# Project B8 - Universal Dome Standoff Bonding Tool

## Preliminary Proposal

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# 1 DISCLAIMER

# 2 TABLE OF CONTENTS

# 3 BACKGROUND

## 3.1 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.

## 3.2 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 least 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 . The pull test is required due to Northrop Grumman’s current process of applying a pull test 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 client 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 $10,000.

# 4 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.

## *4.1 Customer Requirements (CRs)*

As discussed in the project description (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 circuity. 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 four inches 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. 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; so 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 up to 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 of freedom. 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 a durable and robust for future use.

Along with these requirements specified by the client, the design team is requiring that the device be within the budget provided by Northrop Grumman ($10,000). The handling arm shall also be a reliable design for operators and be safe 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 transport for operators. Table 1 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 | Transportability | 0.04 |
| 6 | Ease of Operation | 0.07 |
| 7 | Durability | 0.08 |
| 8 | Reliability | 0.08 |
| 9 | Adjustable Interfaces | 0.09 |
| 10 | Support 10 lbs. in Locked Position | 0.09 |
| 11 | Minimum 3.0 Factor of Safety | 0.06 |
| 12 | Cost Within Budget | 0.03 |
| 13 | Use of Multiple Mounting Arms at a Time | 0.05 |
| 14 | Safe Operation | 0.05 |

As shown in table 1 above, each customer requirement has a corresponding weight. The weights allow the team to show the significance of each customer requirement related to the project which includes ESD compliance, apply axial forces, six degrees of freedom, usable 4”-36” inboard of the ring, adjustable faces, and support 10 lb in a locked position are equally the highest rated customer requirements due to Northrop Grumman specifically asking 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. Despite being a customer requirement, 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. The use of multiple mounting arms at a time and safe operations are ranked at 0.05. The multiple mounting arm 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.

## *4.2 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. 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 also be affected by the principal dimensions (in.) of the device. This will alter the customer requirements associated with mass such as effect if 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 | $25 \pm 5$ |
| 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 (see section 3.1.1 for more details). 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 $\pm 5$ 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. These values are detailed further in section 5 of the report. 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 $360^0$around 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 (Aluminum 7075). Aluminum 7075 has a modulus of elasticity of $10.4 \times 10^6$Psi. 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.

## 4.3 House of Quality (HoQ)

The quality function deployment (QFD) model used to evaluate the customer and engineering requirements for this project can be seen in Appendix (B) near the end of this report. The purpose of this QFD was to relate the requirements given by the client to a set of engineering parameters derived by the team. Defined in detail above, 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 applying forces. 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 and render it unusable. 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. The tolerance set above was based on this idea. 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 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.

# 5 Design Space Research

Before performing the design generation and evaluation for this project, a further analysis of the project was conducted. This allows the design team to understand various aspects of the project that should be considered, which could have been possibly overlooked if research was not conducted beforehand. This chapter describes alternative approaches to designing the standoff bonding tool. These approaches included a literature review, benchmarking, and a functional decomposition. The literature review allowed the design team to research relevant topics in depth to gain a better understanding of various aspects of the project. Benchmarking allowed for the comparison of multiple devices that could be referred to during the design phase of the project. The functional decomposition allows for a visual representation of the sub-functions of the standoff bonding tool to see which subsystems affect one another.

## *5.1 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. These literature reviews can be read in further detail below.

### 5.1.1 Tyler Hans - ESD Compliance

As discussed in section 2, the final articulating device must be electrostatic discharge compliant. Due to the mechanical background of the design team, this customer requirement was the largest unknown. For this reason, an extensive background check into electrostatic discharge was conducted.

Electrostatic discharge is the transfer of electricity from a high charged object to a low charged object.

This is commonly known as static electricity. The charge transferred from one's hand to a door knob or an electric shock from one person to another after someone has rubbed their feet onto carpet is the result of electrostatic discharge. This phenomena is an extreme danger to electrical systems. If a static electric charge were to travel to the electrical components, the charge could damage or burn out the circuitry. This is a problem for the rocketry system because a burnt out circuit could cause the rocket's flight to fail. To get an in-depth understanding on what electrostatic discharge is and how to prevent it from travelling through the design to the electrical components, the following sources were reviewed.

To gain a better understanding of ESD compliance and to have a reference for future applications of the project, the engineering textbook, *Basic ESD and I/O Design* by Sanjay Dabral and Timothy Maolney, was reviewed. This textbook contains in depth analyses of ESD compliance in circuitry while also introducing the topic to the reader, discussing protection methodology, and additional considerations related to ESD compliance [3]. Many of the methodologies discussed within the text include circuitry and how it is affected by ESD compliance. This is important, because the team must gain a broad understanding of how static shock can affect electrical components and methods used for stopping this problem. Three ESD issues that are arising include increased number of I/O (input-output) and power pins per chip, the perpetuation of life by fixing nitrogen in the atmosphere to nitrates, and a cleaner atmosphere by helping to electrostatically clean the exhaust gases produced by factories” [3]. This source allows the team to gain electrical understanding, and be aware of possible solutions that could be designed around, such as the random and current path which are two current designs that make the ESD charge flow through the circuitry either on its own or in a designated path [3]. While these are not problems that the design team will be attempting to solve, this allows the team to have a source to refer to in the future for further background in ESD compliance in electrical systems. Furthermore, this is important because the original project sponsor, Mathew Johns, wanted the team to gain a larger understanding of what ESD compliance is, so that it could be addressed in the final design.

The ESD Association’s ESD Fundamentals informational page was the next source referenced. This overview of ESD introduces the phenomena, discusses principles of ESD control, basic ESD control procedures, materials, training, auditing, device sensitivity, testing, and ESD standards [4]. For the purposes of this project, the principles of ESD control, procedures, materials, and standards will be referred to in the future during the design process. One method of ESD control discussed in this article is the use of proper grounding or shunting that will dissipate any charge away from the product [4]. This is a likely solution for this problem in the future, however it would be desirable for the client if the articulating arm was designed to easily be grounded. Due to this, many of the ESD control procedures and materials available would need to be used by Northrop Grumman operators to ground the device [4]. In the future, if any designs need to follow ESD standards, they can be found in this source.

While the ESD Association discussed how to follow procedures and have the correct operation devices for controlling static shock, the Production Automation Corporation created a page that discusses anti-static, dissipative, conductive, and insulative materials and their differences [5]. Anti-static materials prevent the build up of static electricity and dissipative materials’ charge flows to ground more slowly, and in a more controlled manner [5]. This varies with conductive materials which have a lower resistance than dissipative materials, which allows the electrons to move easily across the surface through the bulk of materials [5]. Insulative materials prevent or limit the flow of electrons across the volume [5]. Since the device will be made to be grounded before operation, it is in the best interest of the team to have the device material be conductive in order to allow the charge to be grounded easily by operators.
To continue on the difference between conductive, dissipative, insulative, and anti-static materials, Transforming Technologies’ article discussing the difference between these materials helps the design team gain a greater technical understanding between them. Figure 1 below details how the difference between all these materials is the surface resistance in Ohm/Square [6].

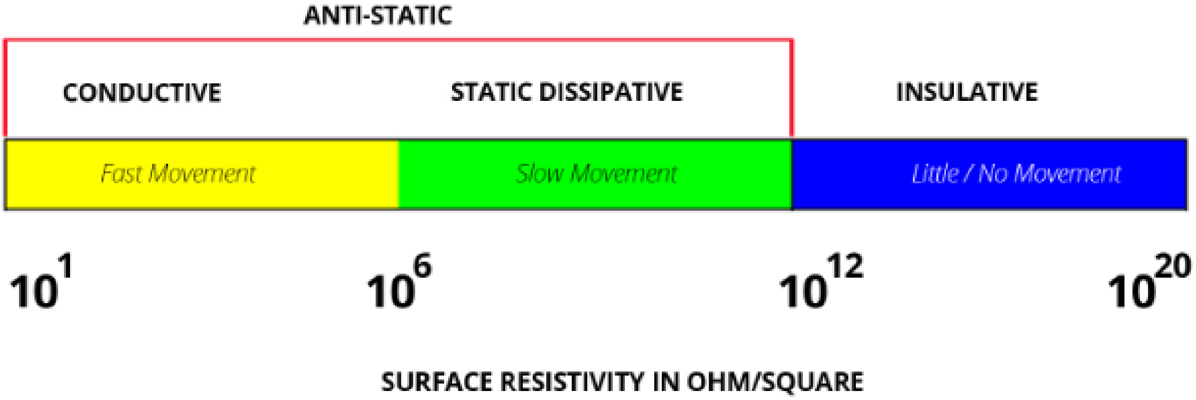


**Figure 1**: Difference in Resistance Between Material Types [6]

As seen above, anti-static is in fact both conductive and dissipative. Anti-static materials prevent the build up of static electricity, so the final design should not be insulative. Conductive materials have a surface resistivity from 1 to $1x10^{5} \frac{\Omega}{sq}$ or volume resistivity of less than 1 to $1x10^{4} \Omega cm$ [6]. Dissipative materials move slower and have a greater resistivity than conductive materials [6]. So articles [5, 6] prove that the design material should be as conductive as possible.

Based on the designs discussed in section 4 of this report, the material will likely be similar to the material used on the rocket motor ring such as aluminum or a stronger metal such as stainless steel. Aluminum has a larger thermal conductivity ($\frac{W}{mK}$) than stainless steel (237 vs 14.4) [7]. This will be considered in future applications of the project since stainless steel costs more than aluminum [8, 9], however stainless steel is stronger than aluminum [10, 11]. Once the design calculations are performed, a further in depth analysis can be done for the material selection of the design.

While ESD compliance is a design consideration that should be referenced throughout the project, for the purposes of this report, further solutions to prevention methods and design alterations were not looked into. This is due to the fact that many of the solutions, other than grounding the device, will be made during the material selection of design project. If there were no material selections that could prevent ESD compliance, a subpart, that would ground the device before being mounted on the rocket motor dome, would be created to solve this problem. However, according to the project sponsor, Daniel Johnson, there are many devices that allow operators to ground devices on site. Moving forward, a further look into ESD compliance, once design calculations are taken, should be made. This will allow materials that are ESD compliant, to be chosen or compared to materials that can pass the material property calculations.

### 5.1.2 Elaine Reyes - Mount to Ring

The ability to mount the device to the Orion 38, Orion 50XL, and Castor 30XL, seen in appendix A, is a requirement to consider in the design process. Clamping the device to the outer rings of these rocket motors requires the need to choose a design that secures the device in place, is adaptable and will not impose any damage to the outer rings. With that being said, this section addresses necessary design considerations for choosing a clamping method, a better understanding of feasible methods, and how this knowledge is applicable to the project.

The first source chosen for this literature review goes over how to choose the right clamp for various applications. This document contains pertinent information for the selection of a clamp which includes the consideration of the device diameter, thickness, clamp pressure/force, clamping area, clamp bolt spacing, insulator cup, insulator cup length, and clamping pressure [12]. In addition to providing the aspects to consider, instructions on reading clamp part numbers were provided to aid in the selection of the clamp. Although this document was brief, it provides information necessary for the initial steps to selecting the clamp that meets the project's requirements.

The second source addresses the principles and classifications of clamping. As previously stated, the device must be secured onto the outer ring of the rocket motor dome without deforming the material it is clamped onto. Other aspects to consider pertain to the actual design of the clamp which includes the materials of the clamp parts, simplicity of the clamping mechanism, and the employment of pressure pads to avoid damaging or distorting the object subjected to the clamping force [13]. This document addresses 19 different classification of clamps with the purpose of guiding the reader to selecting a viable clamping system for their device. Specifically for this project, the use of pressure pads as part of the clamping system may be useful since its purpose is to clamp thin-walled components, mitigating the potential of deforming the ring's material [13]. Additionally, this source provides the general types of clamps that the team can consider such as three-point clamps, two-point clamps, and toggle clamps. This source is useful when considering the clamping mechanism that best suits the team's final design.

Part of designing a clamp requires the consideration of the torque and tensions in the fasteners. The third source provides formulas that relates the torque and clamping force defined by tightening the fasteners to the clamp [14]. This source also provides the yield clamping force and additional formulas pertinent to potential back-of-the-hand calculations for a more in-depth mathematical analysis. Based on the provided formulas, the team will be able to better analyze potential design options supported by a mathematical analysis. In addition to provided formulas, the Machinery's Handbook also identifies appropriate bolt and screw specifications that closely align with the calculations.

The fourth source is a patent of a quick clamping system meant to mount and support objects that may be a pole, table top, or any stable support members for medical equipment [15]. This patent allows instruments and other objects to be moved quickly and easily which is an aspect to consider when deciding the device's clamping mechanism. The patent models a clamping device composed of a C-clamp with an arm having an inner surface position, the other arm pushing against one side of a support member, and an adjustable locking screw [15]. Although this patent was created specifically for mounting medical devices, the team can utilize parts of its design aspects and integrate it with other suitable designs.

The fifth source is another patent which models a U-shaped yoke having a plate member with a hook at one end, a tooth at the other end, and a plate that attaches the two plates together [16]. This patent's purpose is to clamp a device to a wall or roof brace and to support a pump jack pole. The pump jack pole is held in place in a fashion that would be useful for attaching a device that utilizes two arms. Furthermore, this patent, similarly to the previous patent, would be useful in the design of the clamping mechanics that would best fit the team's final product.

### 5.1.3 Brandon Bass - Apply Axial Force

The application of the axial force to secure the bracket onto the standoff while the adhesive cures is an important aspect of the project to consider. The method of force application currently utilized within the proposed final design is the power screw. The purpose of this literature review is to explore the variations of axial force applications, understanding of their physical mechanisms, and how they could be integrated into our design. The proposed methods should be capable of meeting the stated engineering requirement of 20lb of push force and ideally be used for the 50lb pull test. This is a requirement of the project because the adhesive used by Northrop Grumman require these quality control operations to ensure functionality during testing. The method should also ensure that the stability of the design is not compromised in order to mitigate any damage to the sensitive components of the rocket or the outer attachment ring of the motor. To ensure the quality of this review a wide variety of sources will be considered.

The current proposed method of our design is to apply a push force via a power screw or other method mounted to the bracket holder assembly. The advantages of using the power screw include the ability to translate rotational motion into linear motion which will help minimize the complexity of the design. Another design that is being considered includes a floor jack mechanism that would be actuated once the bracket holder is in position. The last method being considered is the variable stiffness spring which utilizes variable force transmission to dial the appropriate force onto the bracket. Using the literature review it will be easier to assess the power screw and other designs relative to the requirements of our project.

The first article selected for this literature review is related to the power screw design that we have proposed for the axial push force aspect of the design. This article contains information pertaining to the identification and selection of lead screws. The thread forms most utilized for power transmission include acme, stub acme, ISO - metric trapezoidal, and worm threads [17]. This article provides insight into the physical phenomenon associated with lead screws such as lead accuracy, matched lead, straightness, backdriving, life and efficiency [17]. Information on the selection of a lead screw based on the nature of the loads, direction and size are factors that will be taken into consideration when designing the final iteration of our design. This article will prove to be a beneficial reference during the design phase of our project.

The second article selected for this literature review expands upon the information on lead screw design and applications provided in the previous article. The push force method of this project will rely on some form of linear motion acting to secure the bracket holder in an effort to facilitate the curing of the adhesive. In order to ensure the quality of this push operation, it is imperative that we consider the best fit and design for the lead screw. This article provides information on a variety of power transmission methods ranging from lead screws to ball screws. Information included on these different methods include the expected load capacity, efficiency, speed, duty cycle, and backlash which are all important factors to consider when finalizing our design [18]. The area of interest of this article will be the benefits and disadvantages of the two power screw designs considering eachs potential to improve the quality of our product.

The third source chosen for this review provides insight into the mechanisms associated with scissor type floor jacks. This source is considered as it is closely correlated with the proposed subsystem design for power transmission to the bracket. This subsystem utilizes much of the concepts composing the section on lead screws but varies enough in operation that it warrants further research. The benefits of the floor jack mechanism is the ability to apply heavy loads with minimal manual input which is a desirable trait as our product is meant to be operable by one to two technicians [19]. The area of interest of this article includes the scissor jack which we plan to redesign to meet the engineering requirements of the project. While the scissor jack is not the preferred method of push force application, it is still a serious consideration for the final design.

The fourth article considered for the literature review analyses another iteration of the scissor jack design which applies hydraulic forces. The hydraulic jack is proposed as a method of push force application due to its heavy force capacity [20]. The common uses of this form of jack is in automotive maintenance and repair, therefore we would need to perform a redesign to fit the purposes of our project. The disadvantages of this system include the increased cost and weight which could negatively affect our efforts to reduce torsional loads on the outer attachment rings of the rocket. This design could prove effective if implemented in a fashion to reduce its weight and size.

The fifth article chosen for this literature review includes a google patent that involves the use of a variable stiffness spring which could provide a potential push force method. The mechanical elements described within the patent include the concepts of adding and subtracting coils from a spring and effectively changing its spring stiffness [21]. This variable force transmission could be a potential solution to the push force method required for the project but may not meet the standards of the 50lb pull test. This mechanism could be easily operable by technicians as well as incurring little weight to the design. Other than the disadvantages associated with the inability to apply this method to the pull test, the concepts involved could be considered for the push test operation.

### 5.1.4 Sage Lawrence - Locking Methods

The primary objective of this capstone project is to position a bracket above a specific location on a rocket motor dome and apply a force. Precisely locating the bracket will require various mechanisms for movement, which need to sum to a total of six degrees of freedom. This allocation for movement presents a conflict when applying a load, as the design will need to be rigid in order to maintain the location of the bracket. To verify that both of these needs are met by the final design, research was performed regarding various locking mechanisms. These subsystems, or some related form of them, could be used to finalize the relative position of each component while an axial load is applied.

At the end of the extended arm, a mechanism will be in place to lower the bracket to the surface of the motor dome. One option for completion of this task is the use of a lead screw, which would allow positioning of the bracket at any depth and provide accurate control over the force applied to the surface. Research into this topic resulted in some of the benefits of lead screws over ball screws in locking applications, as well as the required efficiency for self locking to occur. The article that relays this information covers the different potential materials, including the combination of a stainless screw and plastic nut. This material selection can be used to carry loads of up to 100 lbs, which is more than the maximum load for this design application [22]. Both of these materials will also be able to withstand the humid environment in which the device will be used, and would save weight over an entirely metallic set up, creating a viable option for this locking mechanism.

Another factor of bracket placement involves the need for a universal angular positioning of the bracket on the rocket motor dome. The profile of the dome extends axially toward the center of the motor, creating an uneven mounting surface. The design must account for this, while also being able to lock the angular position when applying a load. The second source utilized for this literature review contains a patent for an angleable camera tripod head, which can lock into any position desired by the photographer [23]. While this specific design is represented in a legal patent and is therefore not usable, it provides a general idea of how locking angular positioning may be achieved.

Multiple aspects of this design require that parts can be accurately positioned with distance as a continuous variable. This  means that the components need to stay in place at any position, rather than at preset distances. In order to accommodate this feature, research into locking methods included machining fits. Information provided in the textbook *Shigley's Mechanical Engineering Design* describes the parameters of a sliding fit [24]. This fit would allow for location of universal joint, or on a rail, while still being manipulable by hand. Using the provided tolerances would allow the team to machine parts that would be relatively easy to handle and would maintain position when let go. This type of fit also improves the ability to lock sliding systems, as some resistance to movement is already provided.

Research was also performed with respect to systems that could lock a component in place along a sliding rail, which resulted in the next reference. This reference contained a patent for a hand clamp, which locks into place on two parallel rods, as seen in figure 2 below [25].

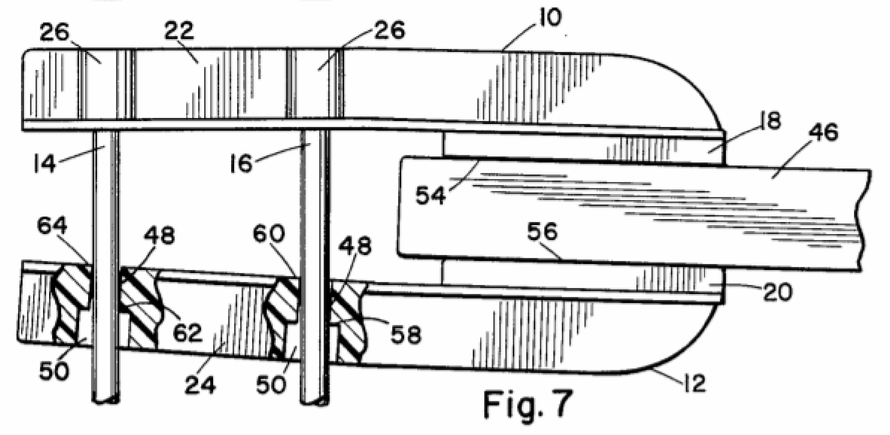


**Figure 2**: Hand clamp in actuated position [25]

The design of this clamping device does not directly show a method for locking onto a sliding rail, but the mechanism for locking the clamp into place provides insight on how to do so. This method could be used to lock a component in place on parallel rails by shifting a portion of the part away from parallel, as seen on the left side of figure (2).

The final article covered in this literature review provides a description of friction locking devices, which utilize the coefficient of friction between two materials to lock them in place, without the need for a key [26]. The use of one of these devices to lock the rail system or any other adjustable portion of the device into a specific position would allow for a simple, lightweight system to control location.

Understanding different locking mechanisms and how to implement them is necessary for the completion of a design that is able to hold desired component positions. Research into this topic has provided many options for the team to explore moving forward, as well as knowledge of methods that may be combined to maximize effectiveness. While further methodology exploration will certainly occur before finalization of the design, these sources provided a useful introduction into locking systems.

### 5.1.5 Dakota Saska - Rocket Motor Basics and Components

Obtaining a strong understanding on rocket motor basics and background information is crucial to have a strong foundation to build the project up from. Without a broad understanding of what the teams design attaches to, various aspects of the design that should be considered can potentially be overlooked. Rocket motors are essentially a controlled, directed explosion that create enormous impulses that reach very high altitudes and speeds. These motors are used in explosive missiles, space shuttles, planetary satellites or anything that needs to travel long distances fast or leave the atmosphere. They are generally comprised of a durable, heat resistant case filled with a propellant (often solid propellent grain rather than liquid fuel), capped off with motor domes with the aft end comprised of the rocket nozzle that directs the exhaust and provides increased propulsion. To gain a better understanding of these various components and general rocket motor basics, four scholarly articles were reviewed.

The first article covered blast-resistant rocket motor cases that utilized an organometallic polymeric resin used to impregnate glass filaments to construct the composite motor case and other inert components. These filament reinforced resin cases provide a lighter weight case, requiring less insulation to be installed, with a greater ease of manufacturing, storage, transportation and stability [27]. This article covered the various layers of rocket cases and how photon energy can damage the system if the correct materials and layering is not applied. This article directly relates to the project design as the case is the main body of the motor, and with an articulating arm that attaches to the aft ring of the case, knowing what this component is constructed out of and how it affects the overall system will ensure that the team accounts for any effects to or from this component. The design shouldn’t interfere with the workings or composition of the case to ensure that the structural integrity of the case and further damage is nullified.

The second component to look at is the nozzle that protrudes from the aft end of the rocket motor which directs exhaust and helps increase propulsion. This component is subjected to the highest thermal environment during working conditions and this article covers the thermal structure characteristic of the solid rocket motor nozzle under thermal flow fields [28]. The experiment conducted in this article compared two nozzle types, one of carbon/carbon while the other was asbestos/phenolic material and how the trials were affected for different temperature ranges. By determining the impact on thermal deformation, stress and contact character of the nozzle structure, durability, reliability and longevity for the nozzle can be estimated for implementation on rocket motors. This article was also directly related to the teams design as the articulating arm will also be attaching to the aft end of the motor and will be directly adjacent to the nozzle. By understanding the material properties and function of the nozzle, the team can ensure they don't affect the nozzle during implementation of the working design.

The next component of the rocket to be considered is the actual driving force of the motor propellant. There are two primary categories of rocket engines depending on the rocket propellant; liquid rocket engines and solid rocket engines [29]. This article covered the two primary rocket types and how they function during ignition. It covered four different types of solid propellant compositions that can potentially be used in various rocket motors. It then covered the different geometries of the fuel within the case and the different burn types acquired. With all the general background covered, the article then showed the total impulse that can be applied for the various propellants and geometries utilized in rocket motors. This article wasn't directly related to the project design for the team but it was related to the overall understanding and functionality of the rocket that the design will be attached to. By understanding all facets of the motor it will ensure that the team doesn't overlook any portion of the design. For example, understanding the total impulse the rocket motor can impart helps us understand why we need the 50lb pull test required by our client, so that the device doesn't fall off the rocket dome when being launched.

Another look at the solid rocket motor propellant was covered in the fourth article which talked about the fatigue and damage during rocket transportation. In a rocket's transportation process, road roughness loads can bring about vibrations that lead to structural damages that can be turned into cracks which leads to negative impacts on the motors reliability [30]. This article covered how various transportation methods lead to vibrations within the fuel and how this is used to estimate fatigue and damage for its lifetime. This article is especially relevant for this project since the rocket motors the team is working on are built in Utah, shipped to Chandler, AZ for modifications and component integration, and then down to Florida or Texas where most of Northrop Grumman's launches are performed. This isn't directly related to what the team is designing but as a whole it is relevant to what is being worked on.

The last article reviewed was the Propulsions Product Catalog provided to the team from Northrop Grumman. This catalog covered nearly all of the rocket motors that are utilized at Northrop Grumman and gave brief details about general dimensions, relative specifications and typical performance. The most important aspect of this catalog was the four rocket motors that the team is specifically designated to attach to. The Orion 50 and 50 XL, Castor 38, and the Castor 30XL are all specific rockets listed within the catalog that the teams articulating arm will mount to. The catalog gives general dimensions of the motor, such as varying diameters from 38"-92" [1] with which our arm should be able to attach to. This is the most relevant article for the team as it covers material that is directly related to the design process and performance of the articulating arm being manufactured.

## 5.2 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.

### 5.2.1 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.

#### 5.2.1.1 *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 [31]. 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 3 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 3:** 6 DOF Robot Arm [31]

#### 5.2.1.2 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 [32]. Figure 4, 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 4:** Dual Arm [32]

#### *5.2.1.3 Existing Design #3: Aluminum Rail Workstation Cranes*

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 [33]. 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 5**: Aluminum Workstation Cranes [33]

### 5.2.2 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 (section 3.3 below) 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.

#### *5.2.2.1* 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 []. 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.

##### *5.2.2.1.1* 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.

#### *5.2.2.1.2* 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.

#### *5.2.2.1.3* 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.

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

The transmit mechanical energy subsystem originates from the customer needs 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.

#### *5.2.2.2.1* 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 it 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.

#### *5.2.2.2.2* 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.

#### *5.2.2.2.3* 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.

### *5.2.2.3* 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 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.

#### *5.2.2.3.1* 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.

#### *5.2.2.3.2* 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 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.

#### *5.2.2.3.3* 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 teams 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.

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

In order to meet the customer requirement for the device to be usable 4"-36" inboard of 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.

#### *5.2.2.4.1* 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.

#### *5.2.2.4.2* 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.

#### *5.2.2.4.3* 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).

### *5.2.2.5* 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 and 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.

#### *5.2.2.5.1* 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.

#### *5.2.2.5.2* 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 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.

#### *5.2.2.5.3* 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.

### *5.2.2.6* 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.

#### *5.2.2.6.1* Existing Design #1: Miter Clamp

The first subsystem-level existing design is the miter clamp that are typically used to hold two objects together at 90 degrees. Typically, miter clamps are 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.

#### *5.2.2.6.2* 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.

#### *5.2.2.6.3* 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.

## 5.3 *Functional Decomposition*

The functional decomposition serves to provide a visual representation and understanding of the flows and sub-functions of our project. The processes that this operation is composed of 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 our design as well as the overall function. The flows that are addressed in the black box model include the hand and bracket which represent material flow, human which is an energy flow, and position which is a signal flow. The overall function of our project 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 and places an emphasis on what is being accomplished by our design rather than how. Using the ideas and information gathered during the creation of the black box model and evaluation of the customer needs we could determine the sub-functions required of our design. The sub-functions identified during this process would allow us to begin the concept generation with the creation of a morph matrix which is further discussed in section 4 below. 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 ensures 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.

### 5.3.1 Black Box Model

This section outlines the team's process of creating and finalizing the black box model. The purpose of creating the Black Box Model is to understand the overall function of the product that will be designed and its appropriate inputs and outputs. There are three categories of inputs and outputs, also known as flows, which includes material(s), energy, and signals. These flows provides 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 hand and bracket. A bracket will be mounted to 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 positioning the device. To know whether the product is pushing the standoffs in place, the product will signal the use through a click or snap noise. Figure 6, as shown below, shows the team's final Black Box Model.

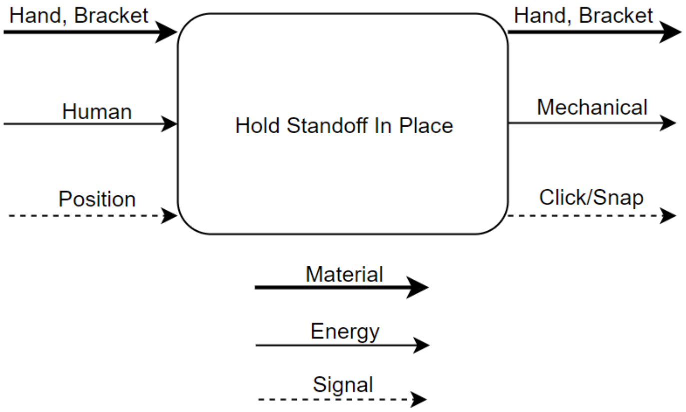


**Figure 6:** Black Box Model

### 5.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

This section covers the functional decomposition model derived from the black box model in figure 6. 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 very deep understanding of the overall function and working of the design. The functional decomposition model presented in figure 7 is an expanded view on the black box model above. 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 flows than it seems.

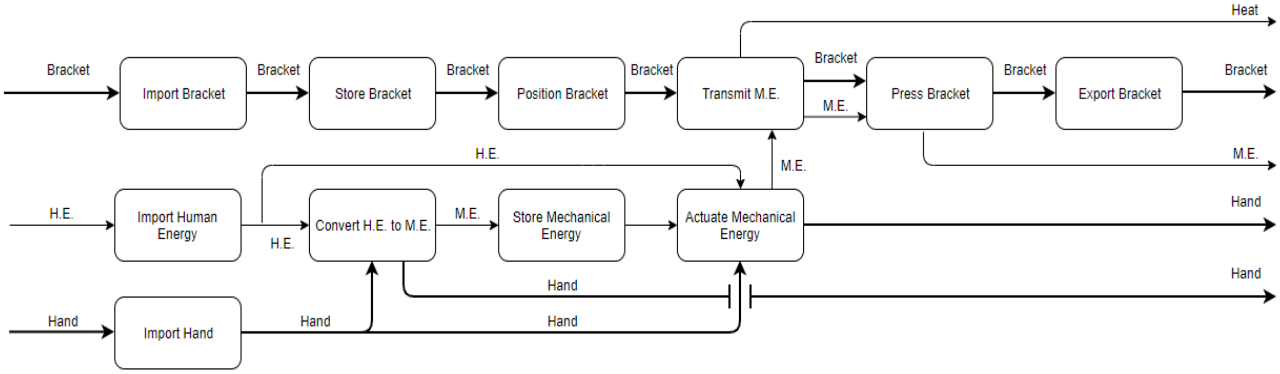


**Figure 7:** Functional Decomposition Model

In figure 7 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 into 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 generation for each sub function and subsystem of the design could be proposed to begin creating various concepts that fit the function of the black box model and functional decomposition. The design being created must import and store a bracket, position that bracket, and apply a force to the bracket during the curing process all by means of human power. These derived sub functions of the design are what will be used to ensure the customer needs gathered from Northrop Grumman are satisfied.

# 6 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.

## *6.1 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.

### 6.1.1 Full System Design #1: Rail Crane

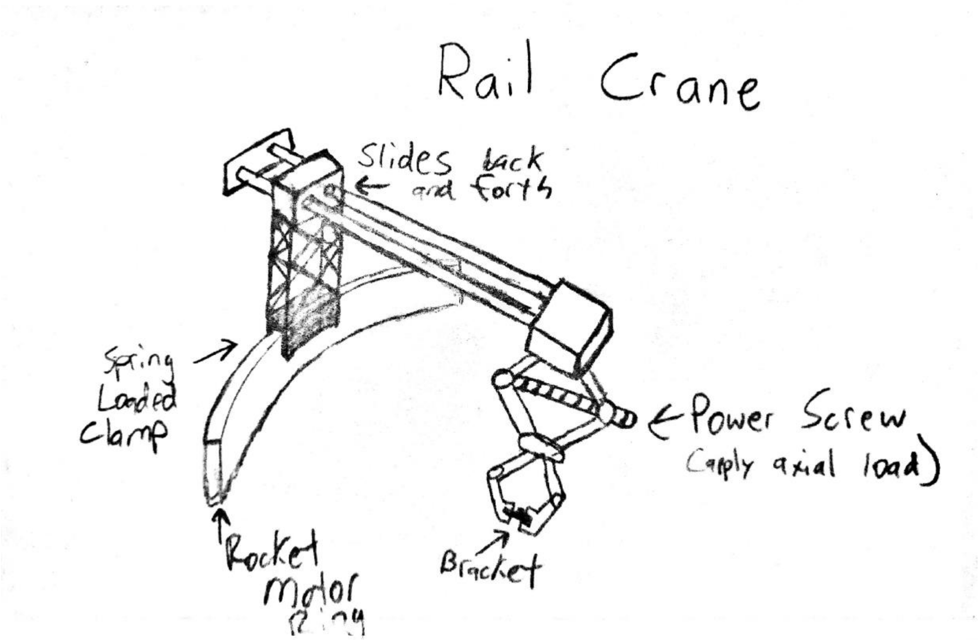
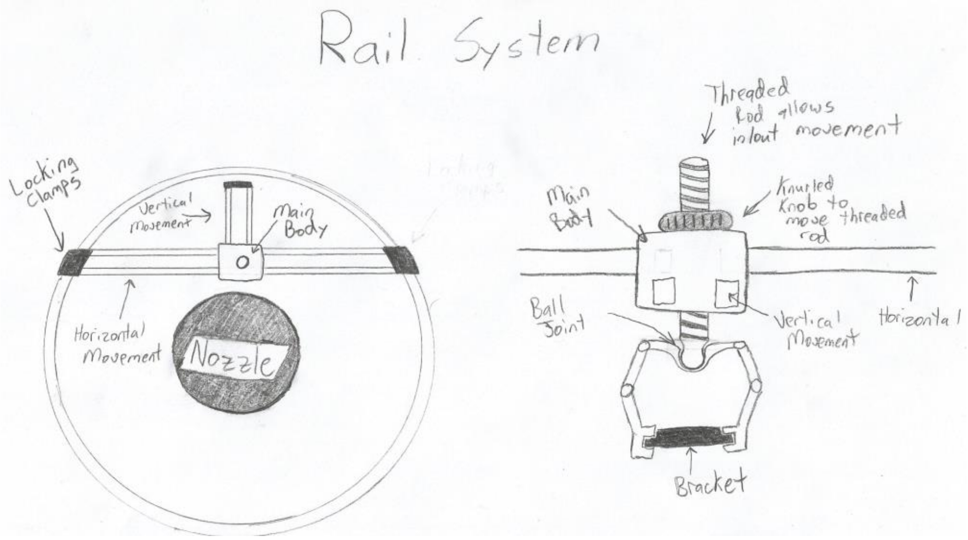


**Figure 8:** Rail Crane Design

Figure 8 above shows a fairly detailed drawing of the first full system concept developed. This design is loosely based off a construction crane that slide 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 50lb 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.

### 6.1.2 Full System Design #2: Rail System



### 6.1.3

**Figure 9**: Rail System Concept

The rail system concept depicted in figure 9, 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.

### 6.1.4 Full System Design #3: Computer Articulating Arm

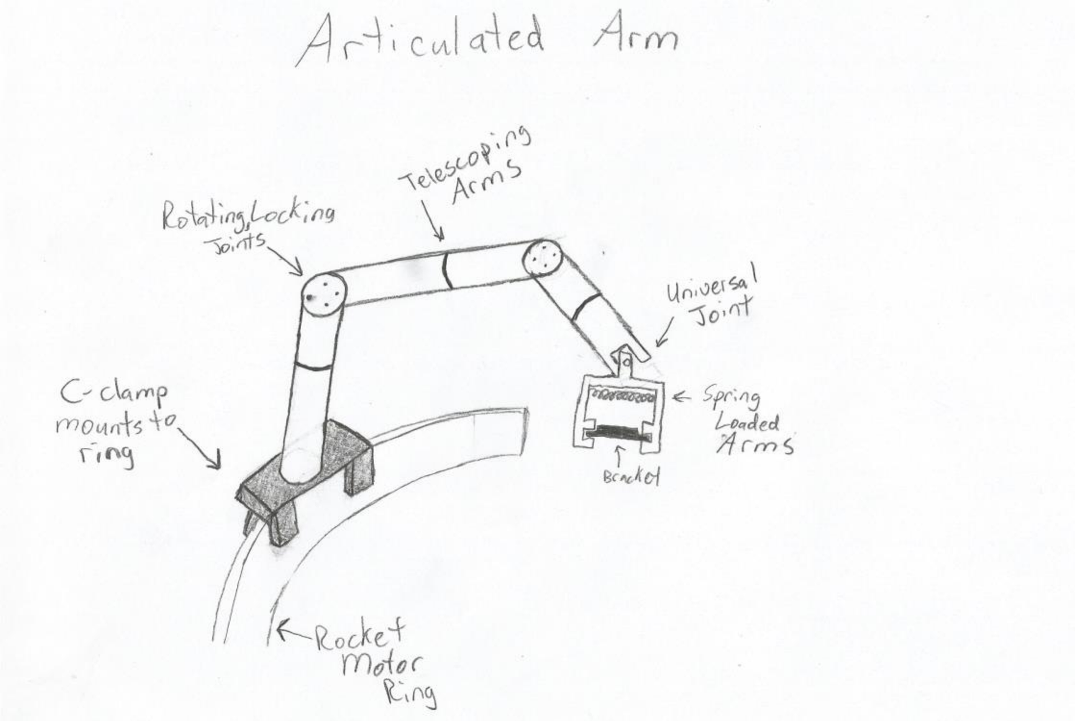


**Figure 10**: General Articulating Arm

The final full concept system that the team generated is a general articulating arm. 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.

## 6.2 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 in figures 6 and 7 above. 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.

### 6.2.1 Subsystem #1: Hold Bracket ("Press Bracket")

The following designs are the proposed concepts that the team generated to hold the bracket. Based off section 3.2.2, the existing designs for these subfunctions, the team generated variations of these to implement on the project.

#### 6.2.1.1 Design #1: Spring Clamp

Figure 11 below shows the teams 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.

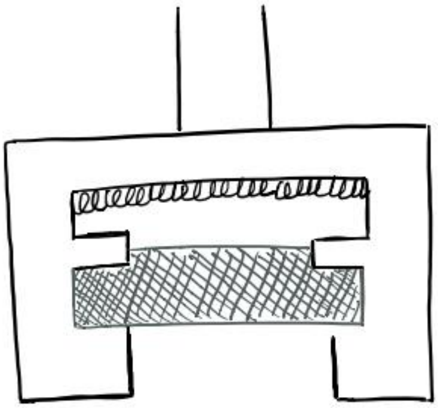


**Figure 11**: Spring Clamp Concept

#### 6.2.1.2 Design #2: Threaded Clamp

The threaded clamp shown in figure 12 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.

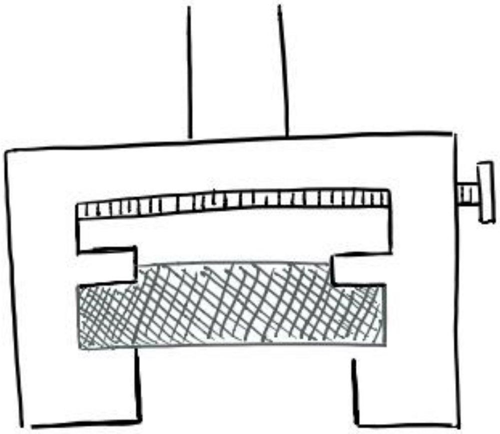


**Figure 12:** Threaded Clamp Concept

#### 6.2.1.3 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 13 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.

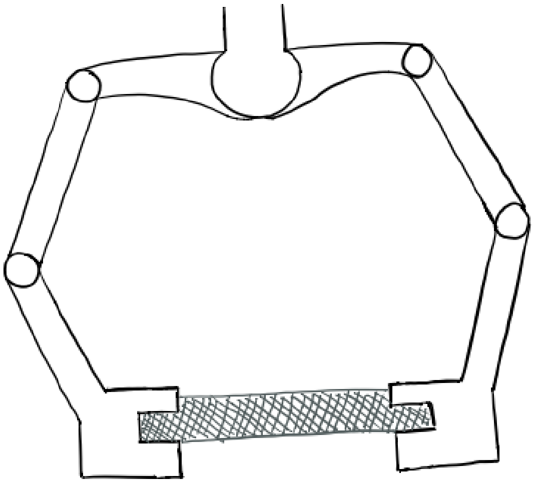


**Figure 13**: Claw Concept

### 6.2.2 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.

#### 6.2.2.1 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 14 below.

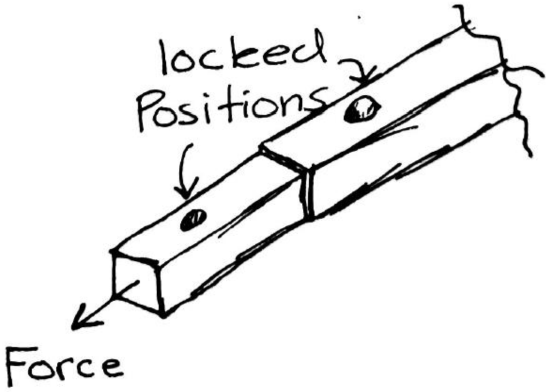


**Figure 14**: Telescoping Method

As seen above in figure 14, 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.

#### 6.2.2.2 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 15 below.

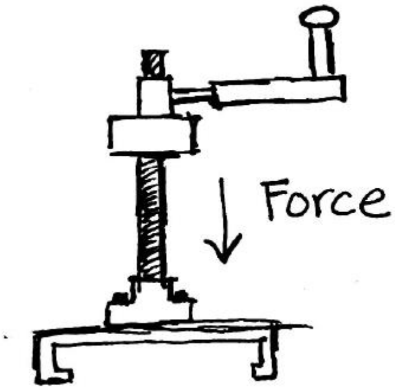


**Figure 15**: Lead Screw

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.

#### 6.2.2.3 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 16 below.

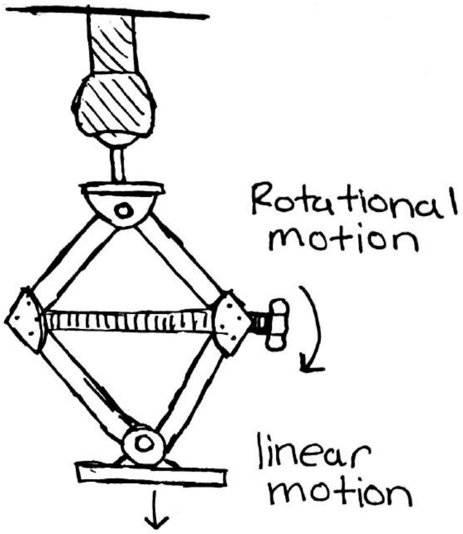


**Figure 16**: Scissor Jack

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.

### 6.2.3 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.

#### *6.2.3.1 Design #1: Locking Ball and Socket Joint*

Figure 17 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 17**: Ball and Socket Concept

#### 6.2.3.2 *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 18 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.

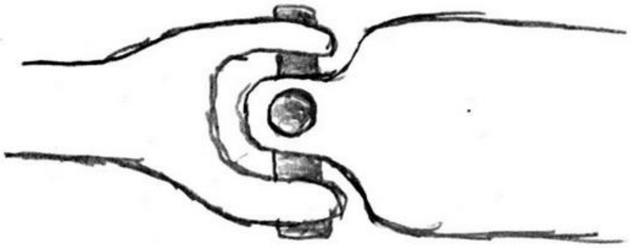


**Figure 18**: Universal Joint Concept

#### 6.2.3.3 *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 19. 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 19:** Parallel Plate Concept

### 6.2.4 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 3.2.2.4. 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.

#### *6.2.4.1 Design #1: Telescope*

The telescope design as seen in figure 20 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.

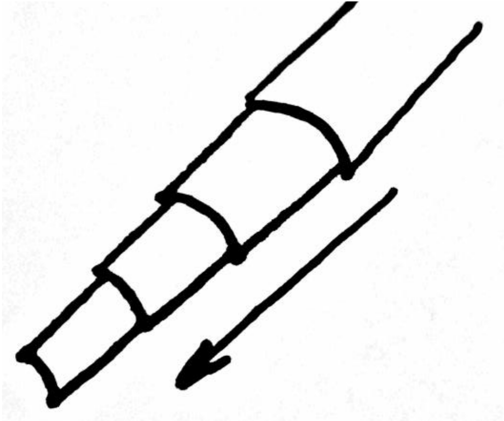


**Figure 20**: Telescope Translation

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.

#### *6.2.4.2 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 21 below.

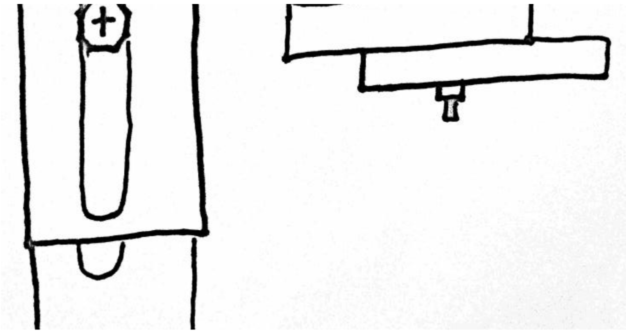


**Figure 21**: Sleeve Translation

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.

#### *6.2.4.3 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 22 below.

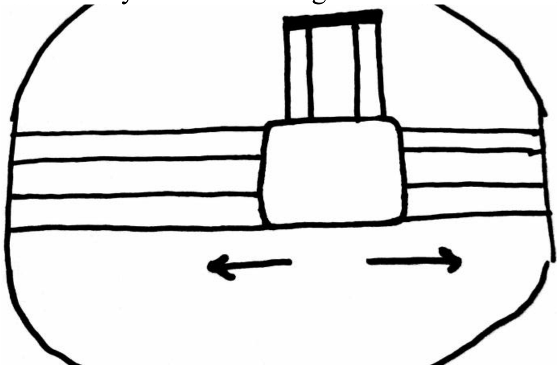


**Figure 22**: Rail Translation

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).

### 6.2.5 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.

#### *6.2.5.1 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 23 below.

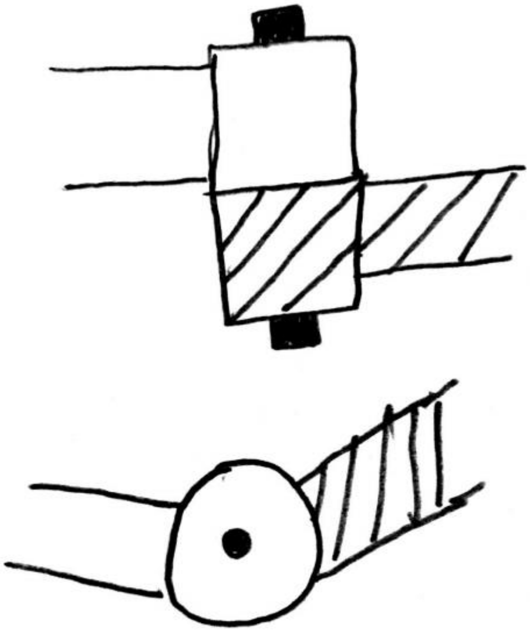


**Figure 23**: Threaded Joint

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.

#### *6.2.5.2 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 24 below.

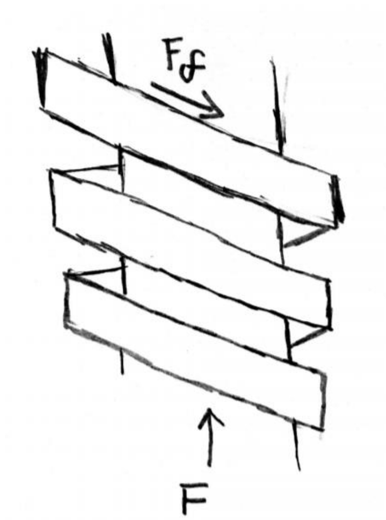


**Figure 24**: Self-Locking Screw

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 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.

#### 6.2.5.3 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 25 below.

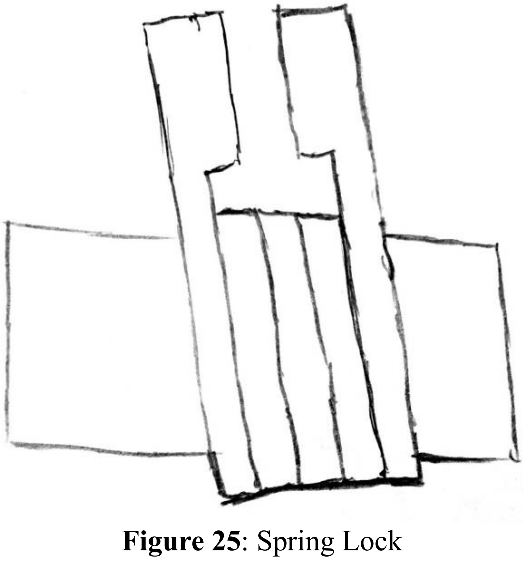


**Figure 25**: Spring Lock

The spring lock design operates similarly to the springs used in a gym to set 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.

### 6.2.6 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.

#### *6.2.6.1 Design #1: C-Clamp*

The implementation of a c-clamp 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.

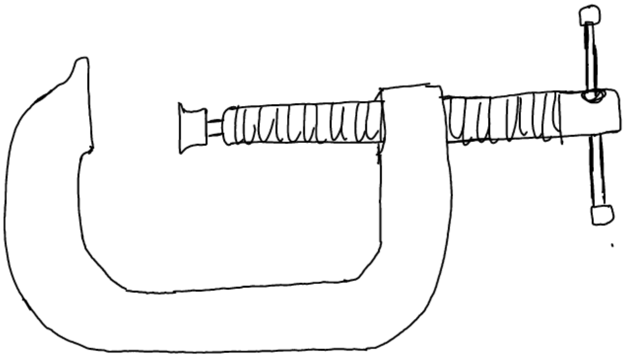


**Figure 26:**. C-Clamp

#### *6.2.6.2 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 27, 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.

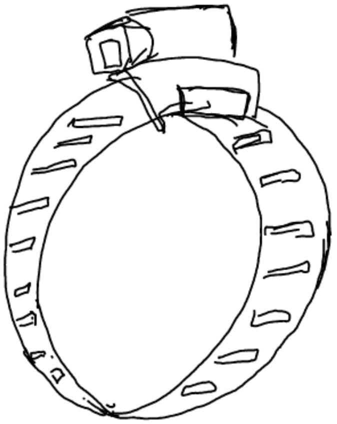


**Figure 27:** Hose Clamp

#### 6.2.6.3 *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 28, 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.

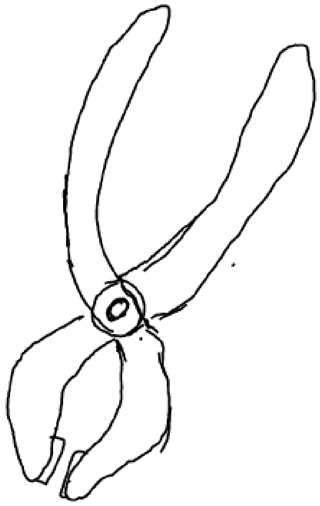


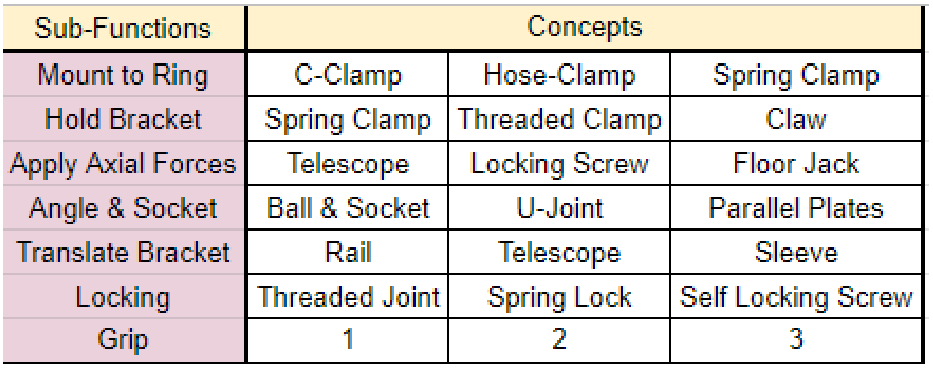
**Figure 28**: Spring Clamp

# 7 DESIGNS SELECTED – First Semester

Various concepts for each of the sub-functions considered in this design were generated in order to visualize the design intent. The section below outlines these concepts and places them into full designs, which are then compared in a pugh chart and decision matrix. Two designs are then selected as best for fulfilment of the customer requirements, which is ultimately reduced to a final design concept. Also included are some back-of-the-hand calculations to justify one of the more complicated decisions.

## *7.1 Technical Selection Criteria*

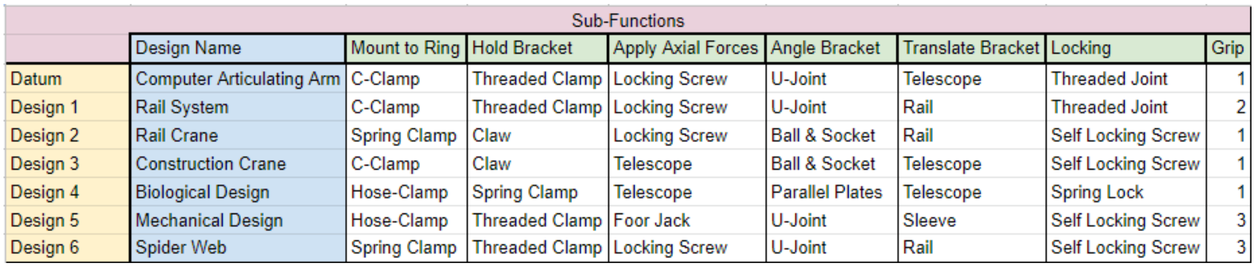
To facilitate a meaningful selection process from the generated concepts, the team utilized the list of sub-functions that were originally sourced from the customer engineering requirements. These sub-functions are centered around locating the necessary positioning of the bracket and holding it in place while applying an axial force. A more detailed breakdown of the sub-functions and the related concepts can be seen in figure 29 below.



| Sub-Functions | Concepts | | |
|---|---|---|---|
| Mount to Ring | C-Clamp | Hose-Clamp | Spring Clamp |
| Hold Bracket | Spring Clamp | Threaded Clamp | Claw |
| Apply Axial Forces | Telescope | Locking Screw | Floor Jack |
| Angle & Socket | Ball & Socket | U-Joint | Parallel Plates |
| Translate Bracket | Rail | Telescope | Sleeve |
| Locking | Threaded Joint | Spring Lock | Self Locking Screw |
| Grip | 1 | 2 | 3 |

**Figure 29**: Sub-Function Concepts

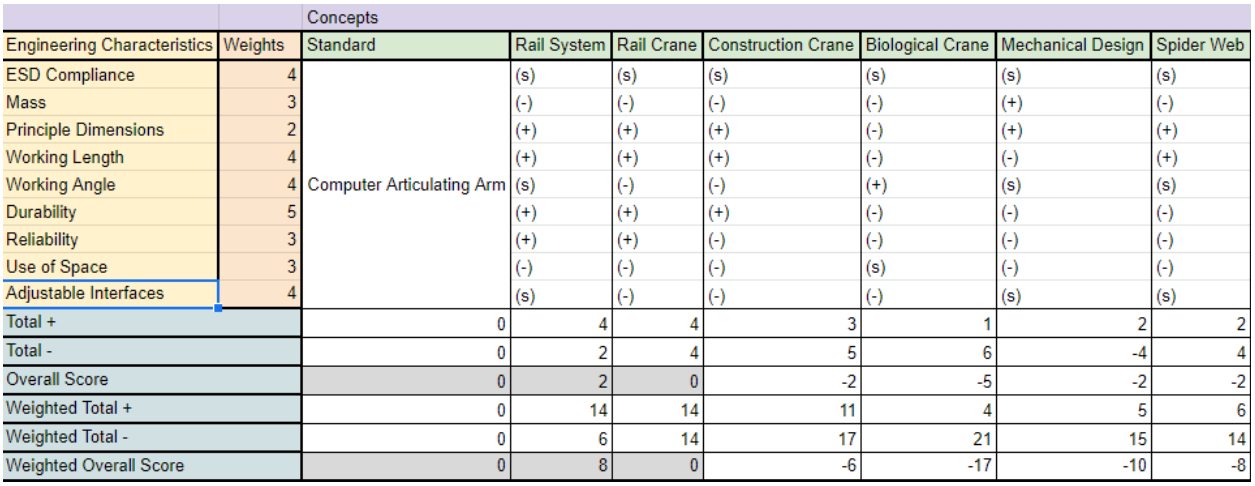
The only sub-function that was not previously introduced is grip. This defines the number of points of contact with the ring. This sub-function was implemented to avoid creating too much of a moment about the rocket motor ring, as distributing this load to multiple points would lessen the individual moments. The primary drawback to multiple attachment points is the amount of area that would be consumed by a single arm, as shown in figure (rail system). This would not allow for the use of multiple arms simultaneously, which is a concern given that many standoffs needs to be placed on each motor. These sub-concepts were organized into complete designs in figure 30 below.



| Sub-Functions | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Design Name | Mount to Ring | Hold Bracket | Apply Axial Forces | Angle Bracket | Translate Bracket | Locking | Grip |
| Datum | Computer Articulating Arm | C-Clamp | Threaded Clamp | Locking Screw | U-Joint | Telescope | Threaded Joint | 1 |
| Design 1 | Rail System | C-Clamp | Threaded Clamp | Locking Screw | U-Joint | Rail | Threaded Joint | 2 |
| Design 2 | Rail Crane | Spring Clamp | Claw | Locking Screw | Ball & Socket | Rail | Self Locking Screw | 1 |
| Design 3 | Construction Crane | C-Clamp | Claw | Telescope | Ball & Socket | Telescope | Self Locking Screw | 1 |
| Design 4 | Biological Design | Hose-Clamp | Spring Clamp | Telescope | Parallel Plates | Telescope | Spring Lock | 1 |
| Design 5 | Mechanical Design | Hose-Clamp | Threaded Clamp | Foor Jack | U-Joint | Sleeve | Self Locking Screw | 3 |
| Design 6 | Spider Web | Spring Clamp | Threaded Clamp | Locking Screw | U-Joint | Rail | Self Locking Screw | 3 |

**Figure 30**: Designs Compiled from Sub-Functions

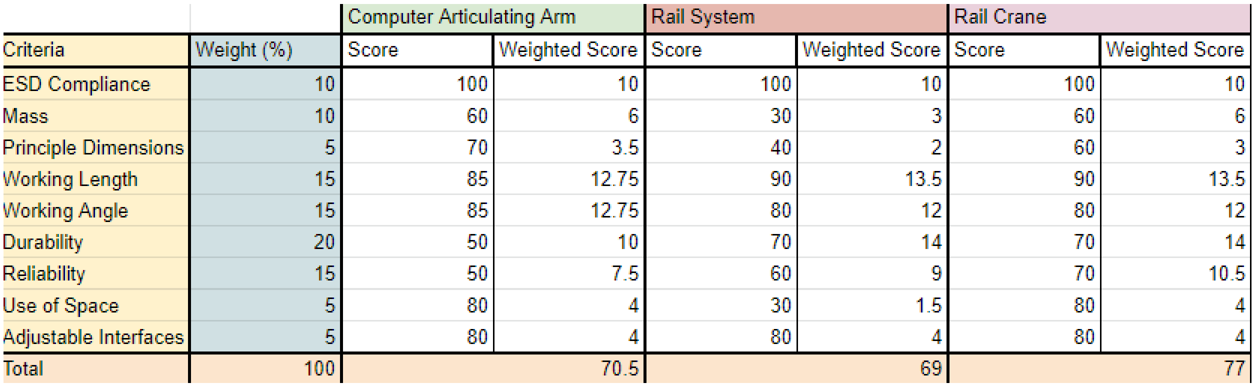
Figure 30 above represents the six generated full system concepts along with the general computer articulating arm that was utilized as a datum. These six designs were compared against the datum in the pugh chart in figure 31. The pugh chart compares each design against the datum for each of the engineering requirements and determines if the design would perform better, worse, or the same as the datum. The sum of better, worse, and same performances were tallied for each full system concept and the top three concepts were kept. From the pugh chart in figure 31, the top three designs of the rail crane, rail system and articulated arm were determined to be the best suited for further analysis.



| | | Concepts | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Engineering Characteristics | Weights | Standard | Rail System | Rail Crane | Construction Crane | Biological Crane | Mechanical Design | Spider Web |
| ESD Compliance | 4 | Computer Articulating Arm | (s) | (s) | (s) | (s) | (s) | (s) |
| Mass | 3 | | (-) | (-) | (-) | (-) | (+) | (-) |
| Principle Dimensions | 2 | | (+) | (+) | (+) | (-) | (+) | (+) |
| Working Length | 4 | | (+) | (+) | (+) | (-) | (-) | (+) |
| Working Angle | 4 | | (s) | (-) | (-) | (+) | (s) | (s) |
| Durability | 5 | | (+) | (+) | (+) | (-) | (-) | (-) |
| Reliability | 3 | | (+) | (+) | (-) | (-) | (-) | (-) |
| Use of Space | 3 | | (-) | (-) | (-) | (s) | (-) | (-) |
| Adjustable Interfaces | 4 | | (s) | (-) | (-) | (-) | (s) | (s) |
| Total + | | 0 | 4 | 4 | 3 | 1 | 2 | 2 |
| Total - | | 0 | 2 | 4 | 5 | 6 | -4 | 4 |
| Overall Score | | 0 | 2 | 0 | -2 | -5 | -2 | -2 |
| Weighted Total + | | 0 | 14 | 14 | 11 | 4 | 5 | 6 |
| Weighted Total - | | 0 | 6 | 14 | 17 | 21 | 15 | 14 |
| Weighted Overall Score | | 0 | 8 | 0 | -6 | -17 | -10 | -8 |

**Figure 31**: Pugh Chart

From the top three designs determined in the pugh chart, they were then compared to one another in the decision matrix shown in figure 32. The decision matrix compares various designs on the basis of customer needs and a weighted score system. The customer needs were each given a weight for the relative importance on the system. Each concept is given a score for the performance of the various customer needs and when taking the weight and the assigned score, the full system concepts could be quantified and compared to one another. As seen in figure 32, the top scoring system was the rail crane with a total score of 77, with the computer articulating arm and rail system with scores of 70.5 and 69 respectively. From this concept evaluation, the team determined that the rail crane was the most promising design to move forward working on.



| | | Computer Articulating Arm | | Rail System | | Rail Crane | |
|---|---|---|---|---|---|---|---|
| Criteria | Weight (%) | Score | Weighted Score | Score | Weighted Score | Score | Weighted Score |
| ESD Compliance | 10 | 100 | 10 | 100 | 10 | 100 | 10 |
| Mass | 10 | 60 | 6 | 30 | 3 | 60 | 6 |
| Principle Dimensions | 5 | 70 | 3.5 | 40 | 2 | 60 | 3 |
| Working Length | 15 | 85 | 12.75 | 90 | 13.5 | 90 | 13.5 |
| Working Angle | 15 | 85 | 12.75 | 80 | 12 | 80 | 12 |
| Durability | 20 | 50 | 10 | 70 | 14 | 70 | 14 |
| Reliability | 15 | 50 | 7.5 | 60 | 9 | 70 | 10.5 |
| Use of Space | 5 | 80 | 4 | 30 | 1.5 | 80 | 4 |
| Adjustable Interfaces | 5 | 80 | 4 | 80 | 4 | 80 | 4 |
| Total | 100 | 70.5 | | 69 | | 77 | |

**Figure 32**: Decision Matrix

## 7.2 Rationale for Design Selection

From the decision matrix, the two most lucrative designs were calculated to be the computer articulating arm and the rail crane, which are shown in figures (computer arm) and (rail crane), respectively. The ability to use many of each of these designs at a time would prove useful when installing the numerous brackets on the motor, and stems from the single mounting point on the ring. A calculation was performed near the end of this report to ensure that a single mounting point would be capable of supporting the loads this design will endure.

Another reason for the success of these two designs is the low mass and ease of handling. This is directly correlated to the single mounting point, which provides a simplified design with less clamps to actuate when moving the device about the ring. The lower complexity of these designs also contributes to the durability and reliability scores, as less moving parts are needed. In total, the rail crane and computer articulated arm were selected by the team as the most viable designs due to simplistic layouts that use little space without compromising the workable area or providing an unacceptable moment about the motor ring.

Of the two designs selected from the decision matrix, the rail crane scored the highest, and is currently the basis for creating the final design. The rail crane scored higher than the computer articulated arm mostly due to a decrease in moving components and locking points, which theoretically makes it the more durable and reliable of the two. The current CAD model, which is still in need of extensive revision, can be seen in figure 33 below.

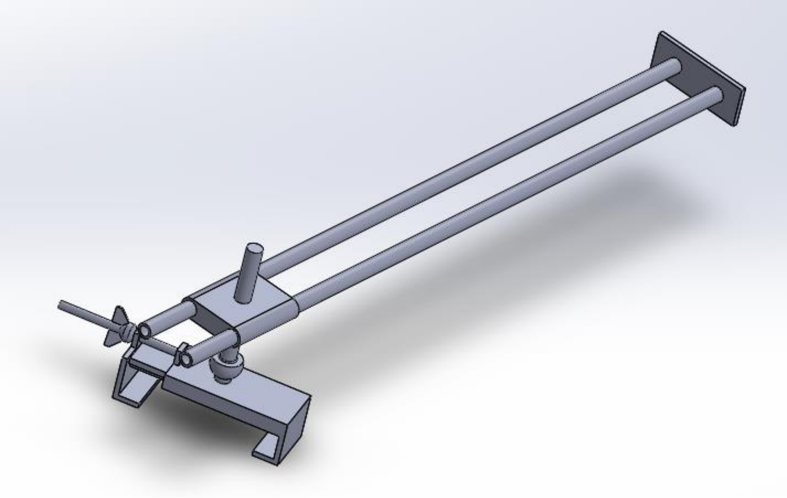


**Figure 33**: Current CAD Model

This depiction of the rail crane system captures the design intent, but leaves out the details for certain sub-functions. The right side of figure 33 will be updated to portray the subsystem that will clamp to the ring, while the left side of the image currently represents an implementation of the power screw design. At the end of the power screw is the ball and socket joint, which will be used to define the angle of the bracket and the claw, which will be used to retain the bracket as it is pressed to the dome.

In order to justify the benefits of a single mounting point, an analysis had to be performed to ensure that the moment about the ring would allow for a factor of safety greater than 3.0. To do this, a worst case scenario situation was derived with the largest diameter ring. The thickness was set to 0.125 inches, which is less than the minimum parameter given by the client. Clamping depth was set to only 1.75 inches, although two inches will be available. Finally, the lever arm for the moment about the ring was set to the specified maximum of 36 inches. The stress distribution that resulted is shown in figure 34 below.

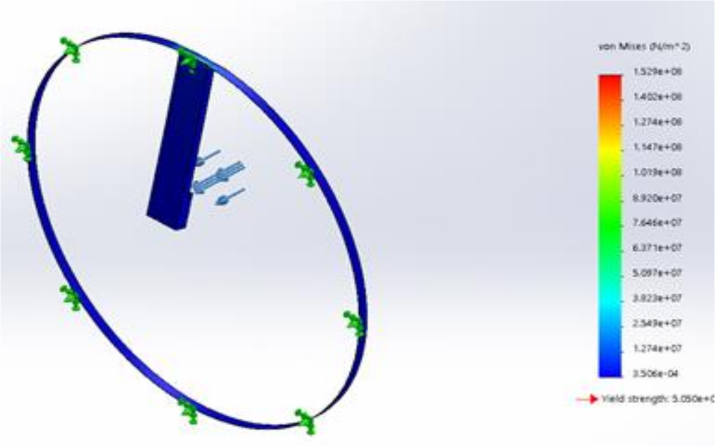


**Figure 34**: Clamp Moment Stresses

This simulation was performed in Solidworks SimulationXpress by fixing the far side of the ring and applying a clamping force on a simplified moment arm, which represents a simplified version of our design at the maximum extension. Assuming an 8 inch wide clamp area, the results of even the worst case scenario situation finalized with 3.30 minimum factor of safety for the ring, proving that a single point of contact would suffice for the loads that will be applied with this design.

Another consideration for the design that will factor into material selection is the friction force required to keep the device from slipping off of the ring. Providing a significant clamping force on the ring is necessary to apply the pull test to the secured brackets, which is more difficult to achieve with a single point of contact. Using coefficients of friction for various materials, the necessary clamping force for each was calculated assuming an opposing load of 50 pounds. The results of this calculation can be seen in figure (35) below.

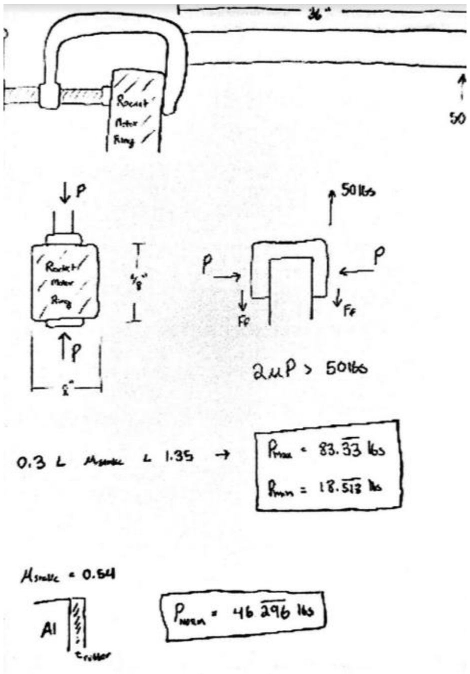


**Figure 35**: Clamp Friction Calculation

The necessary clamping force represented at the bottom of figure (35) assumes that rubber is the material in contact with the aluminum ring, and that the load is evenly distributed to both sides of the rocket motor ring. The force necessary to secure the device was found to be about 47 pounds, which may be less difficult to apply if it is distributed to more than one clamp on the same part of the ring.

# 8 CONCLUSION

The purpose of this report was to follow the design process to select a final design for the Northrop Grumman Standoff Project. To do this, a ranking system between the customer and engineering requirements was made. This allowed the design team to determine which engineering requirements were the most significant to the project based on the ranking system of the customer requirements, seen in Appendix B. By performing a literature review, benchmarking common designs used currently, and creating a functional decomposition, a better understanding of what was needed to design the standoff bonding tool was generated. Then, concepts were created to allow the design team to have multiple options in creating full system designs. With seven full system designs, the design selection process was performed which selected the rail crane design seen in figure 33. This selection was backed up with a pugh chart, decision matrix, and two back-of-the-envelope calculations seen in section 5.2. With these justifications, the design team is confident in the rail crane design moving forward.

# 9 REFERENCES

[1] Propulsion Products Catalog, Northrop Grumman, Falls Church, VA, June 2018

[2] “Aluminum Alloys - Mechanical Properties,” The Engineering Toolbox, 2008. [Online]. Available: https://www.engineeringtoolbox.com/properties-aluminum-pipe-d_1340.html. [Accessed: 18-Oct-2019]

[3] S. Dabral and T. Maloney, Basic ESD and I/O design. New York, NY: John Wiley & Sons, Inc, 1998

[4] “ESD Fundamentals,” EOS/ESD Fundamentals. [Online]. Available: https://www.esda.org/esd-overview/esd-fundamentals/. [Accessed: 18-Oct-2019].

[5] “What is the Difference Between Anti-Static, Dissipative, Conductive, and Insulative?,” Production Automation Corporation. [Online]. Available: https://www.gotopac.com/art-esd-resistivity. [Accessed: 18-Oct-2019].

[6] “Difference Between Conductive, Dissipative, Insulative and Antistatic: ESD & Static Control Products: Transforming Technologies,” ESD & Static Control Products | Transforming Technologies, 29-Mar-2012. [Online]. Available: https://transforming-technologies.com/esd-fyi/difference-between-conductive-dissipative-and-insulative/. [Accessed: 18-Oct-2019].

[7] “Thermal Conductivity of Metals, Metallic Elements and Alloys,” Engineering ToolBox, 2005. [Online]. Available: https://www.engineeringtoolbox.com/thermal-conductivity-metals-d_858.html. [Accessed: 18-Oct-2019].

[8] “MetalMiner Prices: Aluminum Prices,” MetalMiner. [Online]. Available: https://agmetalminer.com/metal-prices/aluminum/. [Accessed: 18-Oct-2019]

[9] “MetalMiner Prices: Stainless Steel Prices,” MetalMiner. [Online]. Available: https://agmetalminer.com/metal-prices/stainless-steel/. [Accessed: 18-Oct-2019]

[10] “AISI Type 304 Stainless Steel,” ASM Material Data Sheet. [Online]. Available: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=mq304a. [Accessed: 18-Oct-2019].

[11] “The Online Materials Information Resource,” MatWeb. [Online]. Available: http://www.matweb.com/search/datasheet.aspx?bassnum=AMEAL00&ckck=1. [Accessed: 18-Oct-2019].

[12] ICT Power Company, "How to Choose the Right Clamp for Your Application," ICT Power Company, [Online]. Available: http://www.ictpowerusa.com/HOW_TO_CHOOSE_A_CLAMP.pdf. [Accessed 14 October 2019].

[13] K. Venkataraman, "Design of Jigs, Fixtures, and Press Tools," John Wiley & Sons Ltd , 2015, pp. 3.1-3.11.

[14] Industrial Press Inc., Machinery's Handbook 27th Edition, New York, 2004.

[15] J. Pryor and J. Ratcliff, "Quick Clamping System". United States Patent 5,326,059, 5 July 1994.

[16] C. Anderson, "Clamping Device". United States Patent 4,432,435, 21 February 1984.

[17] "The Engineer's Guide to Identifying Lead Screw Thread Forms", 23200 Commerce Park, Beachwood, Ohio 44122, 2016.

[18] R. Lipsett, *Why Lead Screws are the Best Fit for Many Linear Motion Applications-and How to Rightly Apply Them*, 1st ed. San Jose, CA: THOMSON, pp. 1-8.

[19] "Everything You Need To Know About Floor Jacks | FloorJacksCenter.com", *FloorJacksCenter.com*, 2019. [Online]. Available: https://floorjackscenter.com/floor-jacks-guide/. [Accessed: 18- Oct- 2019].

[20] "How Hydraulic Jacks Work", *Thomasnet.com*, 2019. [Online]. Available: https://www.thomasnet.com/articles/materials-handling/how-hydraulic-jacks-work/. [Accessed: 18- Oct- 2019].

[21] SpringActive Inc, "Adjustable stiffness Jack Spring actuator", US8322695B2, 2011.

[22] Robert Lipsett Ball Scres & Actuactors Co., "Machinedesign.com," 1 February 2000. [Online]. Available: https://www.machinedesign.com/technologies/nuts-about-power-screws. [Accessed 10 October 2019].

[23] A. J. Christopher, "Tripod Head". United States of America Patent 3,128,982, 14 April 1964.

[24] R. G. Budynas and J. K. Nisbett, Shigley's Mechanical Engineering Design, New York: McGraw-Hill, 2011.

[25] J. R. Ditto, "Friction Locking Hand Clamp". United States of America Patent 4,555,100, 26 November 1985.

[26] Z. Khan, "What is a frictional locking device?," 14 January 2016. [Online]. Available: https://www.couplingtips.com/featured/what-is-a-frictional-locking-device/. [Accessed 10 October 2019].

[27] D. C. Sayles, "*Blast-Resistant Rocket Motor Cases*", [Online]. Available: https://patentimages.storage.googleapis.com/d8/90/37/4b501dde2abbf2/US4054029.pdf

[28] Q. Liu, Z. Sheng, H. Shi, H. Chen, J. Gu, "*Investigation on friction coefficient between solid rocket motor throat components*", The Proceedings of the 2011 9th International Conference on Reliability, Maintainability and Safety

[29] S. Bundalevski, V. Cingoski, S. Gelev, "*Determination of the total impulse of the solid rocket motor by two mathematical methods*", "2018 23rd International Scientific-Professional Conference on Information Technology

[30] Z. Weiyao, T. Xiaozhen, D. Tianbao, W. Wenlong, L. Wei, "*Fatigue lifetime estimation of the solid rocket motor charge by road roughness loads on mechanical methods*", 2016 7th International Conference on Mechanical and Aerospace Engineering

[31] "Six degrees of freedom Robot Arm," RobotDigg Equip Makers, [Online]. Available: https://www.robotdigg.com/product/1463/Six-degrees-of-freedom-Robot-Arm?gclid=EAIaIQobChMI5rPC87bZ5AIVsRx9Ch3RxgQZEAQYAyABEgKnYvD_BwE. [Accessed 16 September 2019].

[32] "Dual Arm," HDT Global, [Online]. Available: http://www.hdtglobal.com/product/dual-arm/. [Accessed 16 September 2019].

[33] Engineered Material Handling, "Aluminum Rail Workstation Cranes - AL SYSTEMS," Engineered Material Handling, [Online]. Available: https://www.emhcranes.com/al-systems-aluminum-workstation-cranes/. [Accessed 18 October 2019].

# 10 APPENDICES

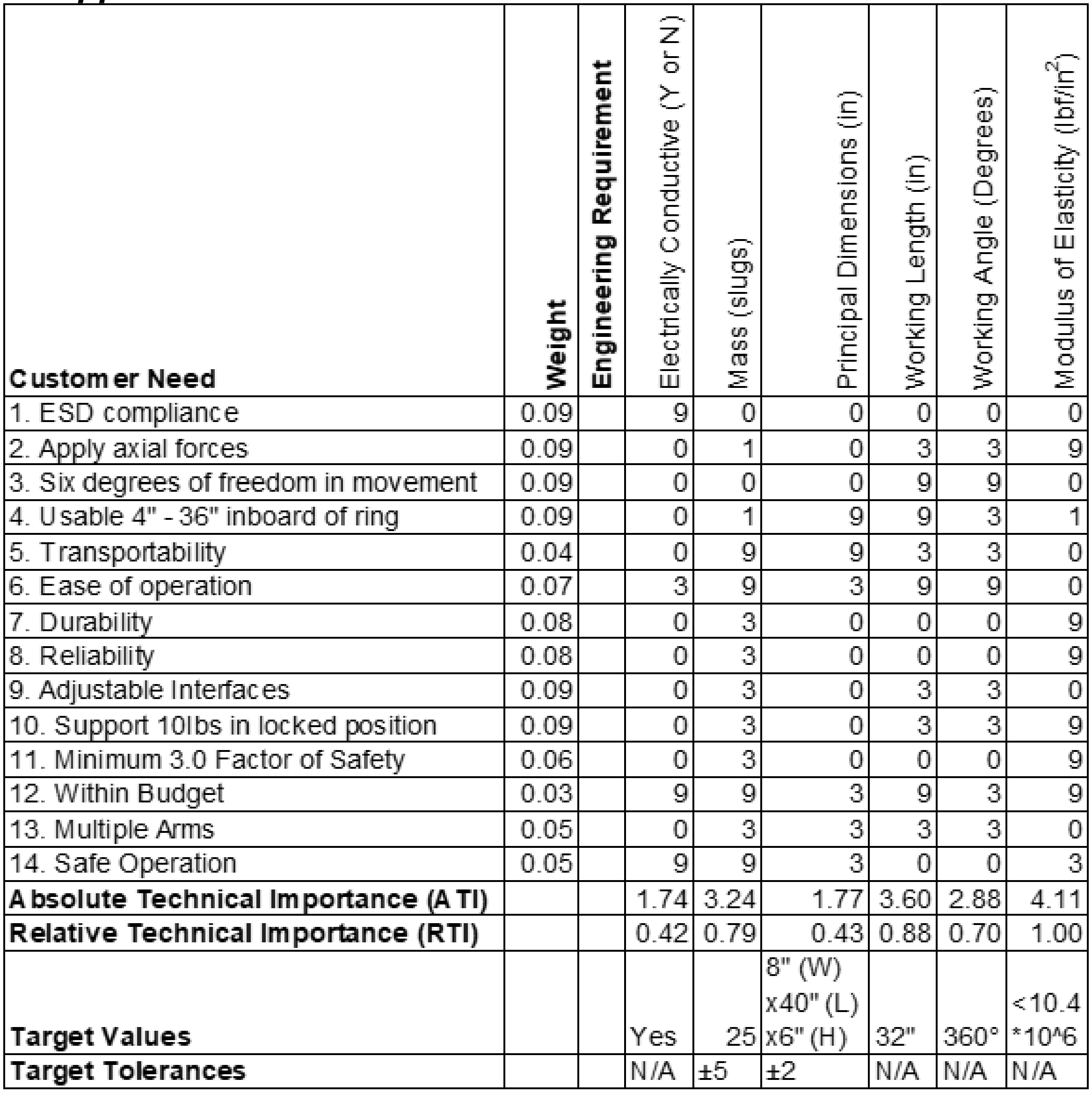
## 10.1 Appendix A: Rocket Motors the Mounting Arm will Mount

### 10.1.1 Appendix A.1. Orion 50XL

### 10.1.2 Appendix A.2. Castor 30XL

### 10.1.3 Appendix A.3. Castor 38

## 10.2 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 |