Northrop Grumman Handling Arm

Preliminary Report

Savannah Hillebrand

Rayne Dobson

Keven Benavente

Sami Scarcello

Tyler Schafer

David McNealy

2018-2019

Project Sponsor: Northrop Grumman Corporation

Faculty Advisor: Sarah Oman

Sponsor Mentor: Steven Hengl

DISCLAIMER

This report was prepared by students as part of a university course requirement. While considerable effort has been put into the project, it is not the work of licensed engineers and has not undergone the extensive verification that is common in the profession. The information, data, conclusions, and content of this report should not be relied on or utilized without thorough, independent testing and verification. University faculty members may have been associated with this project as advisors, sponsors, or course instructors, but as such they are not responsible for the accuracy of results or conclusions.

TABLE OF CONTENTS

Contents

1 BACKGROUND

1.1 Introduction

The purpose of this project is to design a functional, articulating handling arm for Northrop Grumman Corporation (NGC). The team has been instructed to create an original design and produce a fully functional prototype. This prototype must be able to securely hold avionics for soldering, system integration, testing, etc. This device will help prevent expensive parts from being dropped and damaged, as the components can become expensive to repair/replace. By preventing these incidents, NCG will save time and money during their assembly process. The employees of Northrop Grumman will also be benefiting knowing that they will be receiving a high-quality product. Other companies may see the design and decide that they would benefit from having a handling arm for their equipment, as well. There are currently no such handling arms being used in this industry, so the designed arm will be an original design.

1.2 Project Description

Northrop Grumman Corporation has requested that the team design and create a functional, articulating handling arm. This handling arm must be articulating at different joints to allow for maneuverability. The purpose of the arm is to hold NGC's avionics during system integration and testing (soldering, bolting, etc.). The company has had issues in the past with these avionic parts being dropped, and as they are expensive components, repairs become costly. Some stakeholders in this handling arm would be any companies that buy parts made from the handling arm, companies that would be interested in buying the design, and any employees that would be using the arm during manufacturing/testing. The following is the original project description provided by Northrop Grumman.

> "During system integration and testing activities of Northrop Grumman Corporation (NGC) electronics it is necessary to hold avionics in various positions to support integration and soldering activities. Currently these components are handled manually and have been dropped as a result. These components are expensive and often needed for schedule critical projects. NGC is requesting that NAU select one team to design, analyze and build a prototype articulating handling arm that can provide proper support to handle these items."

1.3 Original System

This project involved the design of a completely new handling arm. There was no original system when this project began.

2 REQUIREMENTS

Chapter 2 of the preliminary report contains a detailed description of each customer requirement (CR) and engineering requirement (ER) followed by the House of Quality (HoQ) that relates these requirements to each other. The qualitative customer requirements that were produced and ranked from the client, Steven Hengl, were translated into quantitative engineering requirements and then put into a House of Quality to determine the most important.

2.1 Customer Requirements (CRs)

In this section, each customer requirement will be discussed and ranked. The CRs were derived from the project description given in the beginning of the semester and from the first client meeting. The customer requirements are as follows: reliability, durability, supports size requirements, supports load requirements, budget, benchtop mountable, electrostatic discharge compliant, ease of manipulation, safety and portability. Each requirement will be ranked out of 10 (1 being most important, 10 being least important) based on the rankings that were given by the client.

Reliability is crucial to the project because the team wants to ensure that the handling arm performs consistently well and is trustworthy.

Durability is another main need for the project because, given the load limits for the arm, it is important that it can handle and support the load that it is given without failing.

Originally given as an engineering requirement in the project description, supporting the size requirements for the object the arm is going to pick up is critical.

The primary function of the handling arm is to be able to grab onto a certain sized object, so it is important for the size requirement to be supported.

As well as the size requirement, the load requirement was given in the project description. The handling arm should be able to support the load of the object that it is holding without issue.

Described more in detail later in this report, one of the customer requirements is to propose a budget based on research and benchmarking. Although an exact budget was not given, it is important that the production and manufacturing of the handling arm be reasonable.

Explained in the project description, the handling arm is going to be placed on a benchtop to be used. It is important for the team to make the handling arm benchtop mountable to achieve usability from the Northrop Grumman team.

Electrostatic discharge compliancy is extremely important to keep the user of the arm safe. The arm needs to be able to be grounded so a voltage does not travel through and potentially hurt the people around it.

To move the handling arm in all directions, ease of manipulation is required. This manipulation has to be done manually and should not be difficult for the user to move with one hand.

The most important requirement, ranked a 1 out of 10 by the client, is safety. It is crucial that the handling arm is safe for itself, the part it is controlling, the user and the potential people surrounding it.

The last customer requirement given was portability. Northrop Grumman wants an arm that is easily moveable from one area to another in terms of weight and size.

The remaining weights to each customer requirement can be found in Table 1.

2.2 Engineering Requirements (ERs)

This section discusses the eleven engineering requirements both provided by the client and defined by the team. Each of the requirements, listed in Table 1, must be met by the team in order to provide the client with the best version of the project. The requirements are listed in order from most important to least important, as ranked by our client. The top seven are the requirements the team must meet in order to deliver an acceptable product. The bottom four are goals to aim for but can be reached in other ways if necessary. This table displays the customer requirements on the left, along with their respective weights, the engineering requirements that were created to accomplish the customer requirements, and the target value expected to be met on the right. Additional details outlining each engineering requirement are further discussed in the following sections.

Table 1. Engineering Requirements

Customer Requirements	Ranking	Engineering Requirements	Target
Safety/Robustness	1	Factor of Safety	≥3.0
ESD Compliant	2	Voltage between arm and user	0V
Large Load Capacity	3	Load Capacity	Minimum:1/2 (lbs.) Maximum: 15 (lbs.)
Variable component size	4	Component Size	Minimum: 6.0 x 2.5 x 1.125 (in.) Maximum: 6.0 x 2.5 x 12.375 (in.)
Ease of Manipulation	5	Force required to move arm in unlocked position	20lbs additional force @ locked (lb-ft)
		Degrees of Freedom	Six (df)
Reliability	6	Longevity	Life Cycles
Durability	7	Structural Integrity	Load tested to 125% (lbs.)
Benchtop Mountable	8	Clamping Pressure on Table	9.75 Pressure (psi)
Portability	9	Device Weight	≤50 (lbs.)
Cost	10	Budget	<10,000 ($)

For the safety engineering requirement, the team was given a number of 3.0 as a minimum for all factors of safety tested. This includes tests similar to weight distribution at each joint and each member or stress analysis at critical points. This is to ensure the user is not harmed while working with the arm.

To be electrostatic discharge compliant (ESD), there should not be any voltage moving between the user and the device. This can be accomplished by an ESD mat placed between the benchtop and device. It can also be accomplished by grounding the user to the device.

The device created must be able to support a minimum weight of a ½ pound component, as well as a maximum weight of a 15-pound component. The device should be able to fully support an attached component within these minimum and maximum requirements, as well as keep the component upright in the intended position when locked without the user interfering.

Similar to the load capacity, the device must be able to fully support a component with the following size composition: a minimum of 6.0 x 2.5 x 1.125 inches and a maximum of 6.0 x 2.5 x 12.375 inches. The components must be fully supported in both the unlocked and locked positions without touching the benchtop surface.

For ease of manipulation, at maximum capacity of supporting a 15-pound component, the device must also be able to withstand an additional 20 pounds of force from the user without the device failing or altering the way that the component is supported. The handling arm must also be free to operate in all six degrees of freedom. These degrees are vertical, horizontal, depth, yaw, roll and pitch.

For the longevity engineering requirement, the device needs to be able to function adequately for a desired number of life cycles. This has not yet been determined by the client.

In order to claim structural integrity of the device, it must be load tested to 125% of its maximum capacity. This maximum capacity is 35 pounds, calculated by a maximum component weight of 15 pounds plus the weight the user will place on the device of 20 pounds. The 125% value that the device must be able to operate under is 43.75 pounds.

This device must be benchtop mountable and cannot exceed the pressure force the workstation is rated for. This is calculated using the weight of the handling arm, the weight of the component (plus 25%), and the 20-pound force applied to the arm by the user.

For portability, in order for the device to be easily moved from one workstation to the next by one individual, the device is limited to weighing 50 pounds or less, as per the safety regulations put in place by the client.

To ensure the device is delivered within the client's budget, all material, travel, prototyping, and manufacturing costs cannot exceed $10,000, which was the budget given by the client.

2.4 House of Quality (HoQ)

The House of Quality is important for the team because it shows the most heavily weighted (or most important) engineering requirement derived from the customer requirements. The middle "room" shows the comparison of customer requirements to engineering requirements, the "attic" relates the engineering requirements to themselves, and the "basement" shows the absolute technical importance. The HoQ can be seen in Appendix A.

2.4.1 Main Room (CRs to ERs)

In the house of quality, the customer requirements were compared to the engineering requirements. A low relationship is a "1", a moderate relationship is a "3", and a high relationship is a "9". Since the engineering requirements were derived from the customer requirements (and there is at least one engineering requirement to one customer requirement), there is a pattern that can be seen in the relationship. Each customer/engineering requirement has at least one "9" or high relationship because the engineering requirements were directly derived from how it could accurately meet the designated customer requirement. Each of the customer requirements were given a weight on how important it is. A significant finding from this section of the HoQ is that all most all engineering requirements have at least small relationship with the cost of the arm. This could be due to the fact that making improvements and increasing the quality of the arm is going to increase the overall cost.

2.4.2 Basement (Absolute Technical Importance)

The CR to ER comparisons made it possible to find the absolute technical importance of the engineering requirements, which is the sum of the customer weight multiplied by the score received in the customer/engineering requirement relationship. From this, the engineering requirements can be ranked based on their technical importance. The target values and units for each engineering requirement were also found, which allows the team to recognize which engineering requirement would be the hardest to achieve. From the ranks, it can be seen that the most important engineering requirement for the handling arm is the structural integrity. This directly correlates the client's ranking of safety because the arm must be as safe as possible.

2.4.3 Attic (ERs to ERs)

The team also went a step further and related to the engineering requirements to themselves. This allows the team to see if there will be any issues trying to fulfill all engineering requirements to the highest possible degree. From those relationships, a "++" and "+" are positive relationships, and a "--" and "-" are negative relationships. The negative relationship are the ones that need to be considered carefully because they will cause conflict in trying to fulfill all of the customer requirements. It can be seen that there will be an issue with the cost of the device is almost all engineering requirements because the better materials used and the better the quality of the arm, the most it will cost.

3 EXISTING DESIGNS

Chapter 3 of this report will contain a thorough research of systems in the existing market, a complete functional decomposition, and subsystems that relate to the design of the handling arm. The research process of systems will be thoroughly explained as well as different benchmarking techniques. The handling arm will be broken down into a black box model, functional model and hierarchical task analysis to better explain and visualize the exact functions that the final design needs to include. After this, a subsystem level will be broken down for each individual part of the arm. All existing systems and components were researched using similar products and recommendations from NGC. These systems, functional decomposition and subsystems will be beneficial when designing each part of the handling arm.

3.1 Design Research

The first step to design research was to study any existing articulating arms. To do so, web searches were performed on relevant existing systems. Ideas were taken from the team's knowledge and client and professor suggestions. This presented many small components, mostly relating to photography. The team then considered using a computer monitor mount as a research foundation because they are a prime example of the basic concept of the handling arm. Another source of research for the team was a clamped tabletop device, purely for the clamping feature alone. Three main items came from this research, as outlined in the following sections.

3.2 System Level

In this section, analyses of system level items to base the handling arm off of will be outlined. There were no ideal products found, so different components of each system can be considered while creating the handling arm. The three systems researched were the tablet mount, monitor mount, and robotic arm.

3.2.1 Existing Design #1: Tablet Mount

The first device researched was a tablet mount (Figure 1). This mount has 6 degrees of freedom and includes screw clamp, connected to a post to adjust height of the arm for the mounting system. The mounting system is meant for flat tablets, expanding to mount to the corners of the device. The arms are gas spring adjustable, with two 360-degree pivot joints connecting both arms and connecting the tablet mount. This mount can only hold upwards of 2-pounds, and sells for $94.95 [1].

Figure 1. Tablet Mount.

3.2.2 Existing Design #2: Computer Monitor Mount

The second item researched was a monitor mount (Figure 2). This arm system is tabletop mountable and moves in 6 degrees of freedom, as needed. The arms are gas springs, allowing easy manipulation of the monitor. The mount has a VESA bolt pattern of 100mm x 100mm or 75mm x 75mm for the monitor. The joint at the base and monitor rotate ±90-degrees while the middle joint can rotate 360 degrees. This device can hold up to 33lbs, well over the weight required. This mount is made of aircraft grade aluminum, strong and light, and sells for $129.99 [2].

Figure 2. Monitor Mount.

3.2.3 Existing Design #3: Robotic Arm Kit

The next device researched was a 6 degrees of freedom robotic arm kit (as seen in Figure 3). This was benchmarked solely for the geometry of the device as it is electric powered and not tabletop clampable. This arm is made of plastic, which would not be sufficient for our weight requirement. This robotic arm sells for $299.00 [3].

Figure 3. Robotic Arm Kit.

3.3 Functional Decomposition

In this section, the functional decomposition of a universal articulating handling arm will be discussed. This is done to gain a better understanding of the object's function. In the functional decomposition, there will be a discussion about the inputs and outputs required by the handling arm. The decomposition of the handling arm will be broken down into multiple parts: a black box model, a functional model, and a hierarchical task analysis. The black box model helps identify the main purpose of the handling arm while the functional model breaks down each subsystem/component required and how the handling arm will accomplish the main goal. The hierarchical task analysis gives a step by step procedure on how to properly use the handling arm.

3.3.1 Black Box Model

The black box model helps to determine the main function with inputs and outputs for the handling arm. By creating the black box model, the physical form and the function of the handling arm can be separated. This helps in the concept generation because it allows the team to focus on meeting the functionality of the handling arm while not being restricted by what a typical handling arm looks like.

Figure 4 shows the black box model for the project's universal handling arm. The main purpose of the handling arm is to hold avionics. The materials that the handling arm will interact with is a human hand, avionics, and any tools used, which are also the output materials. The handling arm will also be exposed to energy from humans in order to be manipulated, potential energy once it has been moved, electricity when being soldered on, and heat that comes from the soldering. The energy outputs are potential energy for when the avionic is attached to the arm, heat energy from the arm being moved, and electrical energy from soldering discharge. The handling arm will also signal the user visually by showing whether it is in a locked or unlocked position.

Figure 4. Black Box Model.

3.3.2 Functional Model/ Hierarchical Task Analysis

The team has also created a functional model and hierarchical task analysis to represent the handling arm. These help break down how the handling arm will work because it heavily relies on human interaction for it to function. The functional model will break down how the inputs are converted to outputs and the task analysis will give step by step procedures on how to properly use the handling arm.

3.3.2.1 Functional Model

Figure 5 represents the functional model which builds upon the black box model. The functional model shows a step-by-step analysis of how the inputs are converted to outputs by the handling arm. The inputs are human hand and energy, the avionics that will be worked on, and electricity for soldering. The outputs are the human hand, the avionic, and heat from the soldering. While working with the handling arm, the user will need to unlock and lock the handling arm to provide proper support. The user will be visually signaled by the handling arm on whether it is locked or unlocked. The functional model gives the team inspiration on how to fulfill the functionality of each required component of the arm.

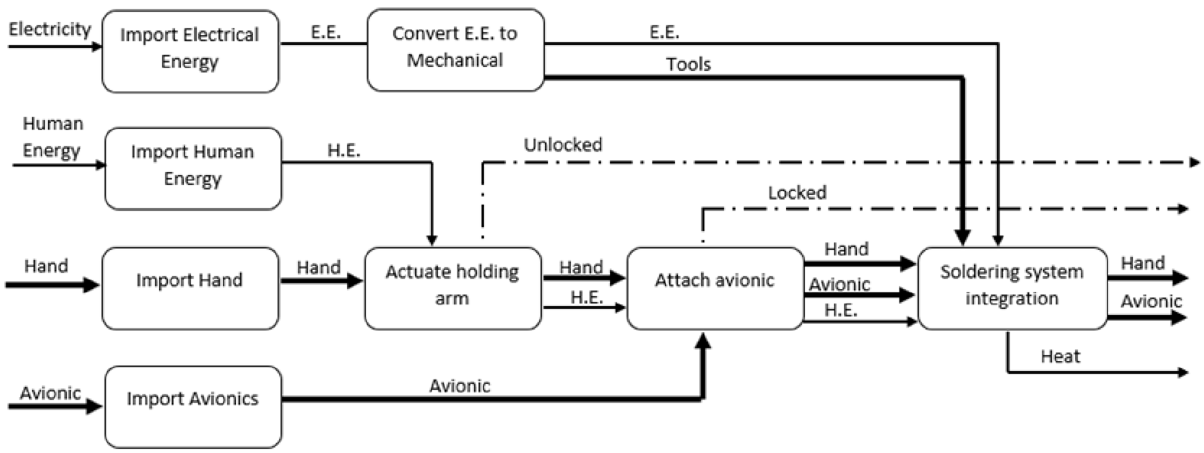

Figure 5. Functional Model.

3.3.2.2 Hierarchical Task Analysis

Figure 6 represents the hierarchical task analysis, which is a guideline for how to use the handling arm. The hierarchical task analysis showed the team any possible failures in the arm, and any possible misuses. This allowed the team to design around these issues and make the arm as safe and easy to use as possible. In order for the user to properly hold and work on avionics, they should follow the steps represented in the figure below. The user should place the arm into position by unlocking the device and locking it once it is in the desired position. The avionic then needs to be attached to the handling arm using the proper grip attachment. Once the user is ready to start their given activity, they should ground the equipment so no voltage is discharged between the arm and the user. Once the user is done working on the avionic, the arm can be unlocked, and the avionic can be removed. These steps help in maintaining equipment and provide proper support for the avionics.

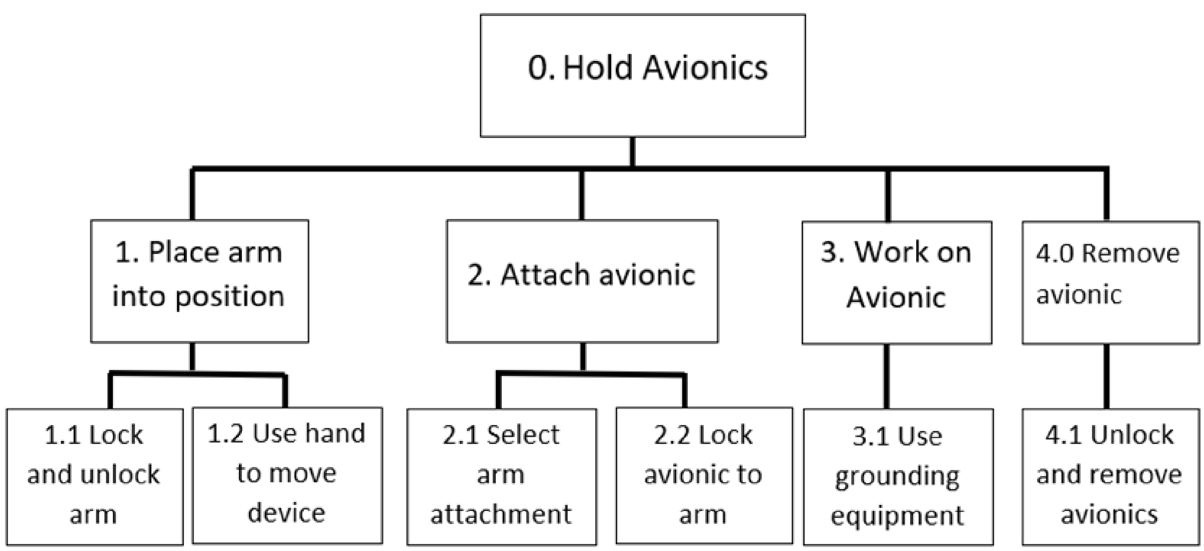

Figure 6. Hierarchical Task Analysis.

3.4 Subsystem Level

To look more in depth at the future design of the handling arm, it is important to break it down into multiple parts and research each thoroughly. Based on the engineering requirements, the handling arm was broken into four parts: table attachments, mechanical joints, head attachments and locking mechanisms. Each of these parts were be broken down into three existing designs that pertain to the corresponding topic. Once simplified, each of the subsystems can be used in the design of the handling arm.

3.4.1 Subsystem #1: Table Attachments

One of the given customer requirements for the arm was that it has to be benchtop mountable. To attain this, a table attachment is needed to secure the arm to the benchtop. The following three different clamp systems were researched and analyzed: c-clamp, spring clamp and hand screw clamp. Any of these subsystems can be used in the design for the arm.

3.4.1.1 Existing Design #1: C-Clamp

C-clamps, usually made of steel or cast iron, in the shape of a C, utilizes a threaded screw that goes through a threaded hole in the bottom of the clamp [4]. The C-clamp is able to be manipulated by tightening the screw around the surface at the desired pressure. To release the clamp, the screw can be loosened and the clamp can be moved to a different surface, satisfying the benchtop mountable and portability engineering requirements of the arm. An example of a C-clamp can be seen in Figure 6.

Figure 7. C-Clamp.

3.4.1.2 Existing Design #2: Spring Clamp

Another type of clamp that could be included on the handling arm is a spring clamp [5]. Unlike the C-clamp, the spring clamp utilizes springs to keep hold of a surface. Commonly seen on desk lamps, spring clamps are a cheap and easy to use. To open the spring clamp, the top and bottom handles are pushed together while letting go of the clamp closes it on the desired surface. While the spring clamp is widely used in multiple existing designs, it can prove to be weak dependent on the springs and materials used and how large it is. This could be a viable component for the arm because of the ability to clamp onto different types/sizes of tables.

Figure 8. Spring Clamp.

3.4.1.3 Existing Design #3: Hand Screw Clamp

A hand screw clamp (Figure 9), usually made of wood, utilizes two screws on each side to close the clamp around the desired object [6]. Because it is made out of wood, it is weaker than a C-clamp or a spring clamp. It also is difficult to maneuver since there are two screws to tighten instead of one. It is important that the user be able to clamp the arm on the desired benchtop with as much ease as possible so this type of clamp could be feasible for the arm, but would require many modifications.

Figure 9. Hand Screw Clamp.

3.4.2 Subsystem #2: Mechanical Joints

In order to provide a handling arm that meets the client's expectations and needs, it must have six degrees of freedom. To accomplish this, the right joints must be selected and analyzed to provide sufficient degrees of freedom. These joints would pertain to the overall human interaction with the arm since they are responsible for maneuverability.

3.4.2.1 Existing Design #1: Universal Joints

Universal joints, which can be seen in Figure 10, allow for two shafts to connect and transmit torque [7]. The joint allows for axial rotation and bending which will add to the degrees of freedom of the system. Universal joints are also relatively cheap and easy to obtain. The main disadvantage is that the joint is prone to wear if not properly lubricated and maintained. The universal joint can be easily applied to the handling arm to help with the ease of manipulation requirements because they rotate easily and have a full range of motion.

Figure 10. Universal Joints.

3.4.2.2 Existing Design #2: Knuckle Joints

Knuckle joints (Figure 11) are ideal for connecting two rods under tension [8], but not under compression. Knuckle Joints allow for angular rotation in only one direction which could be undesirable when striving for six degrees of freedom. This joint also has a high life expectancy, so maintenance would be minimal which is desirable for the project. The knuckle joint does not meet all the requirements desired, but may be applicable if combined with other joints to increase the degrees of freedom of the system.

Figure 11. Knuckle Joints.

3.4.2.3 Existing Design #3: Ball and Socket Joints

Ball joints allow for easy manipulation in any direction in front of it and allows for swinging movement and axial rotation. The movement is limited to the size of the socket opening and shaft on the ball, but still has a wide range of movements [9]. The ball joint also cannot transmit torque, but that is not needed when designing the joints for the handling arm. Overall the ball socket joint meets all joint requirements for the handling arm. An example of a ball and socket joint can be seen in Figure 12.

Figure 12. Ball and Socket Joint.

3.4.3 Subsystem #3: Head Attachments

One of the features that the customer desires is different types of head attachments to put on the end of the handling arm. This is to ensure that anything that NGC needs to be held on the arm has some type of attachment that can secure it to the arm.

3.4.3.1 Existing Design #1: Bolt Pattern Attachment

A bolt-pattern attachment for the arm allows the user to bolt the avionic to the arm using pre-arranged bolt sizes and distances [10]. This allows for a more secure attachment for the heavier components. Once the user attaches the avionic to the arm, there would be no worry about it falling off of the arm because it would bolted in different places. An example of a bolt pattern attachment can be seen in Figure 13.

Figure 13. Bolt Pattern Attachment.

3.4.3.2 Existing Design #2: Claw Attachment

A claw attachment (Figure 14) for the arm would allow the user to attach essentially any component that is within the size requirements [11]. The claws wrap around the object to hold it into place on the arm so it is secure while it is being manipulated. The claw can conform to any size or shape of object, and therefore any avionic NGC needs to work on, so this is a feasible component for the arm.

Figure 14. Claw Attachment.

3.4.3.3 Existing Design #3: Clamp Attachment

A clamp attachment (Figure 15) for the arm would have two clamps that would clamp down on the component on the arm to be worked on [12]. The two clamps would be able to be tightened and loosened to accommodate for different sizes of avionics. This design would be optimal for square parts but can work with many shapes. This component could be useful for the arm is the avionic is within the size capability of the claw attachments.

Figure 15. Clamp Attachment.

3.4.4 Subsystem #4: Locking Mechanism - Tyler

The subsystem for locking mechanisms is based on the locking of joints. Ideally, the team wants all the joints to lock with one knob or switch, so the main focus will be on that. Having all of the joints lock out is important for when the arm is setup for the user, so it can handle more weight and be more rugged for the user to manipulate and work on the avionic.

3.4.4.1 Existing Design #1: Titan Support Arm

The Titan Support Arm (Figure 16) can lock out joints with one screw on the middle joint [13]. This arm has 3 joints with a center joint using a knob that changes the force it takes to move the joints. This system works based on the pressure put on each joint when the knob is tightened. The team plans to order one of these arms to test and reverse engineer to see if it can be scaled into the size needed for our arm.

Figure 16. Titan Support Arm.

3.4.4.2 Existing Design #2: L.O.C.K.

The L.O.C.K. design is meant to lock a joint using an O ring compression knuckle [14]. This is based on a taper and an O Ring to create a locking dynamic of the joint. This could be an option for the team, but would need some modifications because it does not seem as strong as needed and only locks in one place. The L.O.C.K. can be seen in Figure 17.

Figure 17. L.O.C.K.

3.4.4.3 Existing Design #3: Locking Gas Spring

A locking gas spring is a locking mechanism that locks in any position necessary (Figure 18) [15]. This would be beneficial for the handling arm because the arm currently has 2 gas shocks on it but are not lockable. Being able to lock these out would make the arm safer to use and allow it to hold more weight.

Figure 18. Locking Gas Spring.

4 DESIGNS CONSIDERED

This section showcases the team's top five designs as decided by the Pugh Chart (Appendix C, Figure C1, C2). The next five highest-ranked designs are included in Appendix B. Each design has a specific title, descriptions of the notable features, a hand-drawn sketch of the concept, and an advantage and disadvantage list that focus on the customer and engineering requirements. The following designs are not discussed in order of their scores but are grouped as the top five in the following sections with the following five designs located in Appendix B.

4.1 *Design #1: Bio-Inspired Leg Springs*

One of the top designs that the team considered was a concept developed from bush babies in nature. These animals store energy in their legs so that when it comes time, they are able to jump 20-30 times their own height. This ability to store energy and maintain normal functions was the basis for this idea using zero-link springs [16].

As seen in Figure 19, this design features a C-clamp at the base to secure the arm to the benchtop. It also has two joints as opposed to three, similar to the leg shape of a bush baby. The zero-link springs are capable of holding the attached device up, without it falling. The springs will also allow for easy maneuverability, and the ability to lock out at a desired location. The head for this is a ball-joint that would allow for different attachments to be added on. An advantage and disadvantage list for this design is shown in Table 2 below.

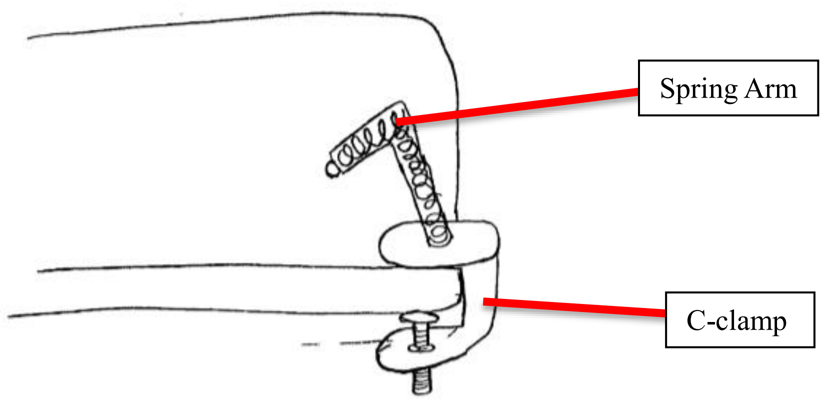

Figure 19. Bio-Inspired Leg Springs.

Table 2. Advantages and Disadvantages for Bio-Inspired Leg Springs.

Advantages	Disadvantages
Ease of manipulation	May not hold up to 43.75lbs without falling at unlocked position
Two joints have less places to fail	Limited vertical adjustment
C-Clamp sufficiently secures arm to table	Unable to have all six degrees of freedom
Easy to ground for ESD compliance	
Not many parts so lower cost	

4.2 Design #2: Clamped Shock Assisted Central Locking Arm

This design uses a C-channel base with two screw clamps to fasten the device to a workbench. A vertical tube is welded onto the top of the base. A sleeve with set screw goes over the vertical tube to make vertical gang adjustment and rotation. A one degree of freedom ball joint is attached to the sleeve at a 45-degree angle. The first link attaches to the ball joint then attaches to the center pivot on the other end. In between the two links, there are a pivot joint and the locking mechanism for the two ball joints at either end. On the end of the second link, there is a "fully rotating" ball joint with quick detach for the different head options. The quick detach consists of a C-clip to lock axial movement as well as a groove and key to lock rotational movement of the head. The central pivot will utilize a knob to rotate two cams that will force two shafts to pin the ball joints in place at either end. The shock assists with ease of manipulation keep the arm from collapsing when the joints are unlocked and help contribute to the overall load factor of safety. Exact materials for all the components have not been decided upon. All of these features are clearly shown in Figure 20 below. Also, an advantage and disadvantage list for this design is given in Table 3 below.

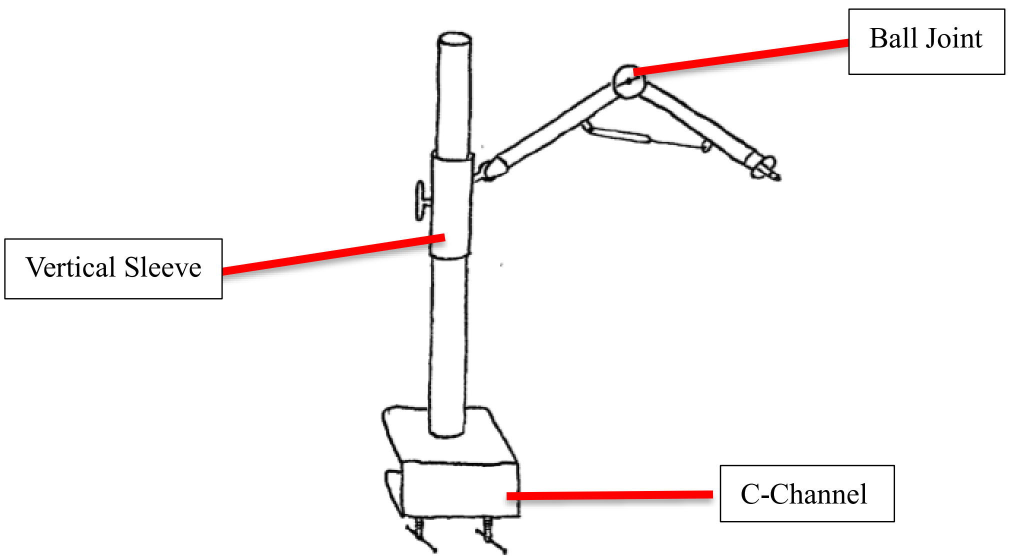

Figure 20. Clamped Shock Assisted Central Locking Arm.

Table 3. Advantages and Disadvantages for Clamped Shock Assisted Central Locking Arm.

Advantages	Disadvantages
Quick detach head system	May not hold up to 43.75lbs without falling at unlocked position
Light weight	Set screw may mar vertical tube
Locks from one position	
Dual clamp attachment to table	
Has all six degrees of freedom	

4.3 Design #3: Bolt-Pattern Mount Head

This design (Figure 21) focuses only on mount head type. The body is made out aluminum and features 3 joints with a bolt-pattern mount head. There is an industrial-grade clamp attached to the benchtop which lacks the ability to adjust to a wide variety of benchtop thicknesses. This design allows the vertical joint to swivel in the base of the clamp so the entire arm can have a full 360 degrees of rotation. There is no designated locking method on this design, however, it has the capability to add a locking mechanism.

The bolt head allows users to attach an avionics system to the arm by bolting the avionics system to the attached bolt mount featured on the arm. This design does not have the ability to switch head mounts as the bolt pattern is fixed and would not be removable. The bolt pattern on the head is a generic bolt pattern used in industry that would allow for a wide range of bolt spacing to be used and adequately attached. The advantages and disadvantages are listed out in Table 4 below.

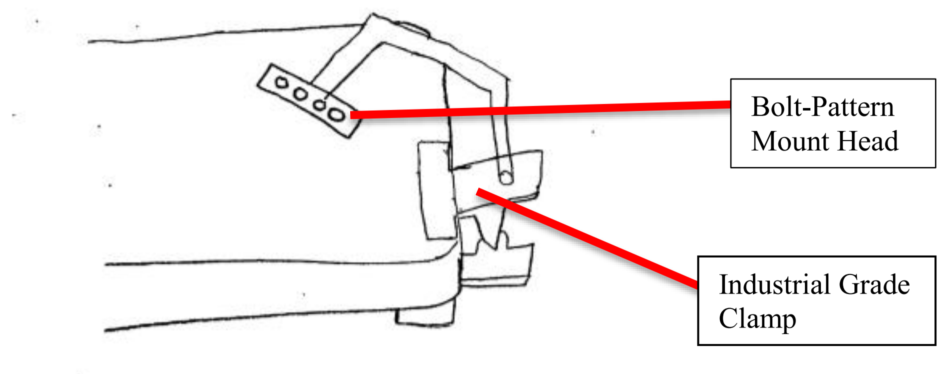

Figure 21. Bolt-Pattern Mount Head.

Table 4. Advantages and Disadvantages for Bolt-Pattern Mounts Head.

Advantages	Disadvantages
Bolt-pattern allows for secure attachment of the avionics system	Bolt-pattern head is not detachable
Full 360 degrees of vertical rotation	Clamp is not easily adjusted to varying benchtop thicknesses
Ability to have a locking mechanism	Three joints are more points of potential failure
	No current locking mechanism attached

4.4 Design #4: Hydraulically Assisted Arm

This design (Figure 22) makes use of a weighted base attached to a cylinder with a sleeve over it. The sleeve is attached to a beam, which is attached to a hydraulic cylinder which are pinned to each other. The sleeve will give the system yaw and vertical movement. The beam and hydraulic will give the system pitch. The arm cannot extend outwards and does not allow for roll. The ideal system would consist of six degrees of freedom which the hydraulically assisted design does not meet. The weighted base is also infeasible because the device must hold an avionic at a lever arm, so the base would have to be a multiple of that. So in order for the weighted base to work properly, it would have to be much heavier than the team's maximum weight of 50-pounds. The weighted base could also be a potential safety hazard if it was not able to hold the weight of the avionic. The hydraulic allows for easy manipulation of the avionic because it will extend at a steady rate. This will make it easy to position the device in desired position before working on the avionic. The hydraulically assisted arm also uses crank straps to hold the avionic in place. This will allow for a secure hold for abstract shapes.

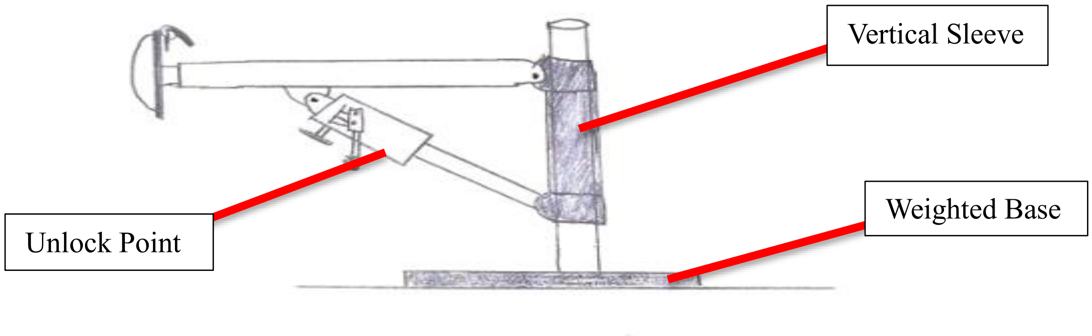

Figure 22. Hydraulically Assisted Arm.

Table 5. Advantages and Disadvantages for Hydraulically Assisted Arm.

Advantages	**Disadvantages**
Ease of manipulation	Not all degrees of freedom
Heavy load capacity	Weighted base unfeasible
Straps allow for secure hold on abstract shapes	Heavy

4.5 Design #5: Clamped Shock Assisted Arm

This design uses a C-channel base with two screw clamps to fasten the device to a workbench. On top of the base is a shaft with ball bearings allowing for full rotation at the base. From there, there is rectangular tube going up to a 1 degree of freedom joint with a shock mount. Another link extends to another 1 degree of freedom joint with a shock mount. On the end of this third link, there is a ball joint with quick detach shaft. The quick detach consists of a C-clip to lock axial movement as well as a groove and key to lock rotational movement of the head. The shocks assist with ease of manipulation keep the arm from collapsing when the joints are unlocked and help contribute to the overall load factor of safety. Exact materials for all the components have not been decided upon. All of these features are clearly shown in Figure 23 below. Additionally, an advantage and disadvantage list for this design is given in Table 6 below.

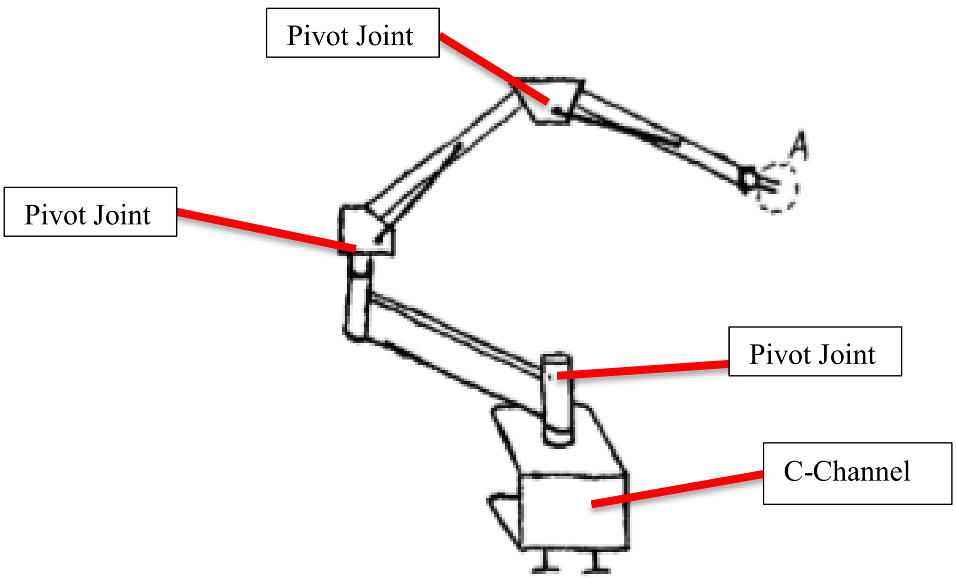

Figure 23. Clamped Shock Assisted Arm.

Table 6. Advantages and Disadvantages for Clamped Shock Assisted Arm.

Advantages	**Disadvantages**
Ease of Manipulation	No current locking mechanism attached
Has all six degrees of freedom	Three joints are more points of potential failure
Dual clamp attachment to table	
Quick detach head system	

5 DESIGN SELECTED – First Semester

Chapter 5 will contain a thorough explanation of the design selected and how it was selected using a Pugh chart and decision matrix. The rationale for the selection will be presented as well as an in-depth description of the design as a whole and the individual subsystems: table attachment, mechanical joints, head attachments, and locking mechanisms. Modifications to the final design will also be explained.

5.1 Rationale for Design Selection

The final design, selected using a Pugh chart (Appendix C, Figure C1, C2) and decision matrix (Appendix C, Figure C3), is a combination of the Clamped Shock Assisted Central Locking Arm and Hydraulically Assisted Arm designs described in Chapter 4. These two designs ranked the highest when analyzed in the decision matrix.

5.1.1 Pugh Chart

Before selecting a final design, the original 20 designs created by the team were put into a Pugh chart to narrow them down to the top 5 (Appendix C, Figure C1, C2). Before ranking the designs, a datum was selected (Figure 23). This monitor stand was chosen as a datum because it satisfies most of the engineering requirements that the arm requires and has similar components to what is needed for the arm. The 20 concepts were individually ranked against this datum for each engineering requirement using a number scale of -1, 0 and 1. A -1 means that the design performs worse than the datum in the specific category, a 0 means it performs the same, and a 1 means that it performs better than the datum. Once all of the concepts were ranked, their totals were summed. The five highest concepts, highlighted in purple, were the Bolt-Pattern Mount Head (Figure 20), Bio-Inspired Leg Springs (Figure 18), Hydraulically Assisted Arm (Figure 21), Clamped Shock Assisted Arm (Figure 22), and Clamped Shock Assisted Central Locking Arm (Figure 19).

Figure 23. Datum for Pugh chart [17]

5.1.2 Decision Matrix

After completing the Pugh chart and obtaining the top five designs, they were put in a decision matrix to find the top two (Appendix C, Figure C3). Each engineering requirement, located on the right side of the matrix, was given a ranking out of 1 based on the importance of each given by the client. The top five concepts were then given a score of 1 through 5 based on how well they accomplished each engineering requirement. A 1 means poor fit, 2 means low fit, 3 means average fit, 4 means good fit, and 5 means excellent fit. After each engineering requirement was given a score, the score was summed. The top two concepts, highlighted in purple, belong to the Clamped Shock Assisted Central Locking Arm (Figure 19) and Hydraulically Assisted Arm (Figure 21), described in Chapter 4.

The first design allows for motion with a greater degree of freedom and allows the operator to lock out all three joints from one location. However, since there is not a shock mounted between the sleeve and the first link, when the device is in the unlocked position, it will likely pivot under the weight of the attached avionics. The second design uses a hydraulic jack between the sleeve and link to provide support and adjustability. The combinations of these designs resulted in a final design that fully satisfied the client's needs to move in all six degrees of freedom and be load tested at 18.75 pounds while in the unlocked position and 43.75 pounds while in the locked position.

10 REFERENCES

[1] “CTA Digital Arm Mount,” Adorama. [Online]. Available: https://www.adorama.com/ctapadhaam.html. [Accessed: 17-Sep-2018].

[2] “Loctek Monitor Mount Heavy Duty Gas Spring Swing Monitor Arm Desk Mount Stand Fits for 10’-34’ Monitor Weighting 13.2-33 lbs - D7L,” Amazon. [Online]. Available: https://www.amazon.com/Loctek-Monitor-Spring-Weighting-13-2-33/dp/B01BXP9LT6/ref=sr_1_5?ie=UTF8&qid=1537070288&sr=8-5&keywords=clamp monitor mount. [Accessed: 17-Sep-2018].

[3] Anon, (2018). [online] Available at: https://www.robotshop.com/en/6-dof-robot-arm-kit.html [Accessed 17 Sep. 2018].

[4] "C-clamp - Clamps - Clamps & Vises - The Home Depot", thehomedepot.com, 2018. [Online]. Available: https://www.homedepot.com/p/Husky-6-in-Quick-Adjustable-C-Clamp-with-Rubber-Handle-99683/302347522. [Accessed: 12- Oct- 2018].

[5] “4 in. Steel Spring Clamp with Handles and Tips", thehomedepot.com, 2018. [Online]. Available: https://www.homedepot.com/p/BESSEY-4-in-Steel-Spring-Clamp-with-Handles-and-Tips-XM10/205512961. [Accessed: 12- Oct- 2018].

[6] "12 in. Handscrew Clamp", harborfreight.com, 2018. [Online]. Available: https://www.harborfreight.com/12-in-handscrew-clamp-60551.html. [Accessed: 12- Oct- 2018].

[7] “Advance Auto Parts - Down for Maintenance", Shop.advanceautoparts.com, 2018. [Online]. Available: https://shop.advanceautoparts.com/p/moog-driveline-products-universal-joint-354/10086740-P?navigationPath=L1*14925%7CL2*15051%7CL3*16357. [Accessed: 12- Oct- 2018].

[8] Knuckle Joints", Doughty-engineering.co.uk, 2018. [Online]. Available: http://www.doughty-engineering.co.uk/cgi-bin/trolleyed_public.cgi?action=showprod_T58730. [Accessed: 12- Oct- 2018].

[9] "J.W. Winco 5NXF1/B DIN71802 Ball Joint, 8 mm Diameter, M5 x 0.8 Tapped Right Hand Thread, M5 x 0.8 Threaded Shank, 10 mm Thread Length with Safety Catch", Amazon.com, 2018. [Online]. Available: https://www.amazon.com/Winco-5NXF1-DIN71802-Diameter-Threaded/dp/B018R9S40S/ref=lp_16411991_1_1?s=industrial&ie=UTF8&qid=1539951103&sr=1-1. [Accessed: 12- Oct- 2018].

[10] “Universal Disc Harrow L-plate for Brearings | eBay", eBay.com, 2018. [Online]. Available: https://www.ebay.com/p/Universal-Disc-Harrow-L-plate-for-Brearings/1248432717?iid=181705966852&chn=ps. [Accessed: 12- Oct- 2018].

[11] "Flexible Lightweight Portable Tripod for Projector DSLR Cameras (Black&White)", Amazon.com, 2018. [Online]. Available: https://www.amazon.com/Flexible-Lightweight-Portable-Projector-Cameras/dp/B00LXG9NN0/ref=asc_df_B00LXG9NN0/?tag=hyprod-20&linkCode=df0&hvadid=167143377764&hvpos=1o2&hvnetw=g&hvrand=14411341506217609834&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9060078&hvtargid=pla-314119775882&psc=1. [Accessed: 12- Oct- 2018].

[12] "K&M 23800.500.55", Sweetwater.com, 2018. [Online]. Available: https://www.sweetwater.com/store/detail/MicStdExtBrkS--k-and-m-23800.500.55?mrkgcl=28&mrkgadid=3316426354&rkg_id=0&product_id=MicStdExtBrkS&campaignty

pe=shopping&campaign=aaShopping%20-%20SKU%20-%20Studio%20%26%20Recording&adgroup=Microphones%20%26%20Wireless%20-%20K%26M%20-%20micstdextbrks&placement=google&adpos=1o1&creative=303058207356&device=c&matchtype=&network=g&gclid=CjwKCAjwgabeBRBuEiwACD4R5ibTLHKsM_DJ6yZRBFV-NphaayV59DfevcCrpgI5C7tCcYiIrw5-pBoC12cQAvD_BwE. [Accessed: 12- Oct- 2018].

[13] “Titan Arm (Orange)", brighttangerine.com, 2018. [Online]. Available: https://www.brighttangerine.com/store/titan-support-arm-orange/. [Accessed: 12- Oct- 2018].

[14] “Innovations and Patents : L.O.C.K.™ Knuckle System", Bklighting.com, 2018. [Online]. Available: http://www.bklighting.com/products/innovations-and-patents/832-l-o-c-k-knuckle-system-information.html. [Accessed: 12- Oct- 2018].

[15] “F. Gas Spring, "Gas Spring, Locking, Steel, Force 30", Grainger.com, 2018. [Online]. Available: https://www.grainger.com/product/BANSBACH-EASYLIFT-Gas-Spring-6FRT9. [Accessed: 12- Oct- 2018].

[16] "Bush baby | primate", britannica.com, 2018. [Online]. Available: https://www.britannica.com/animal/bush-baby. [Accessed: 12- Oct- 2018].

[17] “VIVO Full Motion Single VESA Computer Monitor Desk Mount Stand with Articulating Double Center Arm Joint | for 13" to 32" Screens (STAND-V101)” Amazon.com, 2018. [Online]. Available: https://www.amazon.com/VIVO-Computer-Monitor-Articulating-STAND-V101/dp/B074G56JCQ/ref=asc_df_B074G56JCQ/?tag=hyprod-20&linkCode=df0&hvadid=198057545906&hvpos=1o4&hvnetw=g&hvrand=12454044501909214180&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=1013406&hvtargid=pla-543460906952&psc=1. [Accessed: 12- Oct- 2018].

11 APPENDICES

11.1 Appendix A: House of Quality

Table A1. House of Quality.

	Longevity of Components	Structural Integrity	Component Size	Load Capacity	Clamping Pressure on Table	Voltage Between Arm and User	Degrees of Freedom	Toque Requirement	Factor of Safety	Device Weight
Longevity of Components										
Structural Integrity	++									
Component Size										
Load Capacity	-	-								
Clamping Pressure on Table										
Voltage Between Arm and User										
Degrees of Freedom										
Toque Requirement		-	+							
Factor of Safety		++	-	-						
Device Weight	-	-	--	-	+			-	-	
Budget	-	-	--	-	-	-		-	-	--

		Technical Requirements										
Customer Needs	**Customer Weights (1-10)**	Longevity of Components	Structural Integrity	Component Size	Load Capacity	Clamping Pressure on Table	Voltage Between Arm and User	Degrees of Freedom	Torque Requirements	Factor of Safety	Device Weight	Budget
1. Reliability	5	9	3		1							
2. Durability	4	9	9		1				3			
3. Variable Component Size	7			9				1	3			3
4. Large Load Capacity	8		3		9				1	3		1
5. Benchtop Mountable	3					9		1			3	
6. ESD Compliant	9						9					3
7. Easy Manipulation	6	3		3				9	9	3	3	
8. Safety/Robustness	10	3	3						1	9		
9. Portability	2			9		3		1			9	1
10. Cost	1	1	1	3	1	1	1	1		1	3	9
Technical Requirement Units		Life Cycles	lb	in	lb	psi	V	df	lb	FoS	lb	$
Technical Requirement Targets		-	125% (42.75)	*	*	9.75	0	6	20	≥3	≤50	1450
Absolute Technical Importance		130	106	102	82	34	82	67	105	133	48	67
Relative Technical Importance		2	3	5	7	11	6	9	4	1	10	8

* - Listed size and load requirements in project description

11.2 Appendix B: Supplemental Designs Considered (6-10)

11.2.1 Adjustable Wrench Design

This design (Figure B1) utilizes a c-clamp to mount to the benchtop. A carbon pipe will be attached to the clamp with a moveable and lockable sleeve attachment point for the handling arm. A 360-degree adjustable tubing joint is attached with an interchangeable interface for a head with a bolt pattern and a head similar to an adjustable wrench with crank to grab onto the avionic. Advantages and disadvantages of this design are listed below in Table B1.

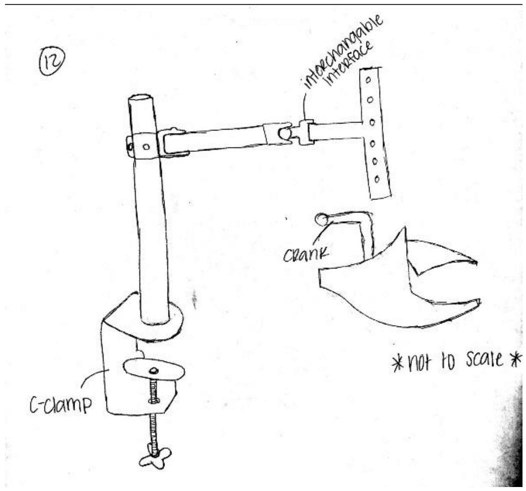

Figure B1. Adjustable Wrench Design.

Table B1. Advantages and Disadvantages of the Adjustable Wrench Design.

Advantages	Disadvantages
Easy Manipulation	Unable to lock arm joint
ESD Compliant	Wrench crank will be tedious while trying to attach avionic
Portable	Wrench may be too heavy depending on what material is used
Universal bolt pattern for easy attachment to avionics with bolt patterns	Custom parts will need to be manufactured
Six degrees of freedom	

11.2.2 C-Clamp Mount Plate Design

This design features a c-clamp to attach the unit to the benchtop (Figure B2). The screw allows the clamp to be adjusted to fit varying table thicknesses. The three joints are made of Aluminum to ensure strength and durability, without adding unnecessary weight. The most notable difference from this design to the previous ones is the mounting plate as the head attachment. A mounting plate allows several different head attachments to be incorporated into the design. Each different head attachment would need to have a universal design to interface with that mounting plate, however. This design is able to lock out all three joints, however it does not have a way to extend any farther in the vertical direction. A list of advantages and disadvantages can be seen in Table B2.

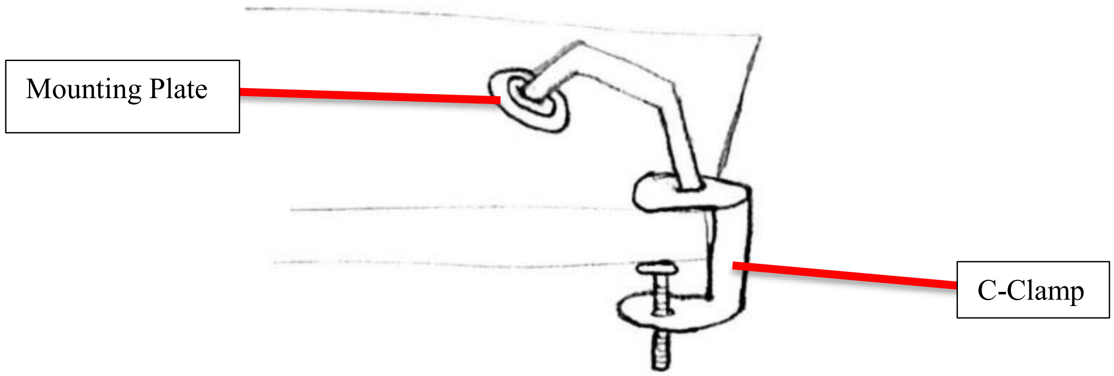

Figure B2. C-Clamp Mount Plate Design.

Table B2. Advantages and Disadvantages of the C-clamp Mount Plate Design.

Advantages	**Disadvantages**
Adjustable clamp to fit most table designs	No vertical adjustment
Locks out	More joints are more potential for failure
Universal mounting plate makes attaching and detaching different heads simple	Heads with universal mounting plate are more expensive
Aluminum is durable and low-cost	
ESD compliant	

11.2.3 Dual Joint Removable Head Design

This design (Figure B3) features a C-clamp similar to the previous design that attaches to the table and allows for varying table sizes. The body consists of two joints that end with a ball joint for the head. This ball joint allows for different head attachments. Additionally, there is no vertical adjustment as far as the position, so that is limiting the degrees of freedom. This body is made with aluminum so that it is durable and low cost. The most important part of this design is the ability to remove and attach different heads. A locking mechanism could be added to this design, but it is not featured in the image below. The pros and cons of this design are in Table B3.

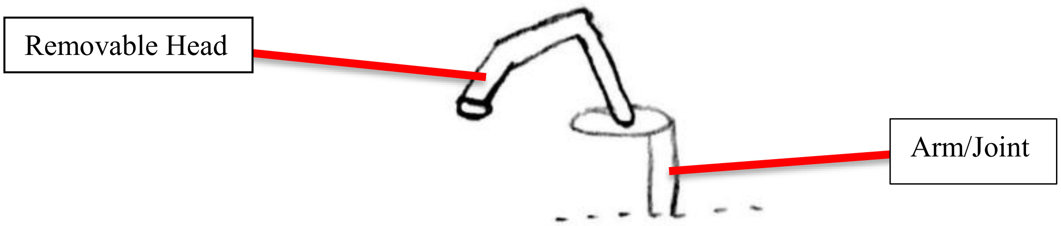

Figure B3. Dual Joint Removable Head Design.

Table B3. Advantages and Disadvantages of the Dual Joint Removable Head Design.

Advantages	Disadvantages
Adjustable benchtop mount	No vertical adjustment
ESD Compliant	Not all 6 degrees of freedom
Aluminum is durable and low-cost	No locking mechanism currently incorporated
Detachable head options	
Clamp mounts to varying sizes of tables	
Potential for a locking mechanism	

11.2.4 Bio-Inspired Hawk Beak

This design (Figure B4) was based on the beak of a hawk and focused only on the head attachment. The locking mechanism, joints, and table mount were not a part of the design because it was focused on the head attachment subsystem.

Much like a hawk's beak, this head attachment has one "hook" on the end to help keep the avionics system in place. The entire attachment has 3 prongs for more ability to secure the system. Because this is more of a subsystem to consider, this design in itself does not actually meet most of the customer requirements or engineering requirements. This design would be adequate for a low-cost option that would be able to rotate in all directions. The advantages and disadvantages of the bio-inspired hawk beak can be seen in Table B4.

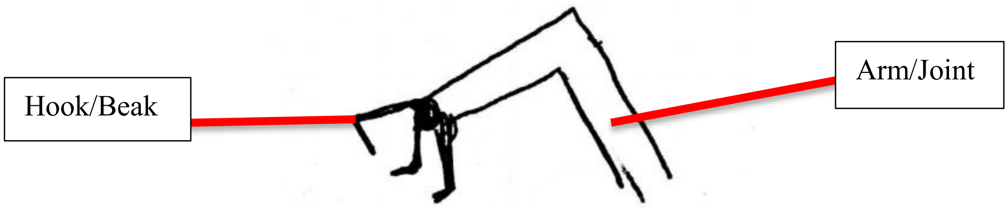

Figure B4. Bio-Inspired Hawk Beak design

Table B4. Advantages and Disadvantages of the Bio-Inspired Hawk Beak design

Advantages	Disadvantages
Hook allows the avionics to be held in place	Prongs are not flexible, only adjustable as a whole unit
Head attachment is compatible with any of the body and benchtop designs	Prongs may get in the way of the user
ESD compliant	Limited manipulation
Lightweight	
Portable	

11.2.5 Rolling Joint Claw

This design (Figure B5) is mainly focused on the portability aspect of the handling arm. The arm is attached to a rolling workbench that can be moved anywhere it is needed. The arm itself has 3 lengths and 2 joints that give it the degree of freedom required by the customer. The clap on the arm clamps down onto the avionic to hold it in place. A list of pros/cons for this design can be seen in Table B5.

Figure B5. Rolling Joint Claw.

Table B5. Advantages and Disadvantages of the Rolling Joint Claw Design.

Advantages	**Disadvantages**
Claws hold avionic to arm	The arm can be adjusted in height, secured to table
Rolling design allows for easy mobility/portability	Square claws do not allow for oddly shaped objects
Joints on arm allow for 6 degrees of freedom	Joints do not lock at one place, each joint must be locked individually

11.3 Appendix C: Design Selected

11.3.1 Pugh Chart

	Visio Computer Mount	Steel tube, ball and socket	Zero Length Spring	Vertical post with vertical pivots	Flexible Lamp Mount	Rolling Joint Claw	Bolt Pattern Mount Head	C-Clamp Mount Plate	Dual Joint Removabl e Head	Bio-Inspired Hawk Beak	Bio-Inspired Leg Springs
	DATUM	1	2	3	4	5	6	7	8	9	10
		Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6	Concept 7	Concept 8	Concept 9	Concept 10
Safety	0	-1	-1	0	-1	1	0	0	0	0	1
ESD Compliant	0	0	0	0	0	0	0	0	0	0	0
Load Capacity	0	-1	-1	0	-1	1	1	1	1	1	1
Component Size	0	1	-1	-1	0	0	1	1	0	1	1
Torque	0	0	1	0	1	0	0	0	0	1	1
Degrees of Freedom	0	0	0	1	1	1	1	1	1	1	1
Longevity	0	0	-1	-1	-1	1	1	0	0	-1	0
Structural Integrity	0	-1	-1	0	0	0	1	0	0	0	1
Compatible with Table	0	1	1	1	0	1	1	1	1	0	1
Device Weight	0	0	0	0	1	-1	0	0	0	0	0
Cost	0	-1	-1	-1	1	-1	-1	-1	-1	-1	-1
∑+	+0	+2	+2	+2	+4	+5	+6	+4	+3	+4	+7
∑-	-0	-4	-6	-3	-3	-2	-1	-1	-1	-2	-1
∑	0	-2	-4	-1	1	3	5	3	2	2	6
Rank	N/A	7	9	6	5	3	2	3	4	4	1

Figure C1. Pugh Chart for First 10 Designs.

	Visio Computer Mount	Lots of 360 Joints	Adjustable Wrench	Shock Turned	Hydraulic	Inclineable Arm	Weighted Base with Central Locking Arm	Clamped Shock Assisted Arm	Clamped Shock Assisted Central Locking Arm	Monkey	Clamp w/ Joints and Corner Clamps
	DATUM	11	12	13	14	15	16	17	18	19	20
		Concept 11	Concept 12	Concept 13	Concept 14	Concept 15	Concept 16	Concept 17	Concept 18	Concept 19	Concept 20
Safety	0	-1	0	-1	1	0	1	1	1	-1	0
ESD Compliant	0	0	0	0	0	0	0	0	0	-1	0
Load Capacity	0	0	0	-1	1	0	1	1	1	-1	0
Component Size	0	1	1	0	1	0	1	1	1	1	1
Torque	0	0	0	0	1	-1	-1	1	1	-1	0
Degrees of Freedom	0	1	1	0	0	0	1	1	1	-1	1
Longevity	0	-1	0	-1	1	1	1	1	1	-1	1
Structural Integrity	0	-1	0	0	1	1	-1	-1	-1	1	1
Compatible with Table	0	0	0	1	0	-1	0	1	1	-1	0
Device Weight	0	1	1	0	0	0	-1	0	1	-1	-1
Cost	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
∑+	+0	+3	+3	+1	+6	+2	+5	+7	+8	+2	+4
∑-	-0	-4	-1	-4	-1	-3	-4	-2	-2	-9	-2
∑	0	-1	2	-3	5	-1	1	5	6	-7	2
Rank	N/A	6	4	8	2	6	5	2	1	10	4

Figure C2. Pugh Chart for Last 10 Designs.

11.3.2 Decision Matrix

		ALTERNATIVES									
Decision Model		**Bio-Insp. Leg Springs**		**Shock Assisted**		**Bolt-Pattern**		**Hydraulic**		**Clamped Shock**	
Criterion	**Weight**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**
Safety	0.15	3	0.45	4	0.6	3	0.45	4	0.6	3	0.45
ESD Compliant	0.15	3	0.45	3	0.45	3	0.45	3	0.45	3	0.45
Load Capacity	0.11	4	0.44	4	0.44	3	0.33	3	0.33	3	0.33
Component Size	0.11	3	0.33	4	0.44	3	0.33	4	0.44	4	0.44
Torque	0.08	3	0.24	4	0.32	3	0.24	4	0.32	2	0.16
Degrees of Freedom	0.08	4	0.32	4	0.32	4	0.32	3	0.24	4	0.32
Longevity	0.07	4	0.28	2	0.14	3	0.21	4	0.28	3	0.21
Structural Integrity	0.07	3	0.21	4	0.28	3	0.21	4	0.28	2	0.14
Compatible with Table	0.07	5	0.35	5	0.35	5	0.35	5	0.35	5	0.35
Device Weight	0.06	4	0.24	4	0.24	3	0.18	4	0.24	4	0.24
Cost	0.05	3	0.15	3	0.15	3	0.15	3	0.15	3	0.15
Total	**1**	**39**	**3.46**	**41**	**3.73**	**36**	**3.22**	**41**	**3.68**	**36**	**3.24**

Figure C3. Decision Matrix for Final Design Selection.