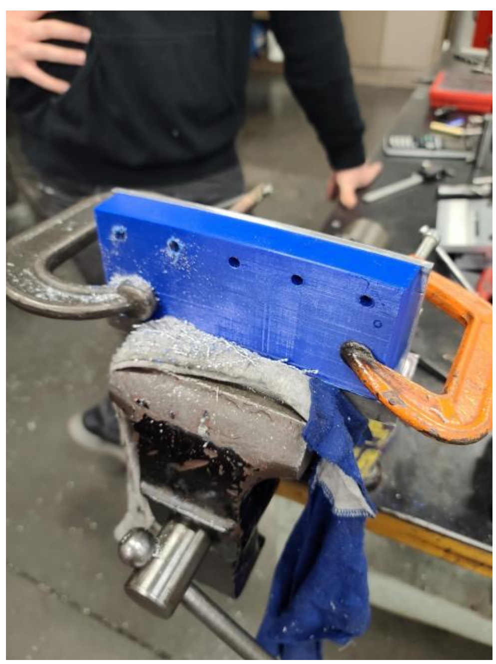


Figure 47: 3D Hole Template Set-Up

In total, the final product is 95% finished from the CAD package. Due to the unforeseen events of COVID-19, the team is unable to perform any further manufacturing in the machine shop. However, work orders for the remaining parts have been submitted and completed by the 98C manufacturing shop. Due to the limited time the team can finalize the manufacturing of the parts, there will be some actions that will not be performed by the team. The team will not manufacture any of the pull test functions of the device as this was an optional manufacturing goal set by the client, instead focusing finalizing the push test for the final device. The torque wrench which was to be purchased for performing accurate pull and push tests on the device will not be completed and will instead be discussed in the final report in detail so Northrop Grumman will understand what was planned. The team will also not apply teflon coatings on various parts to reduce friction and load distribution throughout the design. The only part that still needs to be completed for the push test is the thumb screws shown in figure 48 below.

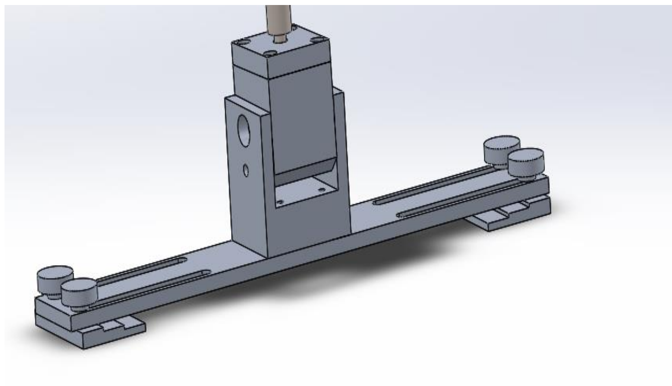


Figure 48: Bracket Clamp

The four thumb screws shown in figure 48 are not and will not be completed by the end of the semester. Instead, an alternate design solution will be discussed. This could possibly be done with parts available at home depot, or just with an explanation on the final report at the end of the semester. In total, the entire design was completed using the mill and lathe machines available in the machine shop excluding the clamping mechanism which used the CNC to create the curvature present on the rocket motor ring.

13.2 *7.2 Design Changes*

Northrop Grumman requested that the capstone team simplify their designs from the PDR presentation to minimize the complexity of the parts while machining and reduce the cost of manufacturing. Along with this, the client has added two project requirements which will be discussed in greater detail in this section. Due to the manufacturing and project requirements that have been made by the client, problems have occurred which required design changes. This section will discuss in detail each design change along with justification. Included in these changes are CAD pictures of each iteration, justification for the changes made, and calculations if necessary to back up the current state of the designs.

13.2.1 7.2.1 Design Iteration 1: Change in rocket motor clamping

Initially, the ring clamp design focused on the ability to interchange clamp jaws, which were built around the geometry of each motor ring, within a streamlined mounting system. This design can be seen in figure 49 below.

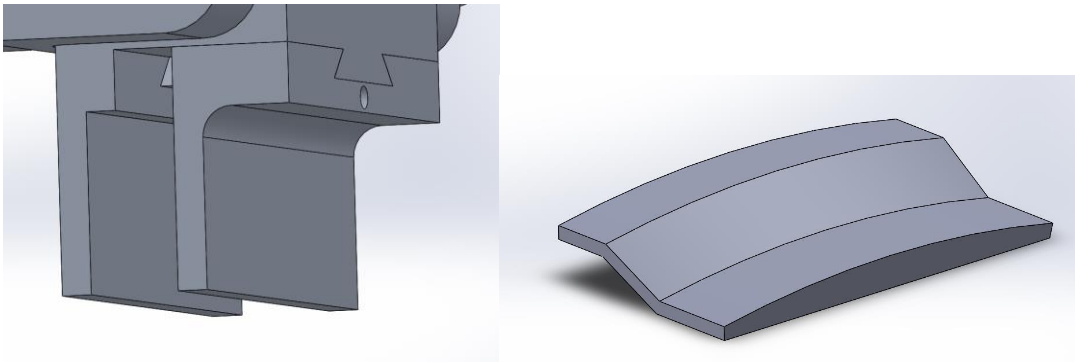


Figure 49: PDR Interchangeable Clamp Jaws

However, this design required extensive CNC machining along with complicated bolted connections and bulky clamping jaws. In order to simplify the operation of the ring clamp, the team decided to integrate the ring geometry into the clamping system itself, which reduced the total machining work while improving the usability of the design. The new design also eliminates the dovetail connection that was initially intended for the system and allows for screws to pass through the existing holes in the motor ring clamp. The slot seen in figure 50 gives the option to position the clamp at any point on the ring while also ensuring that the clamp remains secure during operation.

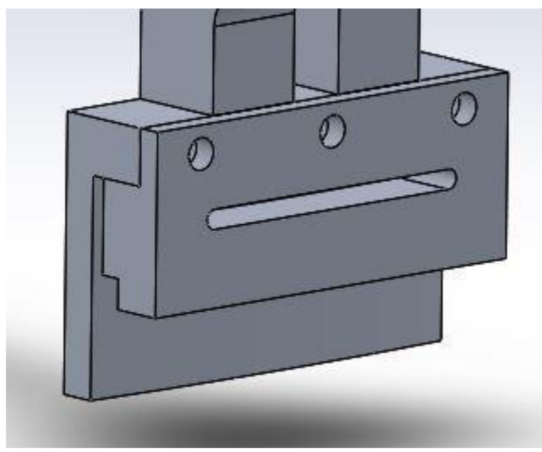


Figure 50: Current Rocket Motor Clamp Design

In order to verify that the clamping design will not cause damage to the rocket motor ring, an FEA was performed to determine the stresses and deflections of the ring when loaded. The FEA seen in Appendix E determines that the factor of safety for this design was 42 which is significantly higher than the 3.0 minimum specified in the project requirements. This analysis included the positioning of the holes located around the rocket motor ring and not just a solid round ring as the holes might be points of failure and stress concentrations.

13.2.2 7.2.2 Design Iteration 2: Change in angling mechanism discussion

The mounting arm must be able to attach to several different rocket motors: Orion 38, Orion 50XL, and Castor 30XL. Due to the curvature of the Castor series rocket motor domes, as seen in figure 51, the device requires an angling mechanism to clear the protrusion of the rocket motor dome.

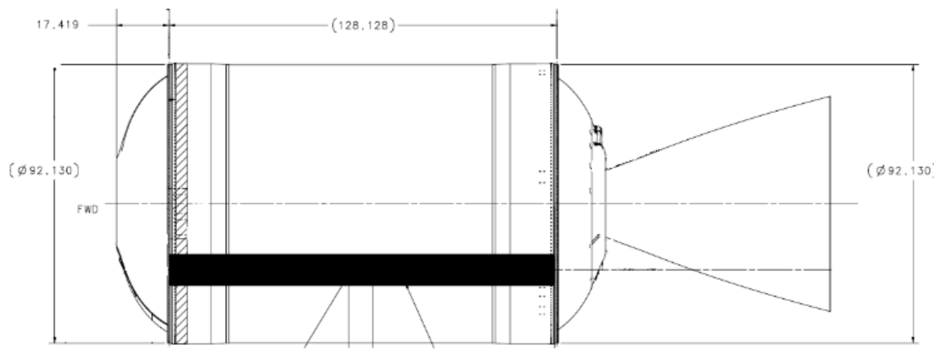


Figure 51: Castor 30 Series Drawing

Originally, the capstone team designed a spring loaded spline shaft mechanism that would allow the hinge section to adjust to multiple angles to conform to the rocket dome profiles. When the splined portion was pulled out, the two hinges would rest on an axle with the outside diameter of the splined shaft to retain hinge alignment. This design can be seen in figure 52 below.

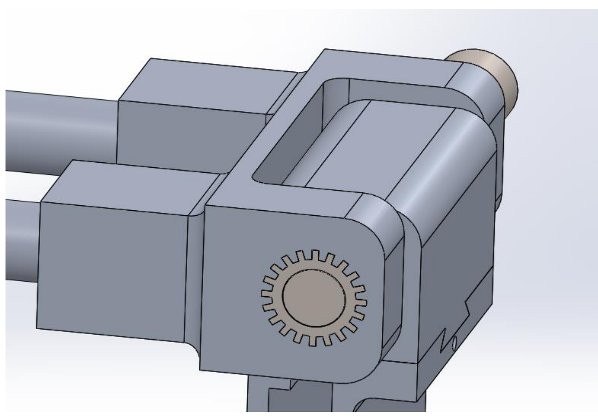


Figure 52: PDR Spline Shaft Mechanism

After presenting the PDR design to Northrop Grumman, one of the main issues they had with the overall design was that the device was complicated to manufacture and should be simplified. Since the spline shaft seen in figure 51 was likely to be outsourced due to the complicated geometry of the design, the team redesigned the angling mechanism and created the current design seen in figure 53.

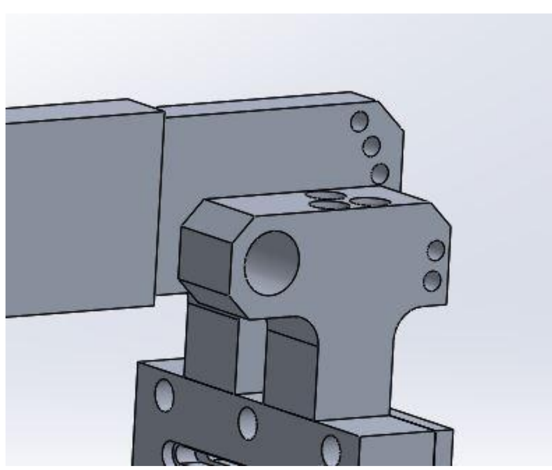


Figure 53: Current Set Pin Angle Mechanism

The current angle mechanism works with six pin slots, located 9 degrees apart from each other that allow the device to increase or decrease its operating angle appropriately. A large pin will serve as the rotating axle that will go through all three of the hinge pieces. The side hinge pieces are attached to the rail system with a set of bolts that allow the device to stay permanently attached to the rocket motor clamps. The center hinge piece, which has five angling holes drilled into the part to allow for the change in angle required of the design is also pinned to the rectangular rail. These quick detach pins will allow the technician to put different length rails onto the design.

This device is less complicated than the previous spine shaft design, however the design does require the use of pins which could result in shear failure. A single pin will be used to resist movement from the entire rail cart lever arm. Since one pin will be used, through a total of three plates, double shear will be imparted to the pin. With a max load of 50lbs resulting in a 360lb internal shear on the pin, a diameter of .207 inches is required for the pin to meet the desired factor of safety of 3.0. Currently the team will use a pin of 0.25 inches, which exceeds the required factor of safety. These calculations can be seen in Appendix F.

13.2.3 7.2.3 Design Iteration 3: Change in rail system discussion

In order to meet the customer requirement of positioning standoff template brackets 4 to 36 inches inboard of the rocket motor ring, the team originally designed a dual rail system, as seen in figure 54.

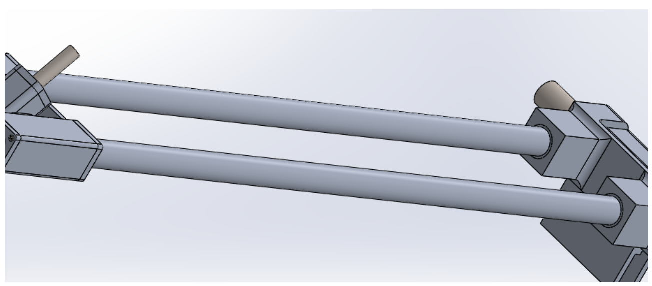


Figure 54: PDR Rail System Design

The original design consisted of two rails that were circular and hollow, with a 1.5” outside diameter and a 1” inside diameter. Instead of similarly sized solid rods, hollow tubing was selected to lower the overall weight of the design while retaining most of the moment of inertia. Cylindrical rails also allowed for the use of readily available linear bearings, which improved the sliding mechanism when repositioning standoff brackets. This design, however, was disregarded due to a change in the customer requirements for the project. As a result of the preliminary design review, the maximum deflection of the rails during operation was requested to be less than 0.1 inches. This was accompanied by a change of the maximum loading condition 50 lbs, which would have occurred during the pull test, to 120 lbs, which provided a 20 lb bonding force for each of up to six standoffs mounted to a bracket. To minimize deflection and handle the newly required maximum load, the intermediate design in figure 55 was introduced.

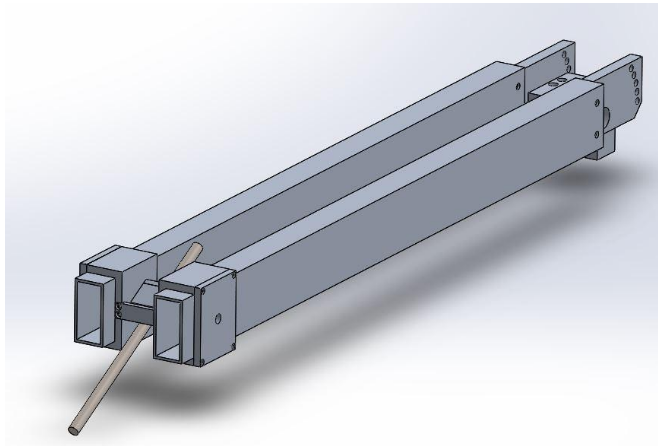


Figure 55: Intermediate Design Change

Due to a recent clarification, however, the design was altered yet again. A clarification in the bonding force, which should have been 20 lbs per entire bracket, allowed for the simplification of the design. With the maximum loading condition now consisting of the 50 lb pull test force, the heavy dual rail system could be reduced to improve operability of the design. However, the rectangular profile of the rail system was maintained to satisfy the requirement for less than 0.1 inches of deflection at the maximum load. The current design, which consists of a single, lightweight rail, is shown in figure 56 below.

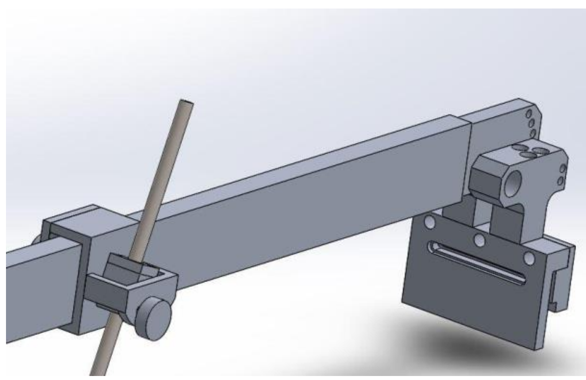


Figure 56: Current Rail System CAD

The singular rail that is to be used in the current design measures 3”x1” with a ⅛” wall thickness. In addition to decreasing the mass of the design, a single rail allows for the device to be more easily operated and reduces the setup time. This rail, in the newly defined maximum loading condition, is also expected to provide a deflection of .082”, less than the 0.1” deflection specified by the customer requirement. The calculations for these deflection values can be seen in Appendix G of this report.

13.2.4 7.2.4 Design Iteration 4: Change in rail cart discussion

Due to the rail system design created by the capstone team, a rail cart was made to allow operators to apply axial forces at set distances inboard of the rocket motor ring and to angle the force applied due to the curvature of the rocket motor domes. The original design for this rail cart can be seen in figure 57 below.

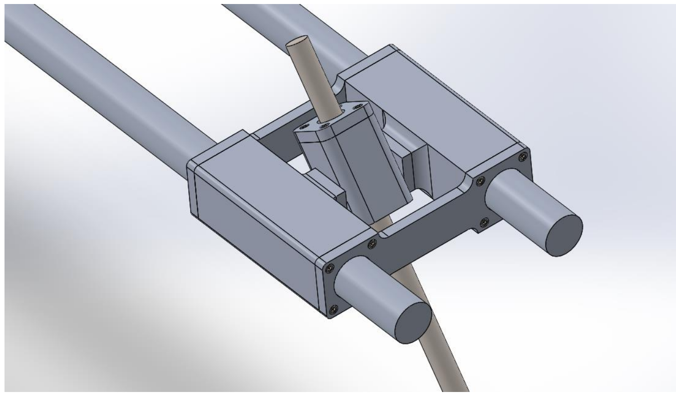


Figure 57: PDR Rail Cart Design

The disadvantages of this rail cart was primarily that the design did not allow the operators to lock the angle of the lead screw that would be applying the axial forces on the rocket motor dome. Due to this and primarily the rail changes discussed in section 1.2.3, the rail cart displayed in figure 58 was designed.

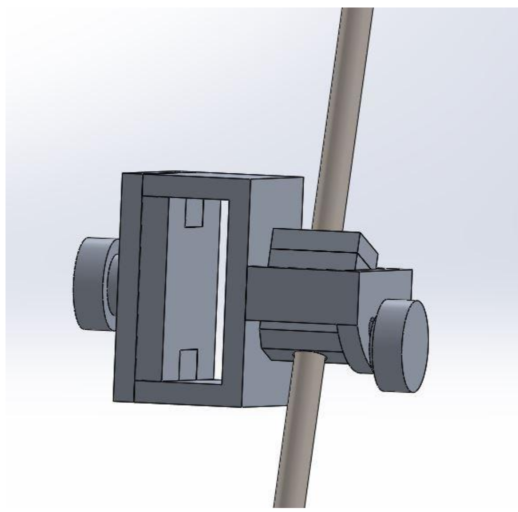


Figure 58: Current Rail System CAD

Since a singular rail is being used in the final design, the rail cart was changed accordingly. The rail cart changed to a rectangular shape to accommodate the 3"x"1 rails. The angling mechanism was moved to the side of the device to still allow operators to angle the lead screw as needed. Two primary changes were made to the rail cart system however that were not made due to the rails. Originally a set screw was going to be used to lock the rail cart so that it would not translate during operation. As seen on the left side of figure 58, a rectangular plate and screw were made to allow the device to press onto the entire side of the rail during operation. The operator would tighten the screw that would press the plate onto the rail which would allow the device to clamp onto the entire side of the rail instead of only tightening a specific spot as it did previously. The second change that was made was an angle locking mechanism seen in Figure 59 below.

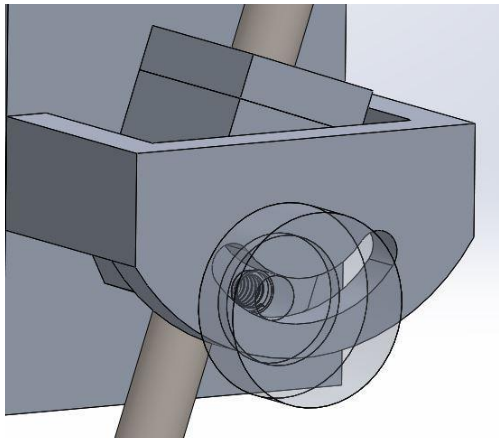


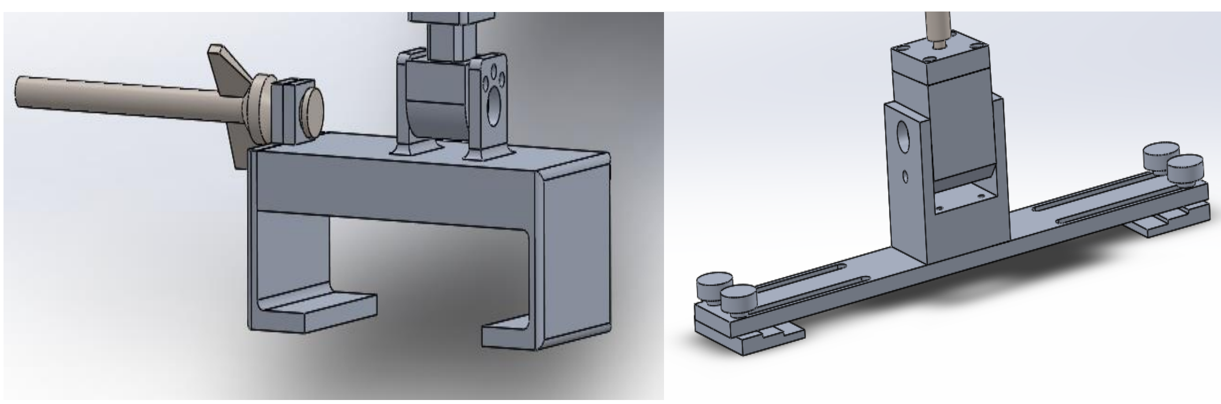
Figure 59: Angle Locking Mechanism

A capped screw was designed to allow the operators to lock the angle of the lead screw during operation. The piece that holds the lead screw housing had a slot milled by a CNC to allow for various locking locations. In the lead screw housing, a threaded hole was made where the screw would tighten into, which would lock the angle of the lead screw.

The only drawback of this design is the existence of an angle of twist that was not previously existent in the PDR design. This is due to the axial force being located to the side of the rail system instead of existing in the center of the design. By performing the calculation for angle of twist on an aluminum 6061 3”x1”⅛” hollow rectangular rail, an angle of twist of .04 degrees was expected. Due to this being approximately 0, the team does not expect this angle of twist to be a problem in the device. The calculation for angle of twist can be further seen in Appendix H.

13.2.5 7.2.5 Design Iteration 5: Change in template holder discussion

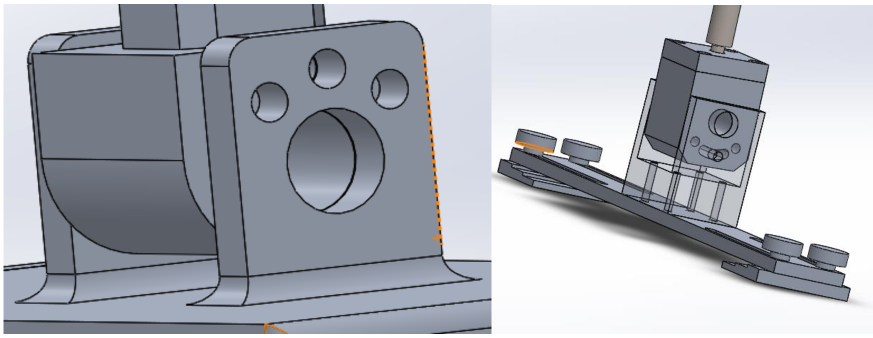
The original design for the template holder used a clamping screw to fix the template to the attachment. This design was inadequate as it did not account for the various sizes of templates that are used by Northrop Grumman. The new design takes into account the various template sizes by using steps integrated into the clamping jaws of the attachment. This will allow a tighter fit around the templates which reduce the chance of the template coming loose during operation. The new and old template holders can be referred to below in figure 60.



(a) **(b)**

Figure 60: Old Template Holder (a) vs New Template Holder (b)

A sub-assembly of the template holder is the positioning mechanism which allows the device to apply force normal to the motor dome. The old design for the positioning mechanism utilized pin holes at normal to and 45 degrees to the neutral axis. This design was changed as it did not allow enough flexibility within the design to achieve angles between those previously stated. The new design allows for an infinite angle between the bounds of 30 degrees on each side. With this added maneuverability of the design, the technicians will be able to find the angle they need and then lock the device in place using a threaded knob (not shown). The modified design of the positioner mechanism can be referred to below in figure 61.



(a) **(b)**

Figure 61: Old Positioning Mechanism (a) vs New Positioning Mechanism (b)

The changes made to the template holder will allow for easier operation of the device, and ensure that any chances for failure due to handler error are mitigated.

13.2.6 7.2.6 Design Iteration 6: Change in spring scale discussion

Northrop Grumman wishes to be able to perform a 20lb push test and 50lb pull test per standoff with the mounting device designed by the capstone team. In order to determine if the axial force performed by the device is accurate, a spring scale was made by the design team during the PDR. This design can be seen in figure 62 below.

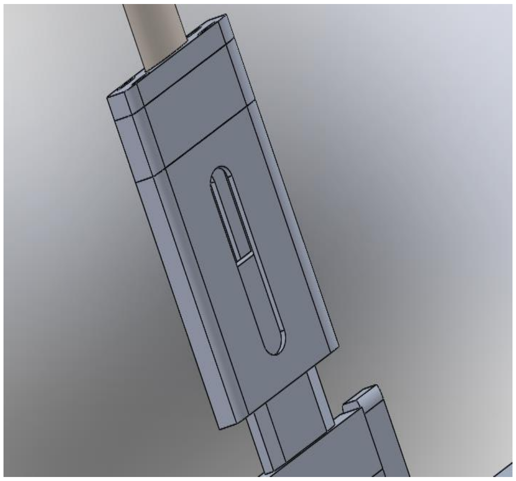


Figure 62: PDR Spring Housing

The spring housing was designed to make a spring display force values with ticks marked on the outside of the housing. This design had some clear existing problems. The spring housing was complicated to manufacture, implement into the design, and required a spring analysis to determine the correct spring to use in the design. In order to simplify the purpose of this housing, a design change was made to remove the housing in exchange for a torque wrench which can be seen in figure 63.

Figure 63: Torque Wrench

A torque wrench allows operators to apply a set force on the lead screw which can be displayed by the tool. This allows for a much similar solution while also reducing the amount of manufacturing for the device.

In order to apply the proper axial loads to the bracket templates it is important to determine the required torque. The torque that is required to raise and lower the loads associated with the power screw were calculated using the torque equations seen below in Table 8. These values will become important when creating the handlers manual for our device and what the tolerances on the torque will be to ensure the correct forces are applied.

Table 8: Torque Equations

Parameter	Equation
Torque required to raise the load [T_R] [1,2,3]	$T_R = \frac{F \cdot d_m}{2}(\frac{l + \pi f d_m \sec\alpha}{\pi d_m - f l \sec\alpha}) + T_c$
Torque required to lower the load [T_L][1,2,3]	$T_R = \frac{F \cdot d_m}{2}(\frac{-l + \pi f d_m \sec\alpha}{\pi d_m + f l \sec\alpha}) + T_c$
Frictional torque of the thrust collar [T_c]	$T_c = \frac{F f_c d_c}{2}$
Efficiency during lifting the load [e] [3]	$e = \frac{Fl}{2\pi T_R}$

The equations that were used for the calculations of the lowering and raising torque are located above in Table 8. The conditions that are expected during the standard operation of our device include a push and pull force of 20 lbf and 50 lbf respectively. The values that were determined for both of these conditions include a torque required to raise a load consisting of 0.313 lbf-ft and a lowering torque of 0.176 lbf-ft. By using these torque values as indicators on the torque wrench, it will be possible to apply forces accurately to the bracket templates.

14 8 RISK ANALYSIS AND MITIGATION

This section discusses how the team mitigated potential failures in the system based on the design decisions. The first part of this section identifies potential failures identified in the fall semester and the second part addresses the design changes in order to mitigate the risks.

14.1 *8.1 Potential Failures Identified Fall Semester*

This section will focus on the potential failures identified during the fall semester. A Failure Mode and Effects Analysis (FMEA), as provided in Appendix I, was used to determine and quantify top potential failures in the team's design. The final product has seven sub-functions which include mounting to the ring, translating the brackets, holding the bracket, applying axial force, locking, angle bracket, and ESD compliance. These sub-functions were used as the possible function failures for the project. By evaluating the severity of the potential effects for failure, and the occurrence and detection of the potential causes for failure, the team was able to identify the top ten potential failures based on the risk priority number (RPN) as shown in Table 9. As shown in Table 9, ten critical failures were found based on their RPN values and provides the actions that the team should take to reduce the likelihood of these failures. The team had identified that the top ten potential failures include: bending of the ring, bracket joint pin shear failure, spline mounting screw shears, clamp slips off, force block slides during axial force test, unable to hold standoff bracket, lead screw breaks, bending of the rails, force block does not slide, and the fish scale does not read correctly.

Table 9. Top 10 Potential Failures FMEA

Product Name	Standoff Bonding Tool	Development Team	18F19				FMEA Number			3
							Date			11/14/19
Part #	**Function**	**Potential Failure Mode**	**Potential Effects for Failure**	**Severity** (1-10)	**Potential Cause(s) for Failure**	**Occurance** (1-10)	**Current Design Controls Test**	**Detection** (1-10)	**RPN** (SxOxD)	**Reccomended Action(s)**
2	Mount to ring	Bending of the ring	Rocket Motor Ring will break	10	Overstressing the ring	5	Visual Indicator	8	400	Moment Ring Analytical Analysis
11	Angle Bracket	Bracket Joint Pin Shear Failure	Inability to carry out the pull test	7	Applied axial force	6	Visual Indicator	8	336	Material Selection Analysis
5, 6	Angle Bracket	Spline Mounting Screw Shears	Device will be unsupported	8	Applied axial force	6	Audibe and Visual Indicators	5	240	Spline Shaft Gear Analysis
2	Mount to ring	Clamp slips off	The device will be unsupported	8	Inefficient clamping force	3	Visual Indicator	8	192	Clamp force analysis
4, 13	Locking	Force block slides during axial force tests	Device cannot be applied to a specific location	7	Applied force exceeds lock capacity	5	Audibe and Visual Indicators	5	175	Material Selection Analysis
3	Bracket slips off	Unable to hold standoff bracket	Unable to hold standoff bracket	7	Incefficent clamping force	3	Visual Indicator	8	168	Clamp force analysis
22	Apply Axial Force	Lead Screw Breaks	Unable to apply axial force	8	Force induced deformation of screw	3	Audibe and Visual Indicators	5	120	Lead Screw Stress analysis
1	Translate the brackets	Bending of the rails	Device is not able to translate toward the standoff location	7	Overstressing the pivots	2	Visual Indicator	8	112	Deformation Test
4	Translate the brackets	Force Block does not slide	Device is not able to translate toward the standoff location	7	Ball Bearing Breaks	2	Visual Indicator	8	112	Bearing Analytical Analysis
15	Apply Axial Force	Fish Scale does not read correctly	Force will not display to operator	5	Spring does not function with the device	2	Visual Indicator	8	80	Spring Analysis

8.1.1 Potential Critical Failure 1: Bending of the Ring

The standoff mounting arm will be attached to the rocket motor dome in order to hold the standoff brackets in place while the adhesive cures. However as seen in figures 64 and 65, the standoff device will only have .2" x 1.25" to attach to the Castor 30 XL and .205" x 1.375" to clamp onto the Orion 50 rocket motor rings.

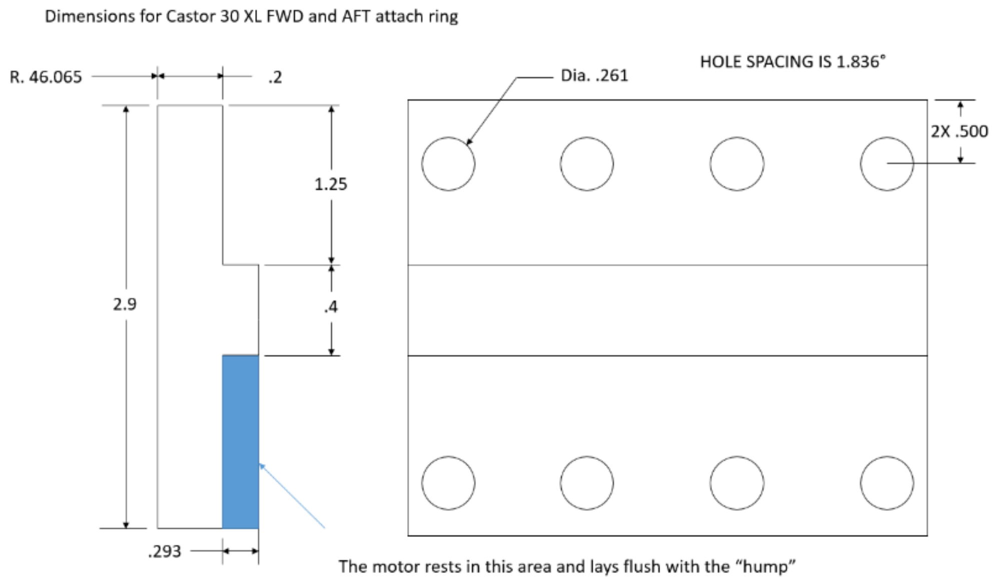


Figure 64: Castor 30XL FWD and AFT attach ring Dimensions

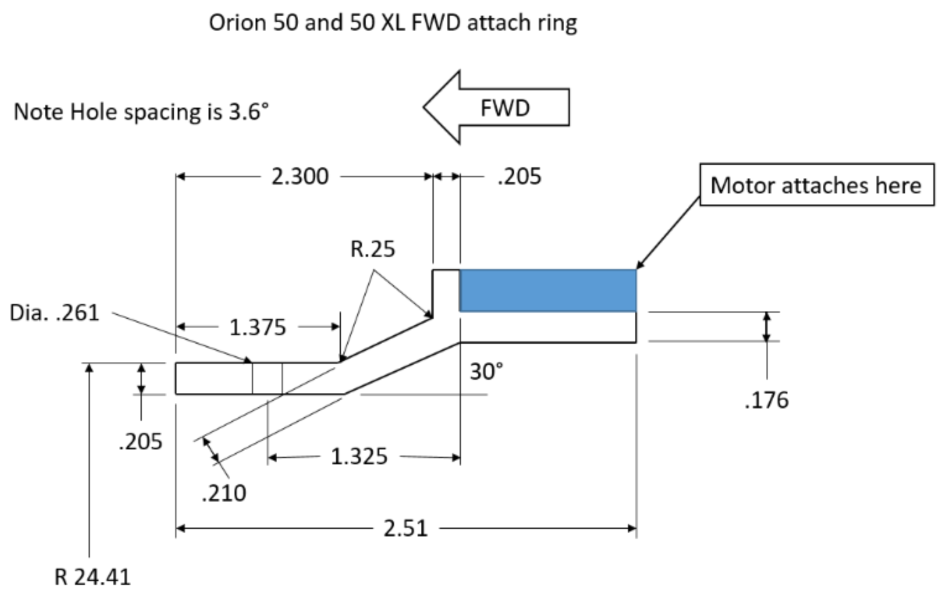


Figure 65: Orion 50 and 50XL FWD attach ring Dimensions

Due to the distance that the axial force will be applied from the rocket motor ring (4-36" inboard), a large moment will be applied to the thin rocket motor ring. Despite being made of Aluminum 7075, the moment could cause bending of the rocket motor ring. If this were to occur, the rocket motor ring would need to be replaced, which could delay usage and drain resources. This is the absolute worst case scenario for the design team and is deemed the most severe of potential failures of the device. That is why this potential failure has the highest RPN values shown in Table 9. To mitigate this failure from occurring, an analysis will be performed which considers the longest moment arm and maximum force to examine the worst case scenario for each ring geometry. The calculations will be performed with Solidworks FEA to visualize the stress concentrations and will be backed with hand calculations. These hand calculations will be used to ensure that the software is providing a reasonable output. The result of this analysis will allow the team to determine the necessary clamp width for load distribution while also ensuring that the maximum moment can be tolerated in all cases.

8.1.2 Potential Critical Failure 2: Bracket Joint Pin Shear Failure

In order to meet the 45 degree pull test requirement specified by Northrop Grumman, the bracket holding component that will mount to the bottom of the force gage will lock in two positions (90° and 45°). In order to lock the bracket in place, a pin will be used to lock between the two different positions. Due to the axial forces that will be performed on the device, a large amount of stress will be applied to the locking pin which could result in shear failure. To mitigate this from occurring, a material selection analysis will be performed to determine the best material and geometry for the pin. In the future, a further analytical analysis may be performed in order to verify that the pin will not suffer a catastrophic failure.

8.1.3 Potential Critical Failure 3: Spline Mounting Screw Shears

As described in the previous preliminary report and section 5 of this report, one of the primary designs that has been considered by the design team is a sliding rail system. The rail system will have two rails that will allow a force block to slide into position to apply the axial forces needed. Originally, the rail system was to move strictly horizontal across the rocket motor dome. However, the Castor 30 series' dome protrudes over the rocket motor ring plane shown in figure 66 below.

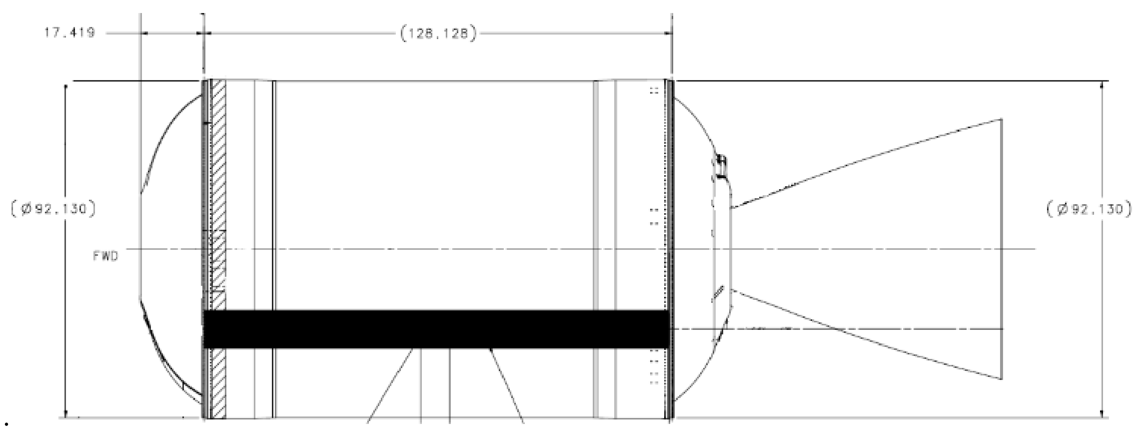


Figure 66: Castor 30 Series Drawing

Due to the dome protruding over the normal plane of the rocket motor ring, the device must be able to angle vertically to account for the profile of the dome. A splined shaft design was made to allow the device to angle the mounting arm vertically. This spline design can be seen in Figure 67 below.

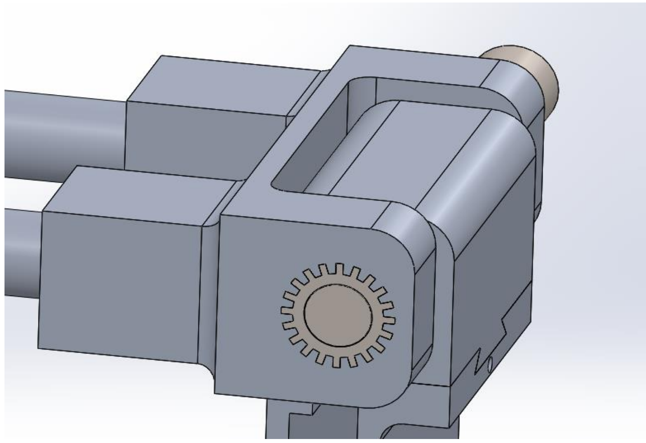


Figure 67: Spline Shaft Design

Due to the teeth of the spline, the axial force could cause damage to the design. This would make the design not lock in a vertical position. In order to prevent this from occurring, an in depth analytical analysis will be performed spring semester. This analysis will focus on mechanics of materials topics including gear teeth, and rotational locations. This analysis will allow the design team to safely select the amount of teeth the spline shaft should have. If the applied axial force is within the 3.0 factor of safety minimum described in the project description section, and whether the spline will be a suitable design for the project team to use. These analyses will be conducted with hand calculations along with an excel sheet that allows the user to change various design variables such as spline teeth and angle.

8.1.4 Potential Critical Failure 4: Rocket Ring Clamp Slips Off

In order to mount onto the rocket motor ring, a clamping device must be designed to secure the device in place. This will allow the mounting arm to hold in a locked position while the axial forces are applied. However, as the axial force is applied, the grip the mounting arm has on the rocket motor ring could loosen and cause the clamp to slip off the locked position. This failure could result in the device, the rocket motor dome, or an operator to be damaged or hurt. In order to prevent this from occurring, a clamping analytical analysis will be made. The primary goal of this analysis, as described in section 3.2, is to solve the exact load distribution along the ring (how much clamp area should be used to disperse the force along the ring) and the necessary clamping force needed to support the design. Solid mechanics hand-calculations, Solidworks FEA, and physical experiments will be conducted by the team. The experiment will be conducted for ME495 lab with the primary purpose of solving the optimal load distribution along the ring which will utilize pressure sensors and strain gauges. Results from the solid mechanics hand-calculations and the experiment will be used to redesign the vise grip to the dimensions that best suit the team's current design along with a Solidworks FEA calculation to prove that the clamping mechanism is feasible.

8.1.5 Potential Critical Failure 5: Force Block Slides due to Axial Force

Described in section 4.1.3, a rail system has been a possible solution for this project. This design will allow the translation of the bracket to be easily performed, while eliminating the use of articulating arms multiple locking positions. In order to secure the force block in place, a locking mechanism must be designed to secure the location of the axial force. As of now, four rail locking rings will be designed to lock the force block on each rail in each location. With the axial force that will be performed by the device, it is possible for these locking mechanisms to fail. This would cause the force block to slide during the axial force which would make the device not have the ability to be locked into place. In order to mitigate this from occurring, a material analysis will be made on the locking mechanism to verify that the lock will not break and perform as needed. Once this is performed, another FMEA will be made to determine the likelihood of this occurring and if the RPN is still relatively high another analytical analysis of the frictional coefficient and clamping forces will be made to determine if this design should be continued with in the final design or if another option should be made.

8.1.6 Potential Critical Failure 6: Bracket Clamp Slips Off

As the project description states, the standoff mounting device must firmly hold the standoff template brackets in place while the adhesive cures. In order to do this, a clamping device was designed by the project team to hold the brackets in place while the axial force testing is conducted. It is possible that while the axial force is done, the bracket clamp could slip off the bracket template. This would prevent the mounting arm from securing the brackets in place as the customer required. This is similar to the rocket ring clamp slipping off as stated in section 4.1.4, however less likely since a lesser moment will be applied to the bracket clamp. However in order to verify that this will not occur, the testing stated in section 3.2 will be referenced along with a lesser clamping force calculation that will be performed by the design team in the spring semester. An FEA analysis will be done with the designed clamp and bracket templates to verify that the hand calculations that were made were correct.

8.1.7 Potential Critical Failure 7: Lead Screw Breaks

In order to translate the axial forces required for the design, a lead screw is required. This power screw design will allow the operator to apply a force with a drive nut, and then keep that force locked in place by the thread position. Failure could occur from the axial force applied on the device which could cause the lead screw to deform. This would make the device unable to apply an axial force to the bracket templates, which in turn caused the device to be inoperable. In order to mitigate this failure from occurring, a power screw analytical analysis will be performed. This analysis will involve determining the right conditions for the screw to be self-locking as well as its ability to provide adequate push and pull force to meet the client's requirements. The objective of this analysis is to find which elements of the power screw directly benefit the project such as the thread form, pitch, efficiency, cost to procure, cost of maintenance and operability. The project could benefit from this analysis by the discovery of the weight incurred by the screw, as well as its ability to apply axial loads to the bracket holder at multiple angles. The length and width of the power screw will also be considered for this evaluation and help finalize the design of the rail cart sub-system.

8.1.8 Potential Critical Failure 8: Bending of the Rails

As described in section 4.1.5, a rail system has been considered by the design team, which would allow the translation of the bracket to be easily performed while eliminating the use of articulating arms with multiple locking positions. The drawback of this design, however, is the fact that a deflection or bend in the rails could occur during testing due to the axial forces being applied onto the rocket motor ring. This could cause the device to be unable to translate the brackets to the appropriate location thus making the device inoperable. In order to mitigate this failure from occurring, a rail deflection calculation will be performed as described in section 3.3. The project description requires a 20 lb push and 50 lb pull test conducted between 4" and 36" inward of the rocket motor ring. At the maximum 36", the 50 lb pull test will generate a large bending moment and shear force within the rails. This analysis will cover the force and bending analysis within the rails and will analyze different materials to predict actual movement and reactions within the rails. These tests will be conducted with hand calculations and backed by MATLAB code and Solidworks FEA analysis to verify the values. These calculations will greatly aid the team in determining what materials are used for the design and how the device will theoretically perform.

8.1.9 Potential Critical Failure 9: Force Block does not Slide

As described in the previous subsection, the rail system considered by the design team will allow operators to slide the force block into position much easier than that of an articulating arm. For this to work appropriately, the force block must be able to slide easily into the correct position. In order to do this, bearings will be installed into the force block to allow operators to easily position the device. As with many other failures described in this section, the axial force performed by the device could result in the bearings to break resulting in the force block not sliding into the correct position. This would cause the device to not meet the translating the bracket sub function. Since the bearings will be at a location where the max force will be applied to the device, it was determined an analysis should be conducted to determine if this can be applied to the final design. This analysis will compare bearing designs to determine: methods to applying bearings to the device, if the bearings would fail under the max load, what materials should be used for the bearings, and if the bearings will cause damage to the rail system under the load of the device. After these analyses it will be determined if bearings could be used on the device, and if so which ones. This analysis will be conducted with hand-calculations as well as MATLAB or an Excel worksheet to verify the values are correct, as well as to create visual aids on the force analysis of the bearings materials.

8.1.10 Potential Critical Failure 10: Fish Scale does not Read Correctly

Currently at Northrop Grumman to test that the brackets are placed in position and will not come off, a fish scale is used to pull the brackets with 50lbs of force to verify that the brackets are in place. The client has asked that the design team implement this into the final design. In order to do this, a fish scale will be placed on the mounting arm with a spring with a given k value. This force scale can be seen in figure 68 below.

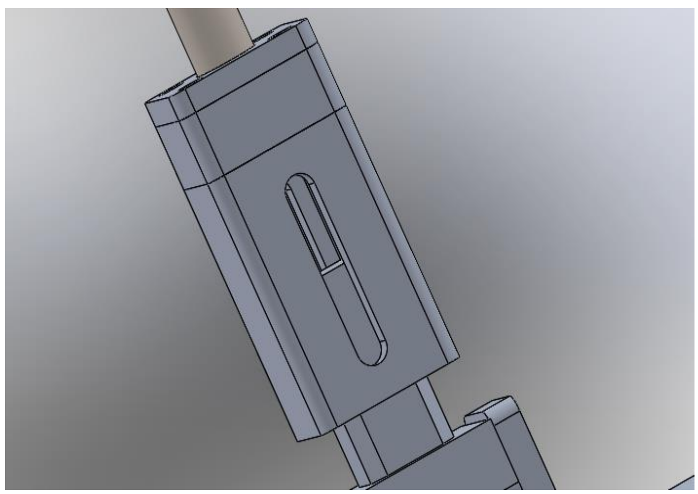


Figure 68: Force Scale Design

Currently the force scale will use the spring implemented inside to allow the reader to see exactly how much force is being applied to the brackets. The problem with this design is that if the spring used becomes deformed due to the axial force and regular use, the force reading would become inaccurate. This will make the operators possible apply a different force to the rocket dome either making the bracket become not secured onto the rocket motor dome, or damaging the rocket motor dome. In order to verify that this design will not have this failure occur, an analytical analysis of springs that could be used in the design will be performed. This analysis will take various spring lengths, coil counts, and materials placed against one another to see which spring would function the best in the final design. For this analysis, an excel sheet will be made to allow the user to change various design variables to verify which spring is the most applicable to the final design.

14.2 8.2 Risk Mitigation

The purpose of this section is to outline multiple potential concerns with the initial design, and how these concerns were mitigated with design changes and considerations. Below are examples of specific design elements that were altered due to the risk of potential failures, all of which attempt to improve on the usability of the design as well.

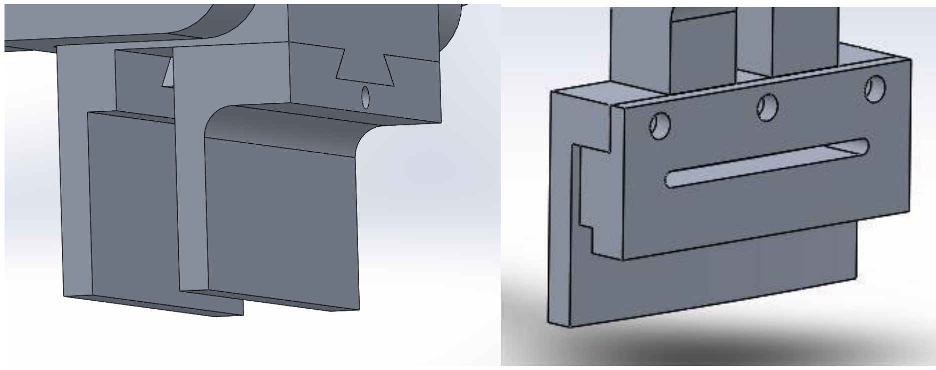


Figure 69: Previous Ring Clamp (Left) and New Design (Right)

When a load is applied to the end of the extended mounting arm, the reaction forces are translated to the rocket motor ring via the ring clamp. The initial design for this clamp, which is shown on the left side of figure 69, included interchangeable jaws, which could interact with the different ring geometries. However, this design was complicated, difficult to physically handle, and did not allow for the mount to pass through the holes in the motor ring. The clamping mechanism also relied on the use of a dovetail, which would have added significant machining time.

The updated design, which can be seen on the right in figure 70 replaces the previous design with entirely interchangeable clamp halves to operate with each specific motor ring. This simplifies the design, creating a system with less uncertainty that is both easier to machine and handle. The new design also allows for the ring clamp to accommodate fasteners that will pass through the holes in the rocket motor ring, eliminating any risk of the clamp sliding off of the ring during operation. A slot was utilized in this design change to allow for access to the holes without limiting the positioning of the clamp about the ring.

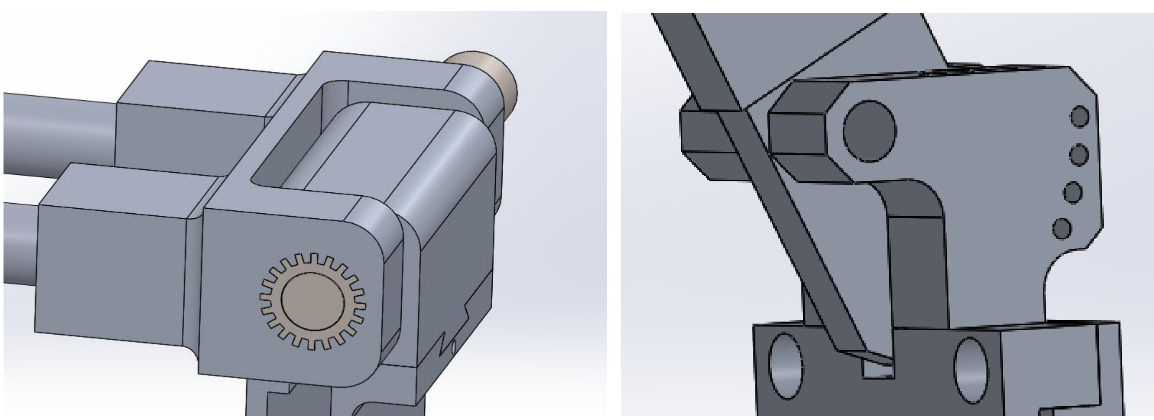


Figure 70. Previous Ring Angler (Left) and New Design (Right)

The initial design that would allow the system to change the angle of the rail relative to the ring is pictured in figure 70. This concept relied on a spline shaft that could support the load induced about the ring during operation, while also allowing for the rail angle to be set at various positions. This design provided challenges in that the arm would not be secure while changing the angle, it would be difficult to machine, and that the moment about the splines would be large due to the small distance from the center of rotation. The large induced moment had the potential to shear the splines from the shaft, which could cause damage to the rocket motor itself.

The new iteration of this design is also shown in figure 71, which utilizes pins to set the angle of the rail system. This provides a much longer moment arm to counterbalance the moment induced by loading the system. In turn, the factor of safety for the system is greatly increased. The design is now stable while changing angles as well, which improves the usability of the system. Machining the complicated splines is also no longer necessary, reducing manufacturing time significantly.

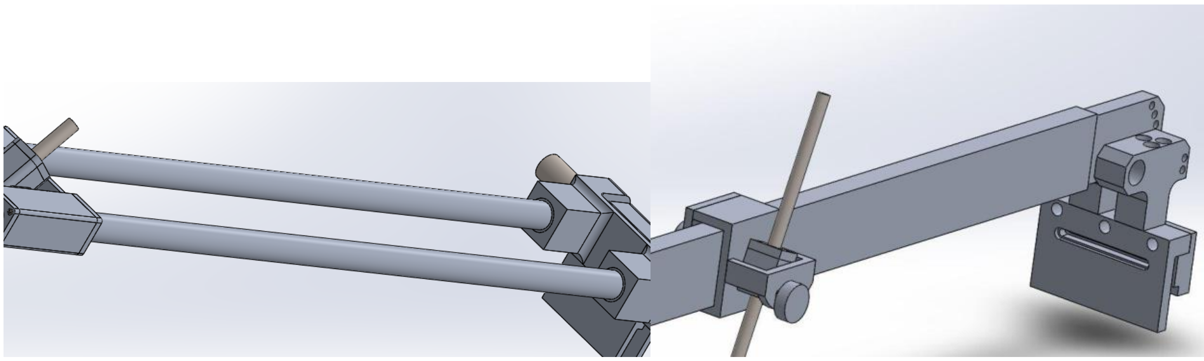


Figure 71. Previous Rail System (Left) and New Design (Right)

The original rail system was designed to translate the lead screw to different portions of the rocket motor dome. This design was simple and lightweight, but would have been cause for relatively high deflections of the rails under the operating load. Aligning the dual rail system with the cart could have also imposed a challenge for the end used, making the installation of standoffs more difficult.

In order to mitigate the issues imposed by the first iteration of this design, a new, single rectangular rail was proposed. With a much larger moment of inertia, the rectangular rail would undergo much less deflection during operation while maintaining a similar total weight. A single rail design is also an improvement from a user's perspective, as two rails do not need to be handled simultaneously while positioning the device. Overall strength and factor of safety for the design have also been improved with this change.

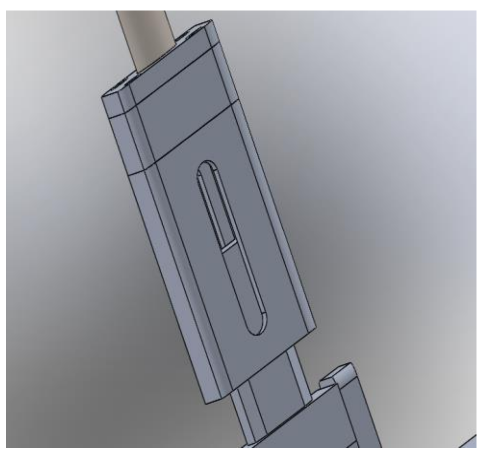


Figure 72. Spring Scale Design

In order to correctly install the standoffs and test the adhesion to the surface, the amount of force that is applied to the mounting bracket must be measurable. In order to meet this requirement, the design initially included a spring scale that was mounted in line with the lead screw, which would have provided a force reading for the operator when using the device.

However, this reading would have been difficult to check from many angles, and would have required extensive machining. The nature of the scale may have also provided unreliable readings, and would have added unnecessary bulk to the design. The new iteration will utilize a torque wrench to turn the lead screw and provide the necessary load on the standoff mounting bracket. This will also ensure more consistent force readings, as fatigue on the spring system will no longer be a concern.

16 9 TESTING

Due to the circumstances of the spring 2020 semester, the team was unable to meet and test the final device. The tests that were planned to be completed to fulfill the testing requirement included tests such as electrostatic discharge compliance, torque wrench, and working angle/length. In substitution of the in-person testing that would have occurred if the semester were to have continued normally, engineering analyses were conducted on the final design. The analyses that were conducted included aspects of the project related to the torque of the power screw assembly, stress concentrations on the motor ring, beam analysis of the hollow rectangular pipe, and angle of twist due to eccentric loading which are included in the analysis section of the report. While these calculations do not provide the same level of insight that on site testing would yield, these engineering analyses however do provide some credibility to the claims that the device can meet the desired requirements.

The design requirements that were satisfied given the engineering analyses conducted by the team included maintaining a factor of safety of 3.0, electrostatic discharge compliant, and performing a 50lb pull test and 20lb push test. The design requirements that were left ambiguous due to being inadequately validatable through calculations and analyses would be the ease of operation by a single technician, and the transferability between the different rocket motor variations. As a result of these analyses, none of the current design decisions were identified to be redesigned as the major requirements as requested by Northrop Grumman were satisfied. Section 3 describes each test that the capstone team was planning on performing.

18 10 FUTURE WORK

Due to the limitations the capstone team experienced by the COVID-19 pandemic, there were several action items the team set out to accomplish which were not achieved. This section will not only go over these uncompleted tasks, but will also go into detail on what should be known if this project was to move on at Northrop Grumman's facilities.

As previously discussed in section 9's testing, the team was unable to perform any testing on the product. While the calculations performed in Appendices C-G provide extensive proof of the overall functionality of the design, further testing should be performed to determine if this product could be utilized as expected.

The final product is about 98% done. The missing 2% is due to a few factors. Every part of the assembly is manufactured. However many of the bracket clamp pieces had to be work ordered through the 98C manufacturing shop at Northern Arizona University. While these parts were made and picked up by the capstone team, they have an extremely tight fit which makes them nearly impossible to assemble together without removing a small amount of material. While this could be worked around, a crucial component in the bracket clamp was lost when the capstone team went to pick up their supplies from the 98C manufacturing shop. The team was unable to enter the fabrication shop to pick up their supplies, so they had to rely on the shop managers to gather all their supplies and leave it outside. Whether it is still located inside the manufacturing lab, was lost in the move, or whatever the mistake may be, this missing piece prevents the assembly of the final product. If the team had 3 days to manufacture, they could likely fix these issues. However, these problems prevent the product from being 100% completed.

Due to the restrictions caused by the COVID-19 pandemic, the team was also unable to manufacture the pull test piece of the final design. This piece would have been interchangeable with the push test bracket clamp, however the team prioritized the push test component. The push test was prioritized because the team was told by the client to focus on the bonding aspect of the project and then deal with the pull test if time permitted it. While this piece is not manufactured, the CAD design is completed.

19 11 CONCLUSIONS

A post-mortem is a process performed at the conclusion of a project which serves to determine and analyze the successful and unsuccessful elements. This process will be performed by dividing the previous semesters project structure into various categories which will then be analyzed for aspects that contributed to the project's success and for improvements that could be made.The categories that will be analyzed include purpose and goals, ground rules and coping strategies, aspects of project performance, tools, methodologies, practices, problems encountered, and organizational actions. For example, the category of ground rules and coping strategies will be explored for any rules that may have been neglected last semester such as meeting time punctuality or for actions that contributed to the groups success such as effective communication between team members. Further examples, including analysis, will be present within the body of the memo.The goal of this process is to determine any deficiencies of last semester's project which may have been detrimental to the cohesion, efficiency, or productivity of the group.

19.1 *11.1 Contributors to Project Success*

The first category to be analyzed encompasses both the purpose and goal of the project which were stated in the team charter created at the beginning of last semester. Taking an overview of last semester, it could be observed that the team never strayed from our original purpose which was as stated in the team charter, "The purpose of the team is to produce a fully functional standoff mounting arm that will replace the taping method currently implemented at Northrop Grumman". Although we were given alterations to the original project requirements, the purpose was maintained. The goals that were put forward in the same document include producing a product which exceeds the expectations of the customer, and setting a high standard for work quality. In this regard, it can be argued that the team has acquired a high standard of work quality as we have been commended by Northrop Grumman for our progress as well as achieving a high grade in the class component. An area of improvement could be applied to the first goal that was stated which requires that we exceed Northrop Grumman's expectations. Over the course of the project, the team has been given many design considerations ranging from rocket geometry alterations, to multi-bracket attachment heads. While it is still possible to exceed these goals, the team has yet to flesh out the specific details for the given design considerations. Using this information we can make decisions on how to move forward with the project and ensure that the goals we have made will be met. The next section will analyze the project elements regarding the ground rules and coping strategies outlined in the team charter.

The ground rules and coping strategies of the team project are located within the team charter and include corrective and preventative actions tailored towards problems such as punctuality, disagreement, accountability, and team discussion. The purpose of this agreement was to ensure that any disputes within the team had a basis for resolution. The ground rules that most contributed to the success of last semester's assignments included the standardization of meeting times and locations. With the consideration of each individual team members schedule, meeting times were created and allowed for the proper discussion of project topics, allotment of time to complete any pending deliverables, and the delegation of future tasks. Coping strategies were used to the benefit of the team as a whole as there were never any catastrophic incidents of late work or conflict between team members. These preventative actions served to encounter and then resolve any issues that may have caused distress down the road. While the project ran smoothly last semester there are still areas of improvement that could be made regarding the ground rules. Punctuality was an area that became more neglected as the semester played out. Due to conflicts of managing multiple team projects, classes, and exams, many team members found issues with attending scheduled team meetings on time or alternatively not showing up at all. Moving forward into the upcoming semester, these problems could be addressed by allowing for more communications between team members preceding a meeting so that there is no confusion regarding the purpose and importance of that meeting. The next section of the project to be analyzed will involve the project performance elements such as time management, product quality, and manufacturing.

The aspects of project performance that were most positive includes the delegation of tasks, product and writing quality. The delegation of tasks allowed each team member to hold about an equal amount of work. By giving each member a specific task to focus on, they were able to produce high quality work by the course's deadlines. The practice of good time management through proper delegation of tasks enabled the team to produce a complete concept for the client. In addition to this, the team also provided him with professional documentation of the product. As a result, the team received feedback from the client which enabled for further improvement on the current state of the design.

As the semester progressed, the team was effective for a number of reasons. For starters, the team distributed the amount of work evenly amongst each other in group settings. At each team meeting, the team would discuss upcoming action items and discuss the best ways to complete them. One way the team did this was by splitting up the project amongst each other in topics each team member specialized in. For example, the team split up the subsystems amongst each other so each team member became the expert in a specific area of the project. This allowed the team to have a person in charge of each part of the device, so that if any design changes needed to be made there would be someone specialized in that area of the project. The use of google docs and slides allowed the team to easily be working on documents at the same time to further increase productivity. The manufacturing lab was also used heavily by the team early on to allow for the creation of small scale testing parts. The team will plan on continuing these methodologies and use of tools moving forward in the project.

A large contributor to the team's success was the advanced training sessions provided by the machine shop staff to aid capstone students. These advanced training sessions greatly helped with the team's technical knowhow moving forward with the project. With each team member being trained on the lathe and the mill, the team has full confidence in building the final prototype for Northrop Grumman. Although the team didn't really use any of the lathe or mill machines for 476C, they will be relied on heavily for the upcoming months of 486C. Additionally, the manufacturing courses provided by NAU are very useful in strengthening the team's technical skills by opening the possibility of welding or CNC machining. Lastly, a few of the team members strengthened their 3D-printing knowledge and abilities by printing various components for the 476C prototypes. Ultimately these technical lessons will all be directly applied to the final build the team will create.

19.2 *11.2 Opportunities/areas for improvement*

The aspects of project performance that were most negative was communication and the organization of team meetings. While the team did receive high grades on all assignments, issues regarding the productivity of team meetings were still present. Prior to team meetings, all members had an idea of the topics that were going to be discussed based on upcoming deadlines, but there lacked structure. A list of action items should be made prior to the team meeting to ensure that all members are on the same page of what needs to get done. Additionally, there's room for improvement in communication. Any ideas regarding the project should be communicated to the entire team. Increase in productivity can be achieved by communicating effectively and practicing good organizational skills.

While the team did use many tools and methodologies to increase the efficiency of the project, there were also those which created an ineffective use of time and decreased production. One routine that the team fell into heavily last year was showing up late to meetings. The team should work on showing up on time or early to each meeting moving forward. The team also had difficulty using google sheets to create spreadsheets for the project. Many times, the team had to have one member of the team create a spreadsheet in excel and import it from excel to sheets so that everyone could see the sheet. This is not very effective as it makes one member get stuck with all the work, while everyone else waits for the completed spreadsheet. The team could try to work with microsoft teams in the future to fix this problem. The team also fell into the practice of not responding to emails and text messages in a timely manner. This should be a top priority for the team moving forward.

Over the course of the last semester, the team was successful in developing the basis for a design that would satisfy the entirety of the customer requirements. While small changes are still necessary to optimize the final product, the development process so far has come without many major setbacks. However, this does not mean that the team was able to avoid problematic situations entirely.

The most prominent issue faced during design was the change of both representation and guidelines after the start of the semester. This led to the alteration of certain design components, as well as completely new considerations. The interpretation of the original project requirements was also an issue, as the individual who wrote them is no longer present at the company. This led to misinterpretation of the requirements and confusion with regard to portions of the design itself, which was all shortly rectified. These problems are still a factor in the ongoing design process, but are all within reason and should not provide too much of a challenge for the team.

The overall quality of work completed by the team thus far has been beyond satisfactory, with no missed deadlines or major shortfalls. However, this does not mean that the organizational structure for the completion of this work was without fault. The timing with which assignments were completed came relatively close to deadlines on multiple occasions, leaving little room for editing purposes. This is a definite point of potential improvement, as earlier completion of assignments would ensure that the editing process returned the best possible final product. Earlier consideration of assignments would also allow for the team to focus more on important tasks, such as presentations, which would provide better communication of design intent.

The organizational structure with regard to dividing up the workload has worked well to date, with early and even splits allowing for each team member to operate with intent. Continuing this, while also attempting to perform tasks further from the respective due dates, will provide a balanced and effective work structure for the team in the coming semester.

21 12 REFERENCES

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22 13 APPENDICES

22.1 13.1 Appendix A: Rocket Motors the Mounting Arm will Mount

13.1.1 Appendix A.1. Orion 50XL

13.1.2 Appendix A.2. Castor 30XL

13.1.3 Appendix A.3. Castor 38

22.2 13.2 Appendix B: QFD

Customer Need	Weight	Engineering Requirement	Electrically Conductive (Y or N)	Mass (slugs)	Principal Dimensions (in)	Working Length (in)	Working Angle (Degrees)	Modulus of Elasticity (lbf/in^2)
1. ESD compliance	0.09		9	0	0	0	0	0
2. Apply axial forces	0.09		0	1	0	3	3	9
3. Six degrees of freedom in movement	0.09		0	0	0	9	9	0
4. Usable 4" - 36" inboard of ring	0.09		0	1	9	9	3	1
5. Transportability	0.04		0	9	9	3	3	0
6. Ease of operation	0.07		3	9	3	9	9	0
7. Durability	0.08		0	3	0	0	0	9
8. Reliability	0.08		0	3	0	0	0	9
9. Adjustable Interfaces	0.09		0	3	0	3	3	0
10. Support 10lbs in locked position	0.09		0	3	0	3	3	9
11. Minimum 3.0 Factor of Safety	0.06		0	3	0	0	0	9
12. Within Budget	0.03		9	9	3	9	3	9
13. Multiple Arms	0.05		0	3	3	3	3	0
14. Safe Operation	0.05		9	9	3	0	0	3
Absolute Technical Importance (ATI)			1.74	3.24	1.77	3.60	2.88	4.11
Relative Technical Importance (RTI)			0.42	0.79	0.43	0.88	0.70	1.00
Target Values			Yes	25	8" (W) x40" (L) x6" (H)	32"	360°	<10.4 *10^6
Target Tolerances			N/A	±5	±2	N/A	N/A	N/A

22.3

22.5 13.3 Appendix C: Bill of Materials

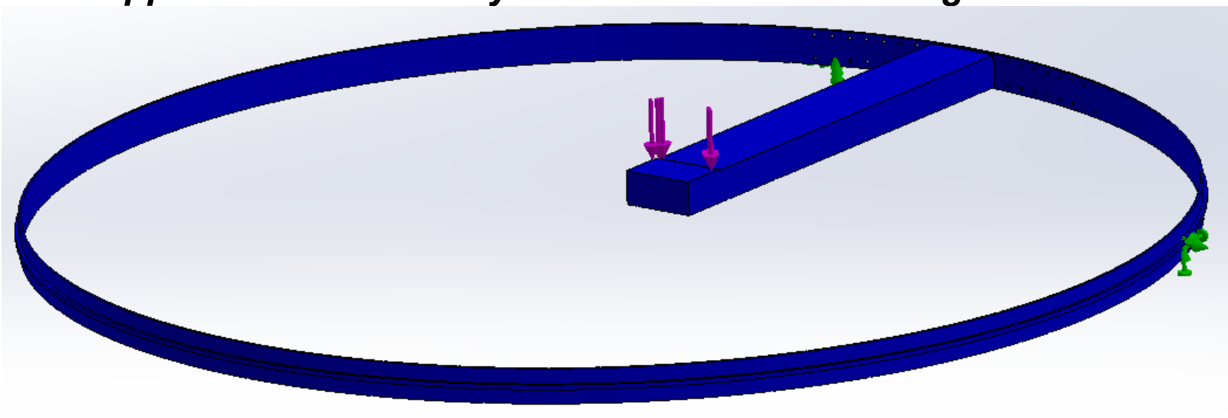
Part Number	Part Name	Quantity	Description/Operation
1	Inner Clamp	1	Ring clamp that goes on the inside of the motor ring
2	Outer Clamp	1	Ring clamp that goes on the outside of the motor dome
3	Motor Clamp Screws	2	Connects the inner and outer clamps
4	Ring hole Screws	3	Threads through rocket ring holes and connects the inner and outer clamps
5	Ring hole screw nuts	3	Locks ring hole screws in place onto the outer clamp
6	P-Piece	2	P-shaped piece which allows the device to angle vertically
7	Rail Mount	1	Long rectangular piece which inserts into the rail and connects to p-pieces
8	¾''x4'' quick release pin	1	Biggest pin inserted through the rail mount and the p-pieces
9	¼''x4'' quick release pin	1	Longest small diameter pin which inserts through the rail mount and p-pieces
10	Aluminum Shoulder Screws	6	Connect the p-pieces to the inner clamp
11	5ft Aluminum Rail	1	Allows the rail cart to translate
12	¼''x1-⅛'' quick release pin	2	Smallest pins which insert through the rail mount and the rail
13	Rail Cart Pins	2	Allows lead screw housing to rotate
14	Lead Screw Housing	1	Holds the lead screw in place
15	C-Channel	1	C-shaped channel piece which clamps around the rail
16	Curved Angling Mechanism	1	Channel piece with a curved hole; angles the lead screw housing
17	Bronze Nut	1	Rests inside the lead screw housing allowing the lead screw to apply an axial force
18	Lead Screw	1	Long screw which applies axial force
19	Top Plate	1	Holds the brass nut inside the lead screw housing
20	#8-32, ½" long Aluminum Socket Head Screws	25	Blue Anodized screws which connects much of the assembly
21	Threaded Knob for Angling Mechanism	1	Locks lead screw housing in place through the curved angling mechanism
22	Lead Screw Knob	1	Knob which rotates lead screw to apply axial force
23	Pressure Plate H	1	H shaped piece which presses onto the rail
24	Pressure Plate C	1	Presses H piece to rail
25	Pressure Plate Nut	1	Allows for the pressure plate to not rotate when rail cart locks into place
26	Front Plate	1	Connects to the c-channel piece to clamp all around the rail, and connects to the pressure plate assembly through its center hole
27	Pressure Plate Threaded Screw	1	Locks rail cart in place
28	Lead Screw Plate	1	Similar to the top plate, but connects to the lead screw rotator
29	Lead Screw Threaded Cap	1	Threads into the lead screw. Allows for bracket clamp to rotate freely
30	Lead Screw Rotator	1	Allows the bracket clamp to rotate 45 degrees normal to surface
31	Slot Angler	1	Slotted piece which holds the lead screw rotator
32	¼''x2-1/16'' quick release pin	2	Pins through slot angler and lead screw rotator locking the angle
33	Bracket Holder	1	Long slotted piece which holds the bracket holders
34	Template Holder	2	Small staircase pieces which hold the bracket templates
35	Thumb Screws	4	Tighten and loosen the bracket holders in place

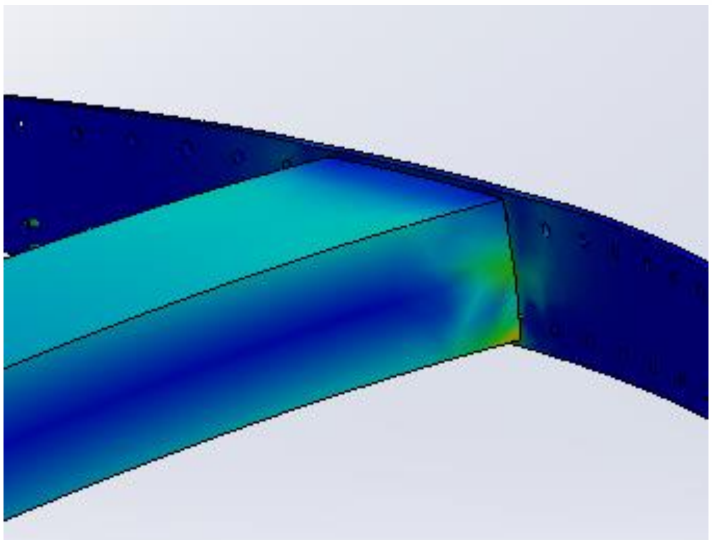
36	Pull Test Piece	1	Threaded into the mounted standoff to conduct pull test

22.6 13.4 Appendix D: Final Budget

Material	Unit Cost	Quantity	Total Cost	Source	Material	Unit Cost	Quantity	Total Cost	Source
6061 Aluminum Block, 4"x4"x12"	100.25	2	248.84	McMaster-Carr	Aluminum 6061 3/8"x2"x2ft	23.53	1	23.53	McMaster-Carr
PLA 3D Printing Filament	12.99	1	14.18	Amazon.com	PTFE Plastic Washer pack of 10	5.88	1	5.88	McMaster-Carr
Linear Sleeve Bearing, for 1-1/2" Diameter	141.17	1	175.05	McMaster-Carr	Aluminum Socket Head Screw, pack of 5	11.88	3	35.64	McMaster-Carr
6061 Polished Aluminum Tube, 1/4" wall thickness, 1-1/2" OD	28.95	1	35.90	McMaster-Carr	Aluminum Shoulder Screw, Socket Head Cap, Hex Socket Drive, Standard Tolerance, 1/16"-18 Thread Size, 3/8" Sholder Diameter, 2" Shoulder Length	5.58	8	44.64	Amazon
Acme Lead Screw, 1/2"x10, 2ft long	31.68	1	39.28	Roton.com	2"x4"x6" 7075 Aluminum Block	99.14	1	99.14	McMaster-Carr
Acme Sleeve Nut, 1/2"x10, Bronze	19.09	1	23.67	Roton.com	3/8" - 8 ACME lead screw	8.88	1	8.88	McMaster-Carr
6061 Aluminum Rect. Tube, 1-1/2"x3"x3/16" thickness, 6 ft long	93.16	2	231.04	McMaster-Carr	3/8" - 8 ACME Bronze Nut	24.62	1	24.62	McMaster-Carr
Aluminum Socket Head Screws, 8-32, 1/2" long, Blue-Anodize	11.88	5 Packs of 5	73.66	McMaster-Carr	TAS 1/2" Aluminum Shredder end mill	110.57	1	110.57	LakeShore Carbide
Strain Gauges	52	1 Pack of 8	80.78	Omega.com	TAS 5/8" Aluminum Shredder end mill	63.74	1	63.74	LakeShore Carbide
Aluminum 6061 3"x1"x1/8" rectangular tubing 6 ft long	76.68	1	23.53	McMaster-Carr	5/8" extended length variable flute	109.94	1	109.94	LakeShore Carbide
6061 Aluminum Rod, 2"x1ft	32.31	1	32.31	McMaster-Carr	5/8" variable flute carbide roughing mill	90.57	1	90.57	LakeShore Carbide
18-8 Stainless Steel Ring-Grip Quick-Release Pin, 3/4"x4"	19.42	1	19.42	McMaster-Carr	5/8" 0.09 radius variable 3 flute	96.83	1	96.83	LakeShore Carbide
18-8 Stainless Steel Ring-Grip Quick-Release Pin, 1/4"x4"	6	1	6	McMaster-Carr	3/8" 0.03 radius variable 3 flute	48.88	1	48.88	LakeShore Carbide
18-8 Stainless Steel Ring-Grip Quick-Release Pin, 1/4"x1-1/8"	4.48	2	8.96	McMaster-Carr	1/4" 1.0 LOC variable 3 flute	31.91	1	31.91	LakeShore Carbide
18-8 Stainless Steel Ring-Grip Quick-Release Pin, 1/4"x2-1/16"	4.69	2	9.38	McMaster-Carr			**Total Cost of Materials**	1816.77	
							Remaining Budget	8183.23	

13.5 Appendix E: FEA Analysis for Rocket Motor Ring





22.8 13.6 Appendix F: Pin Shear Analysis

Pin Shear Analysis

- Single pin must resist moment from entire rail cart lever arm.
  - One long, single pin going through both sides subjected to double shear.
- Max Load 50 lbs, results in 360lb internal shear on pin.
- Required diameter for desired factor of safety in pins is 0.207 in.

$$\tau_{failure} = 32\ ksi$$

$$F.O.S. = 3$$

$$\tau_{allowable} = 10.67\ ksi$$

$$\tau_{Avg} = \frac{V_{internal}}{A_c}$$

$$D_{required} = \sqrt{\frac{4\,V_{internal}}{\Pi\,\tau_{allowable}}}$$

22.10 13.7 Appendix G: Rail Deflection Analysis

Rail System

- Hollow Cylindrical Tube:
  - I_{xx} = .199 in^4
  - A_c = .982 in^2
- Hollow Rectangular Tube:
  - I_{xx} = .95 in^4
  - A_c = .9375 in^2
- Deflection of Cantilever Beam:
  - δ_c = .391 in
  - δ_r = .082 in
    - F = 50 lb
    - E = 10000 ksi
    - L = 36 in
- Weight of Rail System:
  - W_c = 3.46 lb
  - W_r = 3.31 lb
    - ρ = .098 lb/in^3

Hollow Cylindrical Tube:

$$Ixx = \frac{\Pi}{64}(D^4 - d^4)$$

$$A_c = \frac{\Pi}{4}(D^2 - d^2)$$

Hollow Rectangular Tube:

$$Ixx = \frac{1}{12}(BH^3 - bh^3)$$

$$A_c = BH - bh$$

Deflection of Cantilever Beam:

$$\delta = \frac{F L^3}{3 I E}$$

Weight of Rail System:

$$W = \rho A_c L$$

22.12 13.8 Appendix H: Angle of Twist Calculations

Angle of Twist

- Length = 36 in
- Torque = 81.625 in-lbs
  - 1.3625" * 50lbs
- Modulus of Rigidity = $3.8*10^6$ psi
- Polar Moment of Inertia = 1.104 in^4
  - Ix = .950 in^4
  - Iy = .153 in^4
- Angle of Twist = .04°

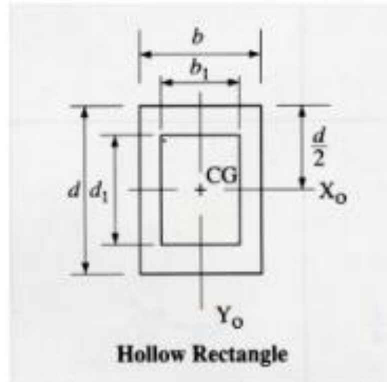


Figure 18. Angle of Twist Dimension Drawing

$$\theta = \frac{TL}{J_{CG}G}$$

$$I_{x_0} = \frac{bd^3 - b_1 d_1{}^3}{12}$$

$$I_{y_0} = \frac{db^3 - d_1 b_1}{12}$$

$$J_{CG} = I_{x_0} + I_{y_0}$$

22.13

22.15 13.9 Appendix I: Complete Failure Mode and Effects Analysis

Part #	Function	Potential Failure Mode	Potential Effects for Failure	Severity (1-10)	Potential Cause(s) for Failure	Occurance (1-10)	Current Design Controls Test	Detection (1-10)	RPN (SxOxD)	Reccomended Action(s)
2	Mount to ring	Bending of the ring	Rocket Motor Ring will break	10	Overstressing the ring	5	Visual Indicator	8	400	Moment Ring Analytical Analysis
		Rocket Motor Ring is damaged			Overstressing the ring	1	Visual Indicator	8	80	
					Stress fractures occur due to regular use	1	Visual Indicator and assembly check	3	30	
		Clamp slips off	The device will be unsupported	8	Inefficient clamping force	3	Visual Indicator	8	192	Clamp Force Analysis
		Clamp Breaks			Overstressing the clamp	1	Visual Indicator	8	64	
					Sliding portion snaps	1	Visual Indicator	8	64	
		Clamp slide attachment is deformed			Overstressing of the clamp	1	Visual Indicator	8	64	
		Clamp attachments fracture			Attachments are maufactured poorly or stress fractures occur over regular use	1	Visual Indicator	8	64	
		Clamp teeth shear			Stress fracture occurs from manufacturing or regular use	1	Visual Indicator	8	64	
					Moment of the mounting arm causes severe stress on the teeth	1	Visual Indicator	8	64	
12	Translate the Brackets	Shear of center pivots in force block	Unable to apply axial force	7	Overstressing the rails	1	Audible and Visual Indicators	6	42	Factor of Safety Analysis
1		Bending of the rails	Device is not able to translate toward the standoff location	7	Overstressing the pivots	2	Visual Indicator	8	112	Deformation Test
4		Force Block does not slide			Friction force is too great	1	Audible and Visual Indicators	5	35	Bearing Analytical Analysis
					Ball Bearing Breaks	2	Visual Indicator	8	112	
1		Rails are damaged			Ball bearing would cause cracks or surface damage	1	Visual Indicator	8	56	
					Sliding would create scratches due to the metal frame of the force block	1	Audible and Visual Indicators	5	35	
					Weight of the rails cause deformation	2	Audible and Visual Indicators	5	70	Deformation Test
13		Force block locks are damaged	Force block is not able to be held in place	7	Formation surface damage of the rails	1	Audible and Visual Indicators	5	35	
					Force Block creates a greater sliding force than the locking force	1	Audible and Visual Indicators	5	35	Bearing Analytical Analysis
					Stress fracture occurs from manufacturing or regular use	1	Audible and Visual Indicators	5	35	Material Selection Analysis

9	Hold Bracket	Clamping screw breaks	Unable to clamp standoff bracket template	8	Stress fracture occurs from manufacturing or regular use	1	Visual Indicator	8	64	Mechanics of Materials Life Cycle Analysis
					Thread shears off	1	Visual Indicator	8	64	Thread Material Properties Analysis
3		Clamp jaw deforms			Stress fracture occurs from manufacturing or regular use	1	Visual Indicator	8	64	Material Selection Analysis
					Clamp shape does not match the bracket template being installed	1	Visual Indicator	8	64	
		Clamp jaws break			Stress fracture occurs from manufacturing or regular use	1	Visual Indicator	8	64	
					Overstressing of the clamp	1	Visual Indicator	8	64	
		Mounting arm cannot be adjusted	Unable to hold standoff bracket	7	Bracket Template mass exceeding mounting arm maximum load	1	Visual Indicator	8	56	
		Bracket slips off			Incefficent clamping force	3	Visual Indicator	8	168	Clamp Force Analysis
		Bracket breaks	Standoffs are not secured in place	8	Clamping force exceeds material max force	1	Visual Indicator	8	64	
					Clamp and bracket contact is minimal causing deformation	1	Visual Indicator	8	64	
22	Apply axial force	Lead Screw breaks	Unable to apply axial force	8	Force induced deformation of screw	3	Audible and Visual Indicators	5	120	Lead Screw Stress analysis
					Moment induced deformation of the screw	1	Audible and Visual Indicators	5	40	
14		Assembly screws break			Overstressing of the device at the screw locations	1	Audible and Visual Indicators	5	40	Material Selection Analysis
					Stress fracture occurs from manufacturing or	1	Audible and Visual Indicators	5	40	
7		Shaft Collar disconnects	Bracket Clamp disconnects from force block	7	Deformation wear of the securing screw	1	Visual Indicator	8	64	Deformation Analysis
15		Lead Screw and Fish Scale box attachment breaks due to axial force testing			Attachment breaks due to continous use or manufacturing	1	Visual Indicator	8	64	Material Selection Analysis
		Fish Scale does not read correctly	Force will not display to operator	5	Spring does not function with the device	2	Visual Indicator	8	80	Spring Analysis
					Spring deforms over continuous use or from manufacturing	1	Visual Indicator	8	40	
					Fish Scale box deforms over continuous testing	1	Visual Indicator	8	40	

4, 13	Locking	Force block slides during axial force tests	Device can not be applied to specific location	7	Applied force exceeds lock capacity	5	Audible and Visual Indicators	5	175	Material Selection Analysis
					Force Block creates a greater sliding force than the locking force	1	Audible and Visual Indicators	8	56	Bearing Analytical Analysis
					Rail deformation is already present	1	Visual Indicator	8	56	
					Frictional Coefficent on rail clamping system is not sufficent for the device	1	Visual Indicator	8	56	
					Stress fracture occurs from manufacturing or regular use	1	Visual Indicator	8	56	Material Selection Analysis
12		Center Block moves rotationally			Applied force exceeds lock capacity	1	Visual Indicator	8	56	
					Side shearing occurs over regular use	1	Visual Indicator	8	56	
4		Center block cart attachments shear			Stress fracture occurs from manufacturing or regular use	1	Visual Indicator	8	56	
					Rotational movement creates deformation	1	Visual Indicator	8	56	
					Applied force exceeds lock capacity	1	Visual Indicator	8	56	
11	Angle Bracket	Bracket Joint Pin Shear Failure	Inability to carry out the pull test	7	Applied axial force	6	Visual Indicator	8	336	Material Selection Analysis
					Stress fracture occurs from manufacturing or regular use	1	Visual Indicator	8	56	
					Moment of the mounting arm	1	Visual Indicator	8	56	
3		Bracket Clamp to Arm attachment shears	Unable to hold standoff bracket	7	Applied axial force	1	Visual Indicator	8	56	
10		Spline Mounting Screw Shears	Device will be unsupported	8	Maufacturing or regular use	1	Audible and Visual Indicators	5	40	Spline Shaft Gear Analysis
					Axial force	6	Audible and Visual Indicators	5	240	
5, 6		Spline Hub breaks			Axial Force is greater than the gear material can experience	1	Audible and Visual Indicators	5	40	
		Spline Shaft breaks			Axial Force is greater than the pin material can experience	1	Audible and Visual Indicators	5	40	
		Spline Shaft Deforms			Axial Force is greater than the pin material can experience	1	Audible and Visual Indicators	5	40	
					Stress fracture occurs from manufacturing or regular use	1	Audible and Visual Indicators	5	40	
-	Does not carry electro static charge	Does not meet ESD Compliance	Damage electronic components	10	Material is non-conductive	1	ESD Test	1	10	Create ESD Testing Procedure
					Device does not have grounding capability	1		1	10	Create ESD Testing Procedure

22.16

22.17