

ME 428/429/430 Senior Design Project

# Modular Attachment System for Tactical Robot

Preliminary Design Report



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## **Abstract**

The goals of this report are to clearly define the problem and the scope of this project, present information regarding background design research, explain the process taken to reach the final design, go over the part procurement and manufacturing process, outline the assembly steps, and verify the design against the criteria through testing. The problem and scope of the project were defined using the constraints provided by the project sponsor, Blueline robotics. Blueline needs a modular attachment system for their tactical robot. The completed background research contains existing robot solutions that deal with similar tasks. Many of these existing robots lack modularity at the base of the arm for a variety of general attachments. As a result, further research of general “quick-release” attachment points or systems was necessary and done through existing patents. Further brainstorming, functional decomposition, morphological matrices, and decision matrices were utilized to come to a design concept for the preliminary design review (PDR). Discoveries through the prototyping process after the PDR led to re-designing components of the design due to parts being too complex and expensive to manufacture. The final design retains all the functionality of the previously proposed design in a simpler, more cost-effective manner. The final design was manufactured both on Cal Poly’s campus, and at the team members’ residences. The final design was verified to have met the given criteria through multiple tests. For organization and project management, a Gantt chart and Quality Function Deployment chart were created to outline goals, establish timelines, and kindle proper design direction under identified specifications.

# Table of Contents

<b>1.0</b>	<b>Introduction</b>	<b>1</b>
<b>2.0</b>	<b>Background</b>	<b>1</b>
2.1	Summary of customer observations	1
2.2	Table of existing designs	2
2.3	Table of patent search results	4
2.4	Summary of the relevant technical literature	5
2.5	List of applicable industry codes, standards, and regulations	6
<b>3.0</b>	<b>Objectives</b>	<b>6</b>
<b>4.0</b>	<b>Concept Design</b>	<b>9</b>
4.1	Ideation and function prototypes	9
4.2	Pugh, Morphological, and Weighted Decision Matrices	10
4.2.1	Pugh Matrices	10
4.2.2	Morphological Matrix and Concept Sketches	10
4.2.3	Weighted Decision Matrix	15
4.3	Final Concept Design	15
4.4	Preliminary Design Risks	20
4.5	Chosen Design Concerns	20
<b>5.0</b>	<b>Final Design</b>	<b>21</b>
5.1	Differences from Concept Design	22
5.2	Design Sub-Assemblies	23
5.3	Structural Prototype	24
5.4	Meeting Engineering Specifications	26
5.5	Safety, Maintenance Considerations, & Cost	29
<b>6.0</b>	<b>Manufacturing</b>	<b>31</b>
6.1	Procurement	31
6.2	Manufacturing	31
6.3	Assembly	33
6.4	Outsourcing	34
6.5	Challenges	34
6.6	Final Budget	35
<b>7.0</b>	<b>Design Verification</b>	<b>36</b>
7.1	Test #1: Bayonet Locking Mechanism FEA	36
7.2	Test #2: Top and Bottom Plate FEA Analysis	40
7.3	Test #3: Industrial Pin FEA Analysis	41
7.4	Test #4: Absorption System Testing	42
7.5	Test #5/6: Watertight to IP65	42
7.6	Test # 7: Time to Attach and Release	44
7.7	Test # 8: Passing Power Through the System and Ensuring Wires Will Not Get Damaged	46
7.8	Summary and Suggestions	47

<b>8.0 Project Management .....</b>	<b>48</b>
<b>9.0 Conclusions and Recommendations .....</b>	<b>49</b>
<b>Works Cited.....</b>	<b>50</b>
<b>Appendices .....</b>	<b>52</b>
<b>Appendix A: Preliminary Analysis of Load Cases .....</b>	<b>A</b>
<b>Appendix B: Quality Function Deployment Chart (House of Quality) .....</b>	<b>B</b>
<b>Appendix C: Ideation Section Results .....</b>	<b>C</b>
<b>Appendix D: Pugh and Weighted Matrices .....</b>	<b>D</b>
<b>Appendix E: Final Concept Design Weighted Decision Matrix Rating Explanation .....</b>	<b>E</b>
<b>Appendix F: CAD drawing isometric view of prototype .....</b>	<b>F</b>
<b>Appendix G: Hand Calculations for Spring Stiffness .....</b>	<b>G</b>
<b>Appendix H: Design Hazard Checklist .....</b>	<b>H</b>
<b>Appendix I: Drawing Package.....</b>	<b>I</b>
<b>Appendix J: Failure Modes &amp; Effects Analysis (FMEA) part 1 .....</b>	<b>J</b>
<b>Appendix K: Design Verification Plan (DVP).....</b>	<b>K</b>
<b>Appendix L: Project Management Gantt Chart .....</b>	<b>L</b>
<b>Appendix M: User Manual .....</b>	<b>M</b>

## List of Figures

<b>Figure 1:</b> Boundary sketch diagram showing the attachment point between the removable robotic arm and the main chassis. The dotted lines represent the boundaries of the project.....	7
<b>Figure 2:</b> Functional Decomposition.....	9
<b>Figure 3:</b> Full System Concept #1.....	12
<b>Figure 4:</b> Full System Concept #2.....	12
<b>Figure 5:</b> Full System Concept #3.....	13
<b>Figure 6:</b> Full System Concept #4.....	13
<b>Figure 7:</b> Full System Concept #3 from the weighted decision matrix.....	14
<b>Figure 8:</b> Isometric view of chosen system level concept. ....	16
<b>Figure 9:</b> Spring Constant vs. Axial Force at Constant Displacement of 0.125 Inches.....	16
<b>Figure 10:</b> Spring Constant vs. Displacement for constant 125lb Force.....	17
<b>Figure 11:</b> Exploded component concept CAD model of dowel-like added support columns. Not pictured are the electrical components to pass the center holes, the spring mechanisms, the rubber strut boot, and the welded connection points. ....	18
<b>Figure 12:</b> CAD model and FEA analysis of the male feature within the Gardena attachment system .....	19
<b>Figure 13:</b> CAD model and FEA analysis of plates and dowel-like support columns incorporated into the vibration dampening system area for added support. ....	19
<b>Figure 14:</b> Exploded view of concept prototype.....	21
<b>Figure 15:</b> Rendered final design .....	22
<b>Figure 16:</b> Exploded view of concept prototype model .....	23
<b>Figure 17:</b> 3D-printed bayonet locking mechanism with both halves locked together. ....	24
<b>Figure 18:</b> Half of the bayonet locking mechanism. ....	24
<b>Figure 19:</b> Structural Prototype with top plate, industrial pins, and bottom plate.....	25
<b>Figure 20:</b> Moment Load Case (Stress FEA) – 150 lbf applied to front left face of force piece to create high moment on the system. Yielded max stress of $4.127e07$ N/m <sup>2</sup> or 5.98 KSI.....	27
<b>Figure 21:</b> Moment Load Case (Displacement FEA) – 150 lbf applied to front left face of force piece to create high moment on the system. Yielded max displacement of $7.824e-03$ mm or .0003 in.....	27
<b>Figure 22:</b> Torque Load Case (Stress FEA) – 150 lbf-in. CW applied to the top cylindrical face of the top connector to create high torque on the system. Yielded max stress of $1.972e07$ N/m <sup>2</sup> or 2.86 KSI .....	28
<b>Figure 23:</b> Torque Load Case (Displacement FEA) – 150 lbf-in. CW applied to the top cylindrical face of the top connector to create high torque on the system. Yielded max displacement of $2.459e-03$ mm or .00009 in. ....	28
<b>Figure 24:</b> The top plate held in the mill vise. ....	32
<b>Figure 25:</b> The top and bottom plate with pins press fitted. Does not include the bayonet connector, jounce bumper, or nuts. ....	32
<b>Figure 26:</b> The bottom plate with jounce bumper set in place .....	33
<b>Figure 27:</b> The top plate is placed on the assembly. ....	34
<b>Figure 28:</b> The unattached bayonet connectors separated to show the bushing.....	34
<b>Figure 29:</b> Exaggerated deformation and color display of stress location in clockwise torsion load case.	36
<b>Figure 30:</b> Exaggerated deformation and color display of displacement location in clockwise torsional load case. ....	37
<b>Figure 31:</b> Exaggerated deformation and color display of stress location in moment load case.....	37

**Figure 32:** Exaggerated deformation and color display of displacement location in moment load case. . 38

**Figure 33:** Exaggerated deformation and color display of stress location in axial load case. .... 38

**Figure 34:** Exaggerated deformation and color display of displacement location in axial load case..... 39

**Figure 35:** Watertight test of epoxy seals between the jounce bumper and the two plates ..... 43

**Figure 36:** Watertight test of epoxy seals between the bushing and bayonet locking mechanism..... 43

**Figure 37:** Checking to see if the epoxy seals between the jounce bumper and the two plates kept the inside of the jounce bumper dry..... 44

**Figure 38:** Checking to see if the epoxy seal between the bushing and bayonet locking mechanism succeeded in keeping the inside of the bayonet locking mechanism dry. .... 44

**Figure 39:** 25-poung weight placed on top of the attachment system while power cord is being passed through. .... 46

**Figure 40:** Power cord is visually inspected to ensure no pinching or crushing occurred. .... 47

## List of Tables

<b>Table 1:</b> Table of Existing Designs.....	2
<b>Table 2:</b> Table of Existing Designs Continued .....	3
<b>Table 3:</b> Table of Patent Search Results .....	4
<b>Table 4:</b> Table of Patent Research Continued .....	5
<b>Table 5:</b> Blueline Robotics Wants and Needs .....	7
<b>Table 6:</b> F32 Engineering Specifications Table.....	8
<b>Table 7:</b> Morphed System Level Concepts.....	11
<b>Table 8:</b> Morphological Matrix .....	11
<b>Table 9:</b> Budget of project and bill of materials .....	35
<b>Table 10:</b> Results of bayonet connector design test .....	39
<b>Table 11:</b> Results of the plate FEA design test.....	41
<b>Table 12:</b> Results of the pins FEA design test .....	42
<b>Table 13:</b> Timed trials and averages of attach and detach times.....	45
<b>Table 14:</b> Summary of Tests.....	47
<b>Table 15:</b> F32 Key Deliverable Timeline.....	48



## **1.0 Introduction**

The SLO SWAT team has been dissatisfied with their current tactical robot because the ones currently in use are outdated and do not contain the full desired functionality. Blueline Robotics was founded in part to design a tactical robot to fulfill the SLO SWAT team's needs. One specific function Blueline Robotics requires is the development of an interchangeable attachment system that will allow their law enforcement robot to be fitted with a variety of tools so that it may be used for a multitude of missions and situations. Blueline Robotics has come to Cal Poly and entrusted this task to the Cal Poly senior design team F32. The overall goal is to improve upon competitors' designs by analyzing similar existing mechanisms and incorporating existing feedback from current users to create a new, refined system. Though similar systems exist, Blueline has a unique product with a unique market that requires a custom solution. The modular attachment system will improve the robot's performance in a variety of situations and widen its usability beyond local law enforcement.

This report will outline the background research completed by the senior design team and the conclusions drawn from existing products and technical journals in the Background section. Additionally, this report will break down the customers' needs and wants, the engineering specifications decided upon to measure the successful integration of the customers' desires, and the thought process behind the ranking of customer needs in the objectives section. The long and robust process from background research to final design concept, as well as engineering assessments and analysis of the chosen design is explained in the concept and final design sections. The manufacturing of the verification prototype is outlined in the Manufacturing section. The design verification and testing of the design verification prototype is outlined in the design verification section. The overall completed design process is outlined in the project management section. Finally, the conclusions from the verification process and suggestions for future manufacturing and design directions are outlined in the conclusions and recommendations section.

## **2.0 Background**

The following section will detail the research process undertaken by the team and summarize the pertinent findings. These findings served as the foundation for the ideation process and further defined the design direction.

### **2.1 Summary of customer observations**

Blueline Robotics is a new company working to provide an improved alternative to the tactical robots currently used by SLO SWAT team with the hope of expanding to other customers in the future. The current tactical robot used by the SLO police is outdated and has multiple shortcomings. Ryan Pfarr, project sponsor and co-founder of Blueline, is closely related to Chad Pfarr, SLO PD's Detective Sergeant and Tactical Commander. Chad Pfarr has provided insight to the project sponsors regarding the shortcomings of the robot currently being used. Blueline hopes their product can meet the needs of the SLO SWAT team and exceed the capabilities of the current robot. The project sponsors have the main chassis of the robot and a basic mechanical arm attachment already designed. They want a universal



attachment point for the chassis which can be used to attach the mechanical arm and, in the future, other attachments such as sensors and cameras. The attachment point has a variety of considerations due to its modular nature and its designed use. The attachment point must be a quick release attachment system, allowing the user to remove and replace the tools in under five minutes. This mechanism must provide a way to transfer power and data back and forth from the attachment to the chassis. Because of the extreme nature of the work done by first responders, this attachment point should be expected to experience a variety of environmental stresses and rough handling throughout the duration of its life.

One of the tasks delegated by the sponsors was to model two different loading situations and use statics and dynamics to analyze the resulting forces at the attachment point of the mechanical arm. The tactical robot was modeled as a box that is 18in x 24in x 8 in (w x l x h) with a bar of length 4ft attached to the box 4in up the 8in side. The heaviest load that the robot arm is expected to bear is a 25lb load positioned at the end of the 4ft arm. The first situation assigned by the sponsors was for the arm to carry a 25lb load over a 4-foot arm and accelerate 2rad/sec. These hand calculations can be found in Appendix A.

## 2.2 Table of existing designs

This section contains a table of existing designs developed by competitors. These designs, along with existing patents, constitute background research. While they are great for reference when considering the scope of this project and seeking inspiration from available solutions, it is important to note that Blueline Robotics requires its own solution specific to the vision its co-founders have. Tables 1 and 2 show the existing designs.

**Table 1:** Table of Existing Designs

Competitor Model	Notes
<p data-bbox="181 1199 587 1268"><b>ICOR - Caliber T5 (ICOR Technology)</b></p> 	<ul data-bbox="711 1199 1414 1446" style="list-style-type: none"> <li>• Weight 150 lb – dimensions 17"x36"x22"</li> <li>• Has a capacity lift of 45 lb</li> <li>• Weather Resistance</li> <li>• Climbs 8" stairs at 45°</li> <li>• Vertical reach of up to 66" &amp; rotation of 360°</li> <li>• 2-way communication, 10x optical zoom camera, wide-angle camera.</li> </ul>
<p data-bbox="181 1562 587 1631"><b>SDA Tactical: LT2/F "Bulldog" (SDA Tactical)</b></p> 	<ul data-bbox="662 1562 1430 1850" style="list-style-type: none"> <li>• 85lbs -Dimensions: 19"x30"x18"</li> <li>• Has 30x zoom camera, 4 axis arms, the arm payload is 15 lb, has bomb disposal</li> <li>• Equipped with an 30x zoom camera.</li> <li>• Has 4 axis arms with equipment for the fifth axis (optional) &amp; tools attached</li> <li>• Has a two-way communication system</li> <li>• Standard price: \$39,000</li> </ul>

**Table 2:** Table of Existing Designs Continued

Competitor Model	Notes
<p><b>SDA Tactical: HD2 "Mastiff" (SDA Tactical)</b></p> 	<ul style="list-style-type: none"> <li>• 110-150lbs - 20"x38"x26"</li> <li>• Has 20x zoom camera</li> <li>• Has 4 axes arms, arm payload is 20lb, has bomb disposal</li> <li>• The camera is stationed along with the arm (20x zoom)</li> <li>• Two-way audio system</li> <li>• Standard price: \$41,500</li> </ul>
<p><b>Robotex Avatar 3: AVATAR EOD Robot (Robotex)</b></p> 	<ul style="list-style-type: none"> <li>• unconventional mount: slow, but easy to navigate through stairs</li> <li>• The arm has 3 axes (1 based rotation, one joints and another joints)</li> <li>• Has a grabber attachments and a gun</li> <li>• robot's arm attachments are installed with a screw-&gt; not quick release</li> </ul>
<p><b>NIC Instruments: ZEUS Robot (NIC Instruments)</b></p> 	<ul style="list-style-type: none"> <li>• Has one arm with attachments (grabber)</li> <li>• Has a lot of special environmental resistances (Water, radiation, fire, etc.)</li> <li>• Geared for quick part changing -&gt; quick release mechanism</li> <li>• 5 cameras, (forward, rear drive, a pan tilt, gripper, 'nomad' on the platform)</li> </ul>

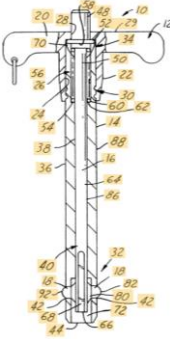
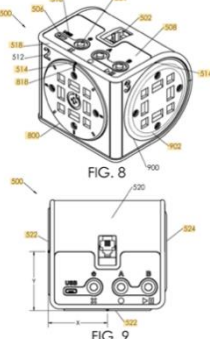
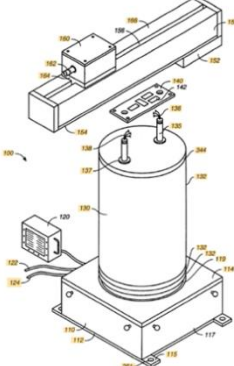
## 2.3 Table of patent search results

Viewing similar patents is a very useful form of background research. Existing patents not only give in-depth descriptions of their modular attachment systems, but also provide detailed drawings of each component that is discussed. In Tables 3 and 4, there are eight different patents listed by numbers that include their patent title, description, a key drawing, and the source for the patent.

**Table 3:** Table of Patent Search Results

Patent Number	Patent Title	Description	Drawing
US20090071281A1	Robot arm assembly	<ul style="list-style-type: none"> <li>• Robotic arm much like the one BlueLine Robotics will sell</li> <li>• Includes a brief description of the attachment system as well as a couple schematics (Fisk)</li> <li>• Went with a spur gear running through the chassis (Fisk)</li> </ul>	
US20120215358A1	Robotic arm system	<ul style="list-style-type: none"> <li>• Includes a more in-depth description of the connection supporting a payload on the robotic system and details on the captive fasteners used (Gettings)</li> </ul>	
US6826977B2	Drive system for multiple axis robotic arm	<ul style="list-style-type: none"> <li>• Attachment system built to support the cantilevered loads of a robotic arm.</li> <li>• Gives a lot of insight into the problems with the current models of attachments systems (Gaylen)</li> </ul>	
US5993365A	Tool attachment and release system for robotic arms	<ul style="list-style-type: none"> <li>• Gives a lot of very useful figures as well as a description of their magnetic flux shunt bar locking mechanism (Stagnitto)</li> <li>• Very good example of an existing quick release robotic attachment system (Stagnitto)</li> </ul>	

**Table 4:** Table of Patent Research Continued

Patent Number	Patent Title	Description	Drawing
US678669B2	Positive lock quick release pin	<ul style="list-style-type: none"> <li>This can be incorporated into any design with a plate and multiple positive quick release pins (Walter)</li> </ul> <p>This will allow the attachment to support the large moments due to the cantilevered loads in tension and compression to avoid buckling.</p>	
US20160005331A1	Modular robot system	<ul style="list-style-type: none"> <li>Has an in-depth section on the attachment systems for each leg of the robot (Ryland)</li> </ul> <p>A good example of a quick release modular attachment system that is capable of passing power through it.</p>	
US6831436B2	Modular hybrid multi-axis robot	<ul style="list-style-type: none"> <li>Independent and interchangeable module attachment system (Gonzalez)</li> <li>It will work in 3 dimensions and be able to support high shear stress and moments</li> </ul> <p>It provides an example of a system capable of providing more accurate movements than required by Blueline Robotics.</p>	

## 2.4 Summary of the relevant technical literature

During the research process, several databases and search engines were used to get a comprehensive view of the current technical literature surrounding the subject of modular robotic attachments. Five of the most applicable and relevant journal publications are discussed below. The first article is by P. Kang, *Mobile Robot Manipulation System with a Reconfigurable Robotic Arm: Design and Experiment\**, which discusses a mobile robotic which can be broken down and made modular as needed (Kang 2378). While this robot design was quite dissimilar from Blueline's, the actuator schematics included in the paper were useful (Kang 2378). The second technical piece of literature is *Design of SMC rover: development and basic experiments of arm equipped single wheel rover* by A. Kawakami. While once again, the body of the robot was very different from the chassis used by Blueline, the description of the connection point between the arm and main body was useful (Kawakami 100). The third article, A

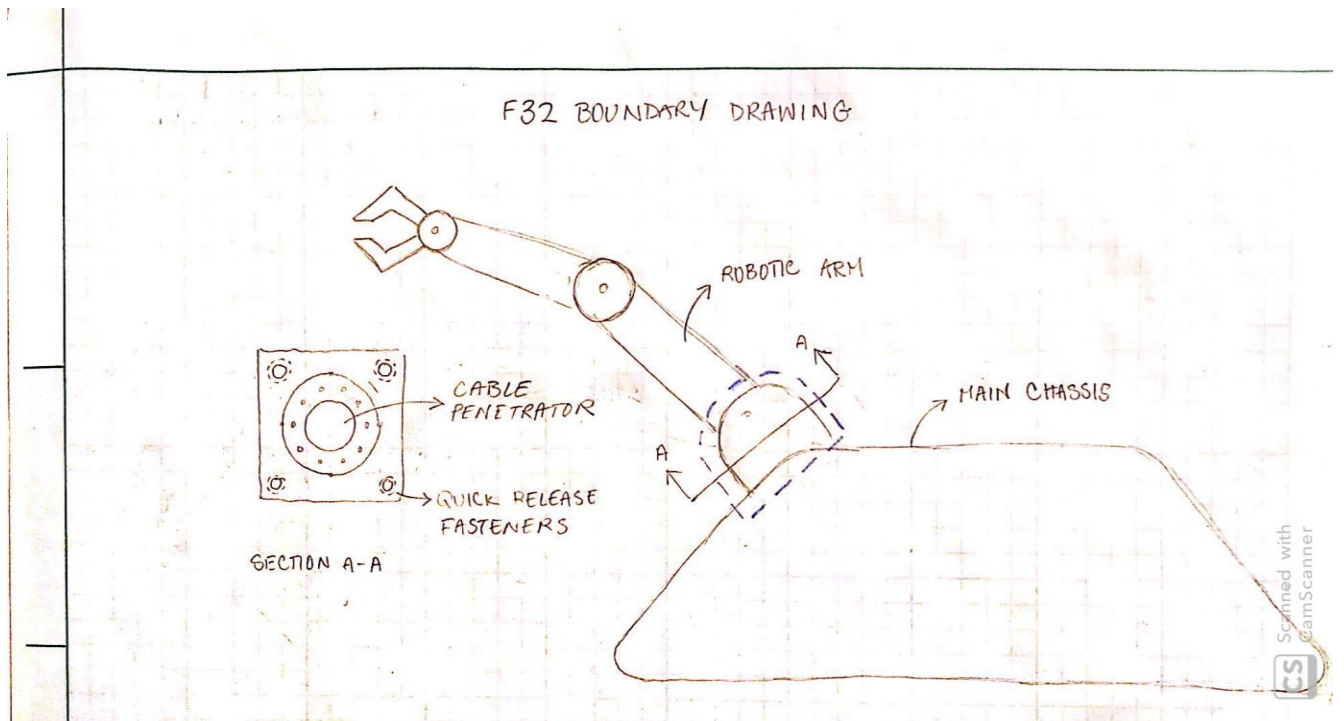
*separable combination of wheeled rover and arm mechanism: (DM)2* by Y. Xu, is notable and interesting in its design of a detachable robotic arm. The design was very mission-specific but was a helpful design to start with nonetheless (Xu 2384). The fourth article was written by H. B. Tan and provides a building block for what a basic robotic arm joint looks like thanks to its general diagrams of the joint and attachment point (Tan 5395). The fifth article, *Design of a low-cost series elastic actuator for multi-robot manipulation*, was written by Campbell and showed an interesting design of multiple robots working together with complicated mechanical shoulder joints (Campbell 5397). The sixth technical source was much more theoretical, with a mathematical model of the loads and reactions of a loaded robotic arm (Kim 1346). Finally, *An Open-Access Passive Modular Tool Changing System for Mobile Manipulation Robots* provided information on tool changing at the end of a robotic arm which could be adapted for larger modular attachments (Berenstein 595). Much of the other literature was either not applicable to the sponsor's project or did not provide sufficient information to prove useful.

## **2.5 List of applicable industry codes, standards, and regulations**

During the research process, it was determined that there were few applicable industry codes, standards, and regulations. The only applicable standard was the Ingress Protection, or IP rating. The sponsor requested that the attachment point be waterproof to IP65, which requires that the attachment point be totally protected against solid foreign objects such as dust and be protected against low pressure jets of water from all directions with limited ingress permitted ("IP Enclosure Ratings"). As more potential industry standards or laws dealing with law enforcement are discovered, they will be noted and documented.

## **3.0 Objectives**

The task presented by Blueline Robotics is that Blueline needs a way to allow their robot to be fitted with a variety of tools to ensure it can be used for a multitude of missions and situations. This system's needs must be achieved quickly and easily for "in the field" moments. This attachment point needs to be able to support cantilevered loads while moving in multiple directions. Additionally, this device must be durable and waterproof to IP65 in harsh environmental conditions. Finally, the cost of the final prototype and design should stay within the desired constraints from Blueline. To better visualize where the bounds of this project lie, a boundary diagram is presented in Figure 1.



**Figure 1:** Boundary sketch diagram showing the attachment point between the removable robotic arm and the main chassis. The dotted lines represent the boundaries of the project.

To further define the task presented by Blueline with listed constraints, a table of wants and needs was created with specific items. These items were already presented and verified by Blueline as ways to constrain the initial work and research. These items can be found in Table 5.

**Table 5:** Blueline Robotics Wants and Needs

Needs	Waterproof to IP65
	Able to support a variety of current and future attachments
	Able to interface with the Mechatronic systems
	Quick release
	Under \$500 prototype
	Pass necessary power and data through to attachments
	Undergo cantilever loads up to 25lbs
Wants	Navigate and survive rough terrain or rugged environments
	Flexibility in choosing what material is used for attachment point
	Rotating (stretch goal)

To begin the design process, a Quality Function Deployment (QFD) was utilized, which can be found in Appendix B. The QFD helps to define the problem in terms of specifications that can be measured to determine whether the customer needs have been met by a design. This process began by defining the customer and their needs and wants. Each of these were evaluated on their importance to the two customers, Blueline and SLO SWAT, and ranked from 0-10. Being able to support a cantilevered

load of 25 lbs. was deemed as the most important for both the SLO SWAT team and Blueline Robotics. Being waterproof to IP65 and able to support multiple attachments was assigned as the next most important function for both customers. The rest of the needs and wants rankings can be found within the QFD in Appendix B. Next, the needs and wants were evaluated to develop a set of tests with measurable outcomes to quantitatively determine whether each need and want was successfully met. Each of these tests, called engineering specifications, were assigned a strong, moderate, or weak correlation for each need or want. Specific engineering specifications that were discussed and decided upon included: finite element analysis (FEA), waterproof testing, and timing the attachment and removal of tools to the robot. Existing products of major competitors of Blueline were also analyzed against the needs and wants of Blueline and the engineering criteria developed in order to better understand the competitors' strengths and weaknesses. Table 6 contains the engineering specifications and below the table is a comprehensive list as to how each specification will be measured.

**Table 6: F32 Engineering Specifications Table**

Spec. #	Specification Description	Requirement or Target (units)	Tolerance	Risk	Compliance
1	Internal Moment	167 lbf-ft	Min	H	A
2	Vibration Testing	Regular movement	Min	L	A, T
3	Ingress Protection	0 lb dirt, water for 17gpm	Max	M	T, S
4	Quick Release	8 minutes	Max	H	T, S
5	Power	40A/50V - 2000W	Max	M	T, S
6	Prototype Cost	\$500	Max	M	A

Each specification will be measured as such:

- The torque will be measured using finite element analysis, modeling the arm as a cantilever beam of four feet with a load of 25 pounds at the end. Basic hand calculations for this specification can be found in Appendix A.
- The vibration testing will occur by operating the robot with attachment system in use to maximum capacity through rugged ground conditions or movement tasks.
- The ingress protection will be done to IP65 which specifies that the attachment is totally protected against dust and that it is protected against low pressure jets of water from all directions, with limited ingress permitted. This will be tested using a garden hose
- The quick release mechanism will be tested by someone attaching and then removing the robotic arm attachment from the chassis.
- The voltage and current specifications will be measured by a multimeter.
- The prototype cost will be measured using the team budget sheet.

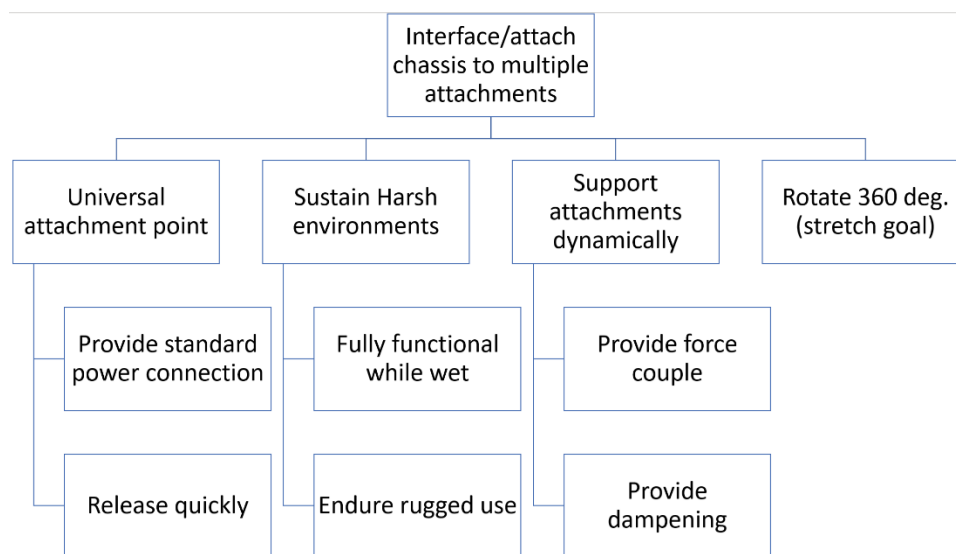


## 4.0 Concept Design

The process taken to ensure the best concept design included performing functional decomposition, various brainstorming sessions using different ideation techniques, creating function prototypes, evaluating them using Pugh matrices, combining all the different function prototypes to create different system concepts, and evaluating them in a weighted decision matrix. The system concept that performed the best consisted of the highest rated function prototypes including a Gardena quick connector, internal electrical connections, and a spring suspension system. A more detailed description can be found in section 4.3.

### 4.1 Ideation and function prototypes

The first step to creating the final system concept was to break down the sponsor's desired product into a set of functions and sub-functions using a functional decomposition function tree. The function tree found in Figure 2 describes four main functions: a universal attachment point, the ability to sustain harsh environments, the ability to support dynamic attachments, and the ability to rotate 360 degrees. Each main function besides the last one consisted of three sub-functions necessary to fully achieve the main function.



**Figure 2: Functional Decomposition**

Once all the subfunctions were defined, three different brainstorming techniques were used to come up with methods of achieving each function. The techniques used were brain dumping, worst possible idea, and brain walking. The brain dumping ideation session was a timed "dump" of all ideas without concern regarding the feasibility of each idea. The goal of this session was simply to create the most ideas possible without regard to quality. This ideation session created many ideas which were then combed through for repeated ideas. Once all repeated methods were combined, each team member picked their top ideas by putting an asterisk near the idea in question. The results of this session can be found in Appendix C-1.

The worst idea ideation technique consists of coming up with methods of achieving the sub functions in the most unusual and 'bad' way possible. The benefit of this type of ideation session is that

it encourages thinking outside of the box and can help overcome idea fixation. This session ended up producing the least number of useable ideas and did not end up facilitating any beneficial discussions. As such, the results of this session are not included in the appendices.

Brain walking is the most visual of all the ideation techniques used as it entails each group member drawing their ideas for the sub functions. The drawings from the brain walking session can be found in Appendix C-2. This session was completed last of all the ideation sessions and was really the place to compile the different things discussed and produced by the brain dumping session.

Once the brainstorming sessions were completed, several of the methods developed through the sessions were created for the function prototypes. These prototypes each addressed at least one sub function from the functional decomposition diagram. These prototypes were made of easily accessible materials including cardboard, wire, toilet paper tubes, and play dough. They were made to be semi-functional. These models highlighted the narrow design constraints of this project as many of the prototypes overlapped in functionality and method.

## **4.2 Pugh, Morphological, and Weighted Decision Matrices**

Once the sub functions were developed and methods of achieving each subfunction prototyped, the methods for each sub function were rated against like methods to obtain the best concepts for each subfunction. This rating process was completed using Pugh matrices. Utilizing the top ideas from each function, a morphological matrix created full system concepts which were then sketched and evaluated in a weighted decision matrix. From the weighted decision matrix, a top system level concept was chosen.

### **4.2.1 Pugh Matrices**

Once the sub functions were developed and prototyped, the top four functions were chosen, and one was assigned to each group member. The top four functions chosen were: Supports dynamic loads, provides standard power/data connection, releases in under five minutes, and fully functional while wet. Further evaluation of each function was done using Pugh matrices. A Pugh matrix compares different ideas for a specific function or subfunction using a set of criteria defined in the house of quality as engineering specifications. The current solution to the problem is defined as the datum and each idea is compared to the datum and given a rating of better, worse, or same. Each idea is compared to the datum and evaluated on its ability to meet the engineering specifications comparatively. Ideas that meet a given engineering specification better than the current solution (the datum) is given a +1. Ideas that do a worse job than the datum at meeting a given engineering specification are given a rating of -1. Ideas that are neither better nor worse than the datum are given a rating of 0. Once each idea has been rated against the datum for every engineering spec, their scores are tallied, and the top method is chosen. Each of the four Pugh matrices can be found in Appendix D.

### **4.2.2 Morphological Matrix and Concept Sketches**

The benefits of the Pugh matrices are apparent when creating the morphological matrix. A morphological matrix takes the engineering specifications and places them in one column, and then takes each function assigned to a Pugh matrix and places them in columns as well. Each column contains the different methods or ideation concepts for that function. A variety of system concepts can be compiled by picking and choosing different function concepts and combining them in new ways. The top

ideation concepts from each function can be combined to create the best system level concept. For example, one full system concept generated was a slide in plate, a spring-loaded suspension system, a standard internal electrical connection, a Gardena connector, and an O-ring or gasket style waterproofing. Five full system concepts, available in Table 7, were compiled using the morphological matrix in Table 8.

**Table 7: Morphed System Level Concepts**

Idea #	Morphed Characteristics Description
1	slide in plate, Balloon, connection points outside, Twisting bolt, Ballon, gear rotation)
2	Combination of best ideas: Slide in plate, Spring loaded system, standard plug in through center, gardena, pressed O-ring, rotation under chassis
3	External thread, Spring load system (w oil), Prongs connection, Thread/Set in slots, welding edges
4	collar w screw, spring loaded damping, internal connection points, gardena, pring, system rotates as a whole
5	Male and Female style mounting brackets, large single spring loaded base on chassis side, power centered, each male feature is either thread with screws or ball and pin style, tight presses o-ring on outer inside sandwiched circumference, system rotates underneath as a whole

**Table 8: Morphological Matrix**

Required Function	Possible Solutions (Ranked Best -> Worst)						
Support dynamic loads	Slide in plate locked with two screws	Plate with 4 screws directly connected to chassis	External threads	External Latch mechanism	Collar with screw to tighten	Male & Female style bracket on chassis and attachments	Permanent support arms/rib wedges from attachment to chassis
Provide dampening	Balloon tighten the grips and support the arm (absorbing force)	2 layers of pins (1 with metals and 1 with soft material)	Spring Load system (with oil) x4 in each corners	Spring load system with one spring type dampening feature around entire system	Alternating layer of material at the base -> soft ones absorbing more.	Pneumatic or pressurized cylinder around/incorporated into connection area	
Provide standard power/data connection	Have connection point for 1 standard plug in the hollow center of system	Have connection point(s) just on the outside of system for ease of access	Direct metal connection (no wires)	Have prongs that latch together when connecting the attachment.			
Release quickly, under 5 min	Gardena	Twisting Bolt	Spring loaded ball and pin offshoot	Spring loaded latch	Ball and pin	Set in slot and twist to lock tight	Set into claw like latches that click into grooves
Fully functional while wet, IP65	Incorporate tight pressed O-ring	Shower curtain type rubber outing or cover seal around entire system (think of rubber at base of a joystick or gear shifter)	Balloon grips the arm -> should close anying clearance from water entering	Welding edges together			
Rotate 360 deg. (stretch goal)	System has to rotate as a whole from underneath in chassis	System has incorporated rotational capabilities with no barriers (fasteners, etc.)	Rotation using Bearing at the bottom	Use gears to rotate the whole attachment system			

Each team member sketched at least one of the full system level concepts. Each sketch can be seen in Figures 3 through 7. System concept 1, in Figure 3 consisted of a slide plate locking mechanism held down by slots on three sides with connection ports that align. System concept 2, in Figure 4 of a simple large external thread system for the attachments. Additionally, optional support arms can be added for extra load support. System concept 3, in Figure 5 consisted of consisted of a slide in plate, a spring-loaded suspension system, a standard internal electrical connection, a Gardena connector, and an O-ring for waterproofing. System concept 4, in Figure 6 consisted of consisted of a combination C-clamp collar and Gardena quick connector with an O-ring for waterproofing, a spring-loaded suspension system, internal electrical connections, with the whole system rotating. System concept 5, in Figure 7 consists of a simple male/female mounting bracket system with a watertight gasket seal and optional single cylinder spring dampening mechanism around the centered power connection.

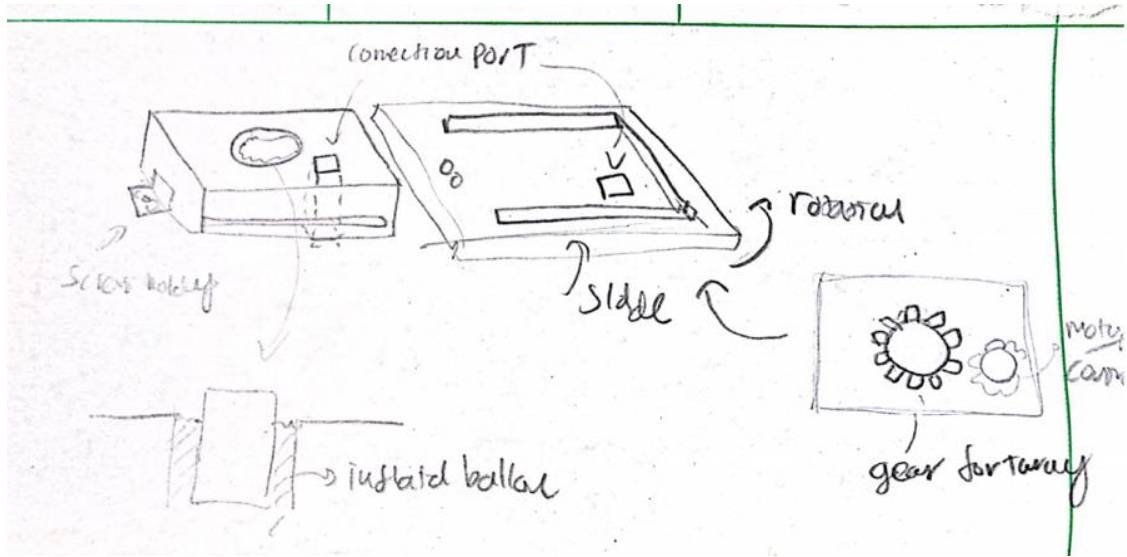


Figure 3: Full System Concept #1

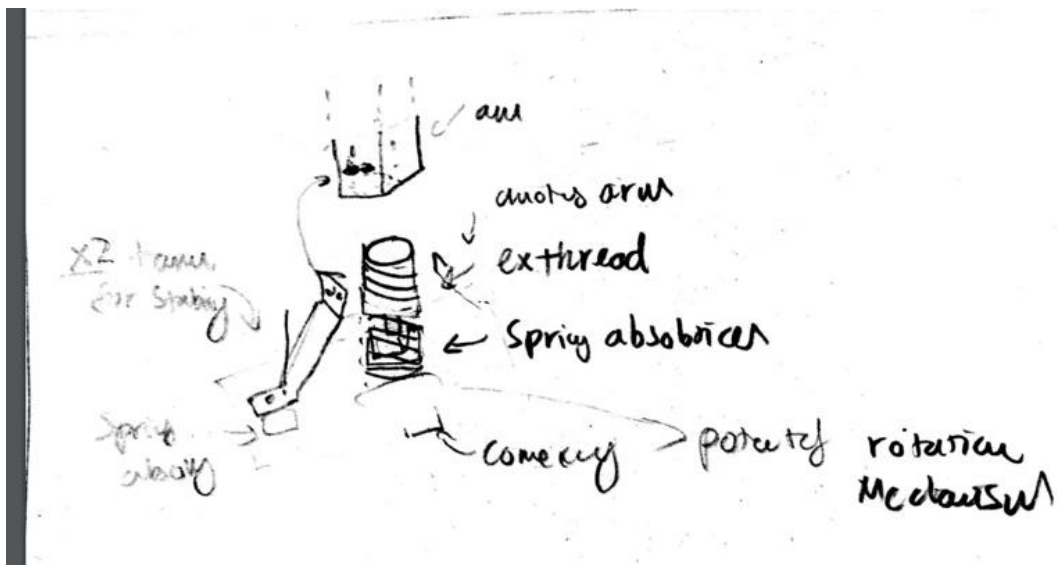


Figure 4: Full System Concept #2

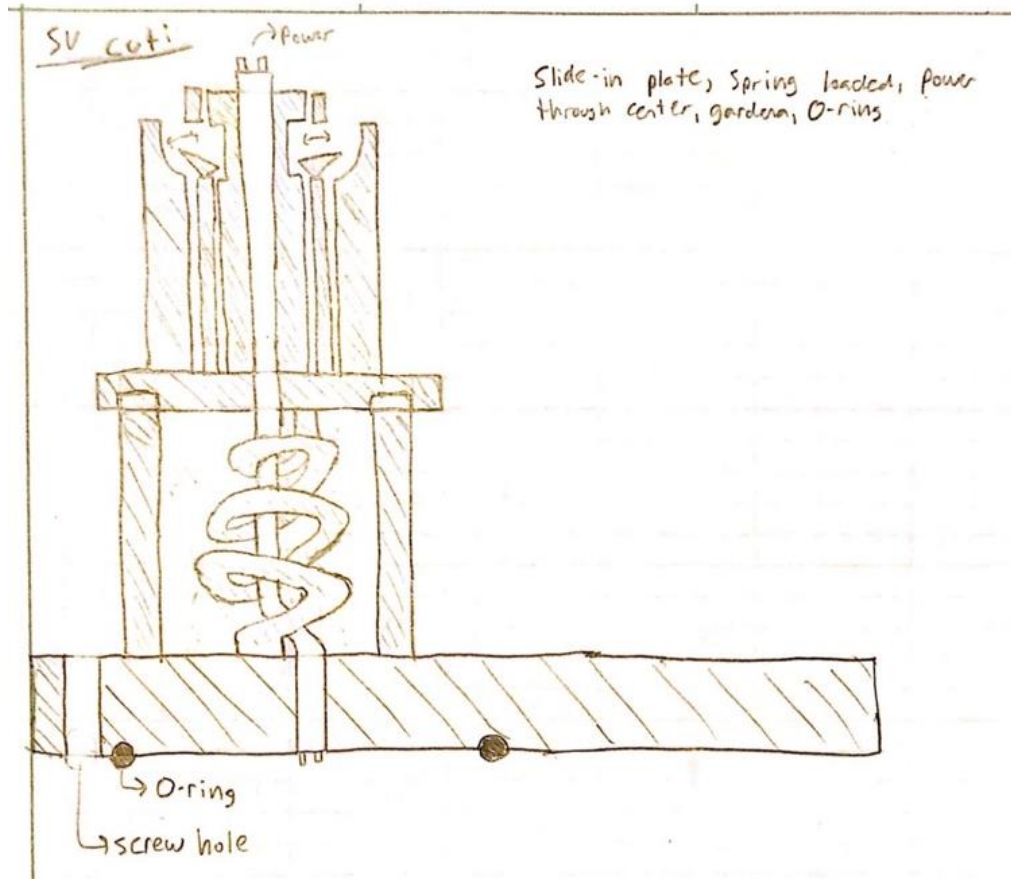


Figure 5: Full System Concept #3

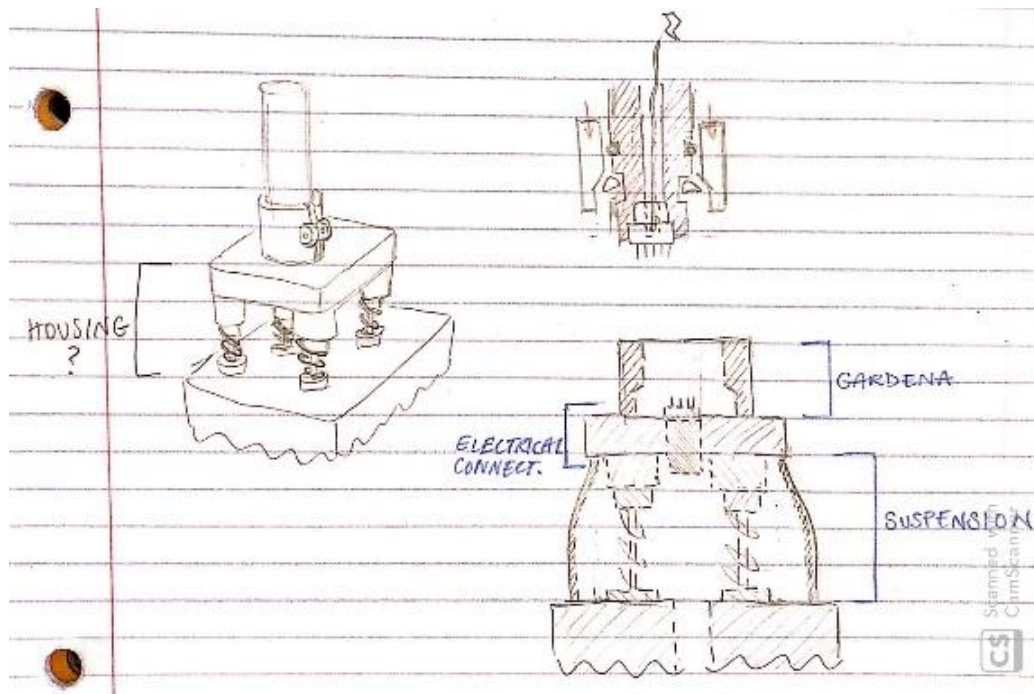
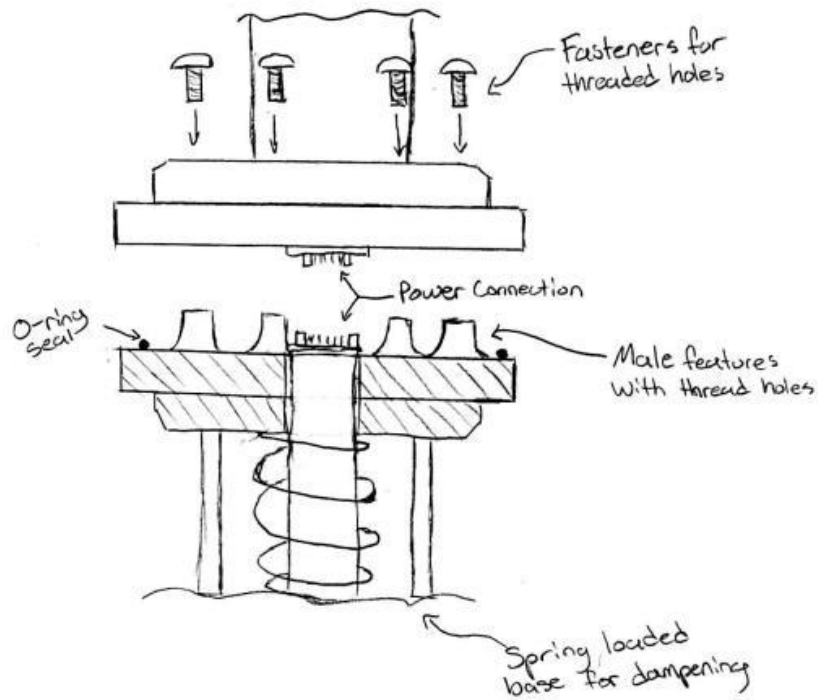


Figure 6: Full System Concept #4



**Figure 7:** Full System Concept #3 from the weighted decision matrix

Many of the concept level designs contained repeating or similar characteristics, such as the spring-loaded suspension system. Unlike the suspension system ideas, there was more diversity in the method of quick connector and waterproofing in each concept sketch. For example, Figures 5 and 6 utilized the Gardena quick connector, while Figure 1 utilized an inflatable, elastic material to hold attachments in place and provide waterproofing. Figure 5 and Figure 7 both utilize a single central shock that will absorb the vibrations and provide dampening. This set up is different from Figure 3 which does not utilize any sort of shock or spring system to absorb these vibrations but rather an insulated balloon that will also act as the watertight seal. Figures 7 and 6 attachment systems will be welded onto the chassis. This will allow the attachment system to handle the cantilevered loads better than if the system were screwed in like in Figure 4. The concept in Figure 7 utilizes a simple yet extremely rigid connection point as to where the Gardena style connection in Figures 5 and 6 are feared to be less rigid and less capable of supporting desired loads. However, the concept in Figure 6 does utilize an extra “after attached” clamp for additional rigidity instead of the load being purely on the Gardena style attachment point. The Gardena style attachment would likely be the quickest and easiest system overall to complete, but it should be noted that all concepts are projected to be well under the desired assembly completion time. Additional concerns may fall onto the spring dampening features of each concept. It is still up to further investigation and discussion whether the vibration dampening is a highly essential function to the degree at which it is being considered. This is because while each attachment point is a great solution for the function of supporting loads, the added spring mechanisms create for more attachment points relocating the desired location of where those necessary loads are supported.

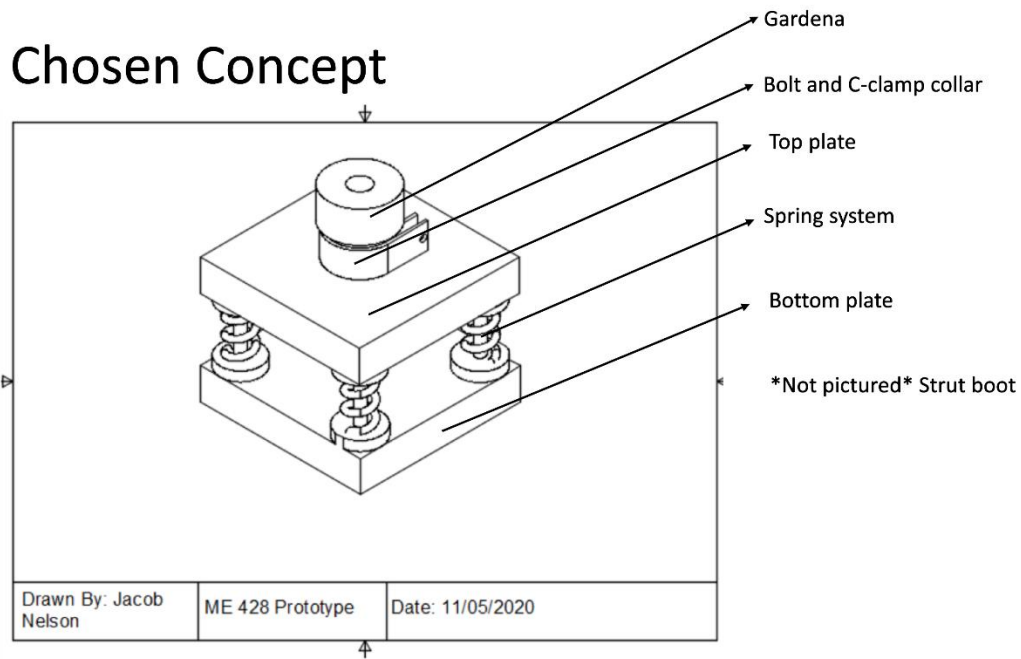
### 4.2.3 Weighted Decision Matrix

The weighted decision matrix, found in Appendix D-6, compared the five different system level concepts on their ability to meet the QFD's specifications. Each specification was assigned a weight corresponding to its importance. For each engineering specification, the system concepts were rated from 1 to 5 with 3 meaning a satisfactory meeting of the system requirements and a 5 meaning an outstanding meeting of the system requirement. The specification weight was then multiplied by the system design's rating to give each system concept a weighted rating for each specification. Once a concept had weighted ratings for each specification, it was given a total score which was then compared to the other system concepts to determine the design which best met the project requirements.

The system concept with the highest rating was concept #4, which can be seen in column four of the weighted decision matrix in Appendix D-6 as well as in Figure 6 in section 4.2.2. System design #4 ranked the highest at 321, followed by design #5 at 316. System design #4 consisted of an altered Gardena collar, a spring-loaded suspension system, internal electrical connectors, and O-rings to ensure waterproofing. Design system #5 consisted of a male and female mounting bracket with internal electrical connectors, a spring suspension system, screws to mate the two bracket pieces together, and a gasket for waterproofing. While system design #5 is simpler and easier to manufacture than #4, #4 uses O-rings and has a quicker release mechanism than #5. The use of O-rings is more desirable than gaskets due to the finicky nature of the latter and the quick release mechanism was deemed a relatively important goal to meet. When compared against the decided criteria, design #4 met or succeeded all criteria except the maximum prototype cost and the stretch rotating goal. The criteria and rating will be discussed further in Appendix E.

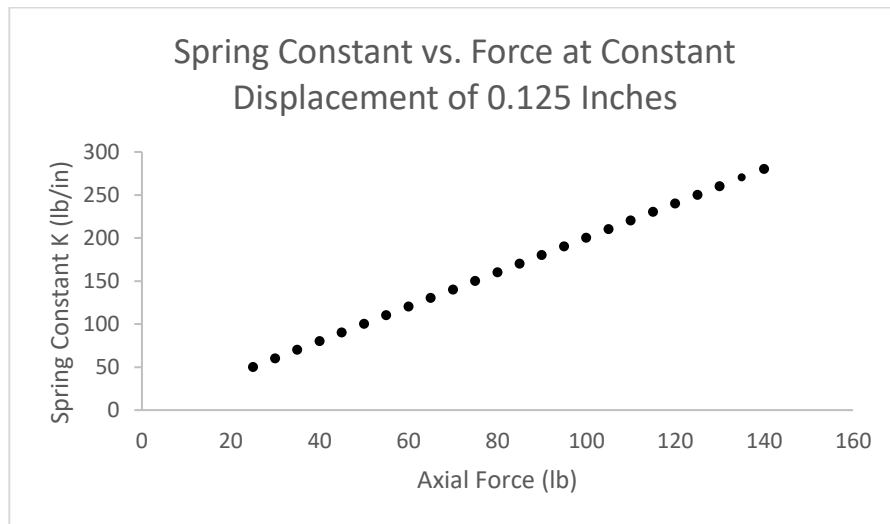
### 4.3 Final Concept Design

The senior design team decided to move forward with the highest rated design concept shown in Figures 6, 8, and 14, and Appendix F. This design consists of the Gardena connector and four spring suspensions. The Gardena connector utilizes a collar that slides down over the attachment and that presses beads into slots in the robotic arm, which prevents the attachment from becoming displaced. The Gardena connector allows for quick release and is easily waterproofed by adding an O-ring pressed between the collar and the attachment. The Gardena connector design also uses a simple spring suspension system, similar to ones found in RC, or remote-controlled vehicles to provide vibration and impact support. A rubber strut-boot-like feature connected between the top and bottom plate will create a sufficient seal to keep water out. One of the goals of this design is to buy various components, such as the Gardena connector, the spring suspensions, and any fasteners, off-the-shelf, reducing manufacturing costs. With this design, the dynamic cantilevered loads will be absorbed into the chassis by welding the housing to the chassis. A few issues were discovered through concept prototyping including the potential for undesired spring buckling. Handling the dynamic loads with spring suspension without any additional support to constrain the springs to vertical motion, may cause undesirable spring buckling. Further discussion on concerns with the chosen design are located in section 4.5. Without knowing the exact dimensions of the robotic arm, the sponsor will be using, it is impossible to give exact specs on the chosen design.



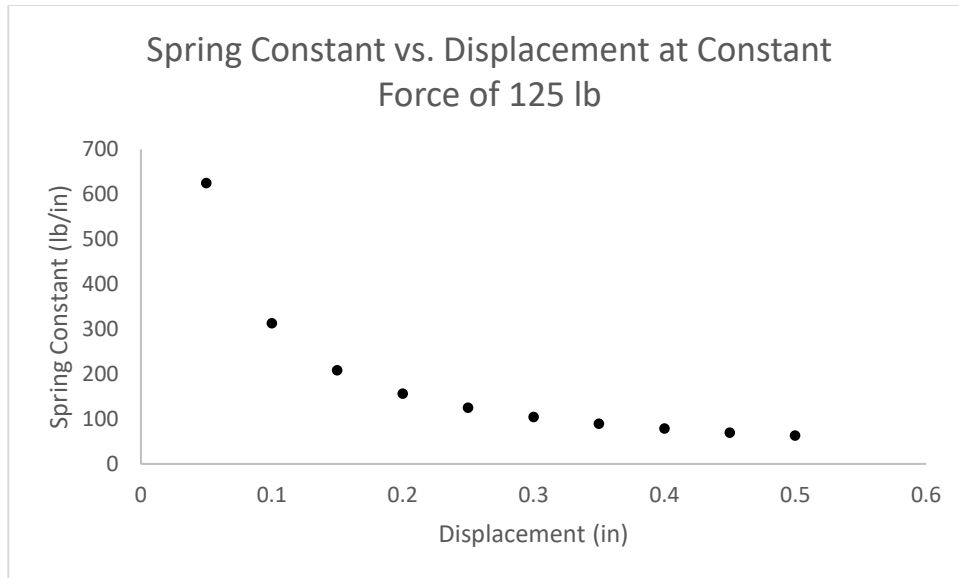
**Figure 8:** Isometric view of chosen system level concept.

In order to prove the efficacy of the chosen design, a variety of engineering analyses were completed. The first was a basic analysis to find a range of spring constants that will satisfy the criteria provided by the project sponsors. The hand calculations for the equations can be found in Appendix G. The hand calculations were done using the given load case of a 25 lb. cantilevered load. The cantilevered load was translated over to the attachment point and modeled as a 25 lb. axial load. Then, using the equation of force for a spring, the spring constant was found in two different cases. Figures 9 and 10 show the results of this analysis.



**Figure 9:** Spring Constant vs. Axial Force at Constant Displacement of 0.125 Inches

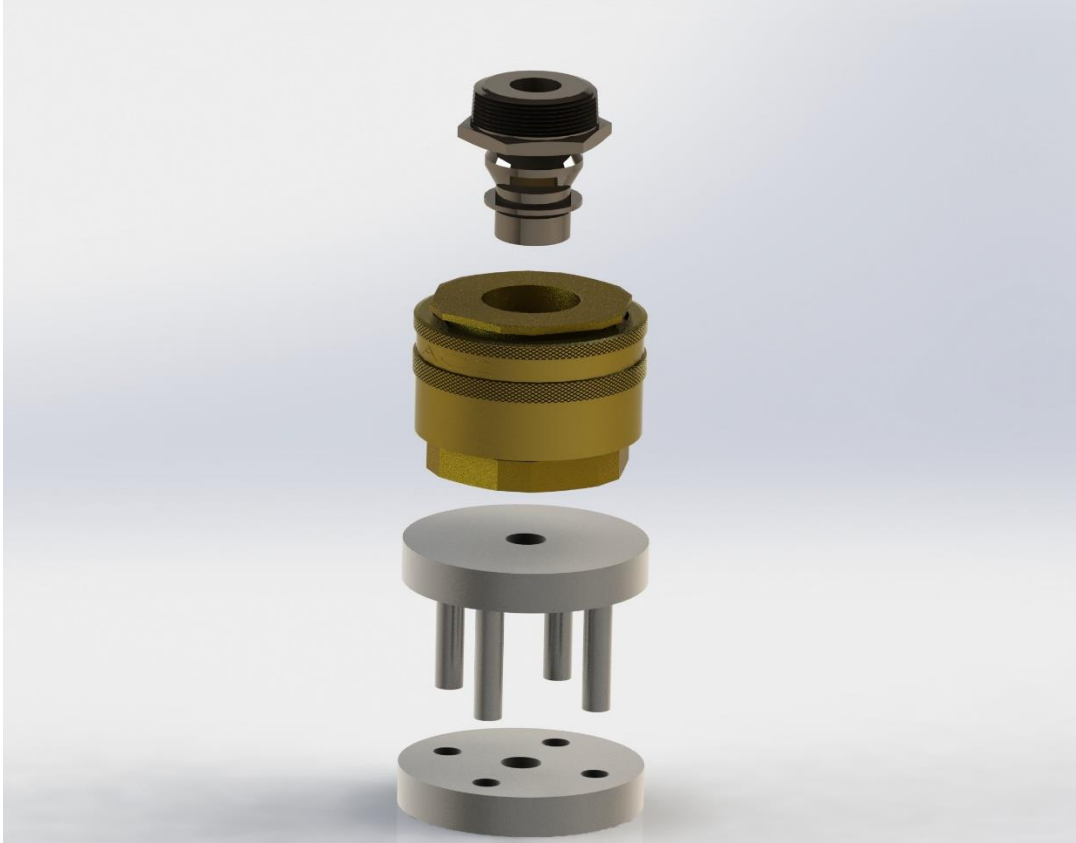




**Figure 10:** Spring Constant vs. Displacement for constant 125lb Force

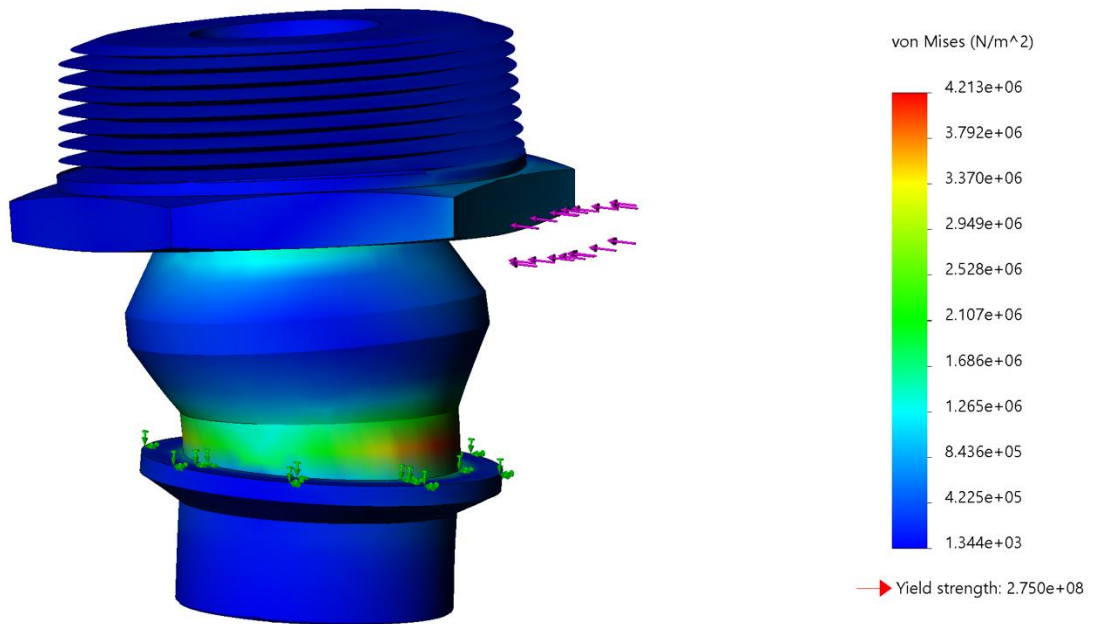
For Figure 9, a constant displacement of 0.125 inches was selected as this is around a maximum value of allowable displacement that will not interfere with the attachment systems precision. A linear relationship is shown and the most useful region for this project will be between 25lb and 125lb of force. The expected load case is 25lb so looking at spring constant from this value to five times this value will help to give us a range of spring constants to look for when selecting stock parts. Figure 10 shows the relationship between the spring constant and the displacement while holding the axial force constant at 125 lb. This force was chosen as it is five times larger than the expected load case so it will provide a factor of safety of around 5. The critical range in this plot is between a displacement of 0.05 to 0.2 inches. As discussed above, it is expected that a displacement larger than 0.125 inches will start to interfere with the precision of the attachments. This suspension system will be housed within a flexible and compressible strut boot, not pictured on the drawing in Figure 8.

Due to concern regarding spring buckling under heavy loads, additional concept CAD models were created containing additional support features. The additional features added to these models consisted of 4 dowel-like columns that would accompany the spring system. These columns would be fixed to the top plate of the design seen in Figure 11 and fit through holes in the bottom plate with a tight clearance fit. The bottom plate would be fixed to the chassis by a weld for extra rigidity. When the springs compress, the dowels slide through the holes in the bottom plate into a clearance zone within the chassis. These dowels would not slide through too far with the correct spring constants applied to the system springs. These rods, similar to scaffolding, would provide additional rigidity to the attachment system, preventing unwanted rotation and buckling under the cantilevered loads. It is important to note again that the rubber strut boot would still house the entire lower system. A simplified exploded component concept model of this can be seen in Figure 11. It is additionally important to note that the spring mechanisms, the electrical components passing through the middle, and the welded connecting points are all not pictured in this model.



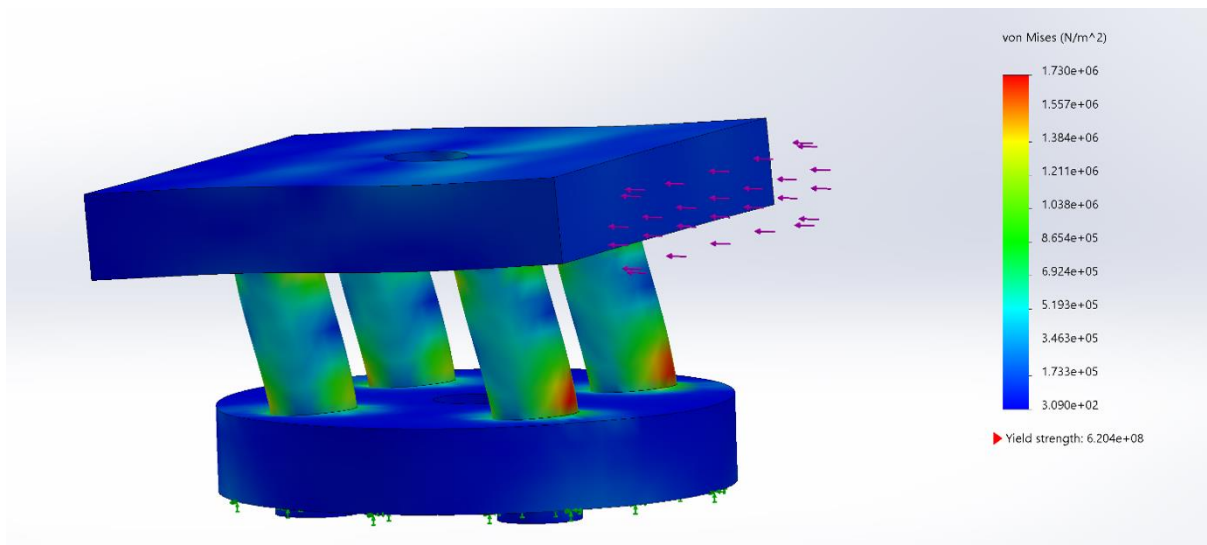
**Figure 11:** Exploded component concept CAD model of dowel-like added support columns. Not pictured are the electrical components to pass the center holes, the spring mechanisms, the rubber strut boot, and the welded connection points.

This concept CAD model allowed the opportunity for some situational load cases. With the worry of the Gardena connection point being the focus point of the loads on the system, the male portion was tested with preliminary FEA (finite element analysis) in SolidWorks simulation. In this analysis seen in Figure 12, the locking collar was fixed and the rest of the of the component was subject to a perpendicular 25lb load. The material tested was alloy stainless steel. This is because stainless steels would be prone to rusting in rougher conditions.



**Figure 12:** CAD model and FEA analysis of the male feature within the Gardena attachment system

In addition, the loads were proposed to potentially focus on the vibration dampening system area. If this were to happen, it would be valuable to know if the added dowel-like support columns could support these loads. Therefore, additional FEA was conducted on just the two plates and the columns. The same alloy stainless steel was used as before from the SolidWorks material library. The bottom plate was the fixed geometry as it would be welded to the chassis, and a perpendicular load of 25lb was applied. The result of this study can be seen in Figure 13.



**Figure 13:** CAD model and FEA analysis of plates and dowel-like support columns incorporated into the vibration dampening system area for added support.

Overall, the analysis of these models showed that they would barely be capable of supporting these loads on their own while escaping wear. However, these are extreme scenarios as they would normally be connected in succession and work together to support the loads. Additionally, that does not include the spring mechanisms and added collar for additional rigidity in the Gardena. With that, it is believed the overall design would only meet the standard of the requirements. Ideally, the design would exceed the standard set out by the specifications and requirements so additional design modification may be required as progress is made. Altogether, the design is justified so far.

From here it is important to note that each of the full system concepts shown in section 4.2.2 offer unique solutions to each essential function and should not be forgotten moving forward. If a problem were ever to arise in the design, substituting one sub system from a different system concept with the sub system in the chosen system concept may provide a valid solution. Even a future combination of the original concepts is something to consider as analysis and testing may or may not validate the existing design moving forward.

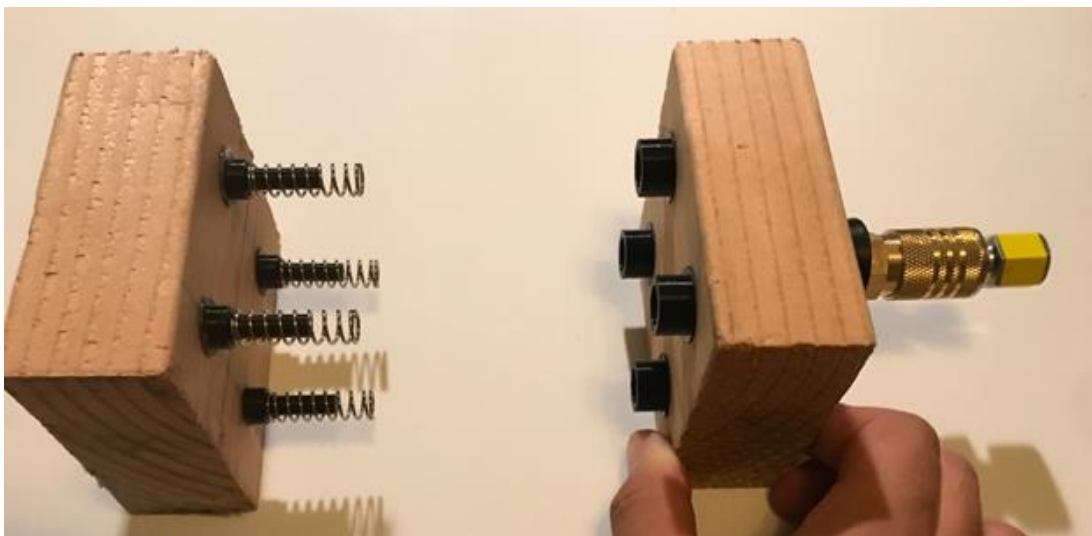
#### **4.4 Preliminary Design Risks**

An analysis of the design risks was completed using the Design Hazard Checklist in Appendix H. The checklist indicates that the bending of the spring system and the locking mechanism of the Gardena collar both could result in pinch points, potentially squeezing or pinching the fingers of the users. A way to mitigate this would be the chamfering of edges and the strategic placement of a strut boot to cover the springs and protect users. Finding a strut boot small enough for the current design is a priority and one of next steps of this project. It is anticipated to be completed by January 18<sup>th</sup>, 2021. Additionally, this system will be used in extreme environmental conditions including fog, and high and low temperatures. If these conditions are not considered when choosing materials, environmental factors could impact the functionality of the system causing thermal expansion or rusting. Leaving flexibility in choosing the materials for the system is a project criterion. Once the design is finalized and the different pre-made components have been selected, the sponsor will have the ability to choose the materials of the rest of the system.

#### **4.5 Chosen Design Concerns**

From the concept prototype of the chosen design, seen in Figure 14, two key issues were discovered. The first design concern has to do with the availability of Gardena connectors in the sizes most likely required by Blueline. Assuming an arm with a diameter a quarter of the overall width of the robot, the Gardena connector would have to have an internal diameter larger than 4.5 inches. Most Gardena connectors on the market are for hoses and have diameters of around one inch. These off-the-shelf Gardena connectors may be too small in diameter for passing power to the attachments and manufacturing a custom Gardena connector would be costly and complex. Additionally, the Gardena is a unique connector and any attachments used with the robot would have to the male half of the Gardena attached at the base, increasing the complexity and cost of those attachments. Minimizing any customization is vital to keep the prototype under the required budget of \$500. Besides the Gardena connector, the concept prototype also illuminated issues with the spring dampener

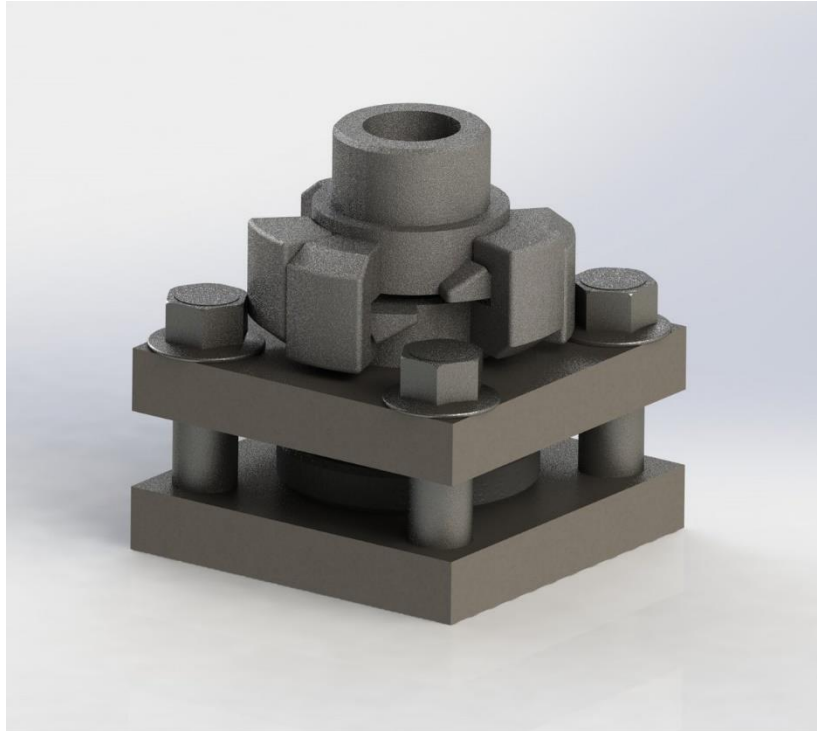
system. The system, while successful in absorbing the vibration from the chassis, may experience unintentional and undesirable spring and column buckling due to the cantilever dynamic loads. The spring dampener system can be seen in Figure 14. These depict a 3D printed model of stock RC suspension parts which will be bought off-the-shelf. The 3D printed model is capable of absorbing vibrations but not capable of provided dampening. When a moment was applied to the top plate, there was a resulting bending moment in the spring system. This caused the springs to buckle, not only reducing their vibration isolating efficiency, but also increasing the likelihood of spring failure. Additionally, the cantilevered loads will be accelerating up to 2 radians per second which will cause torsion throughout the system. This too will cause buckling in the springs, again reducing efficiency and risking failure.



**Figure 14:** Exploded view of concept prototype

## 5.0 Final Design

After the Interim Design Review (IDR) at the beginning of the second quarter of this project, the concept underwent a large redesign, with several main components being altered or removed. The final design consists of three main subassemblies: the top assembly, the absorption assembly, and the bottom assembly. The top assembly contains the bayonet locking mechanism, the top plate, and a bushing. The absorption assembly consists of three different types of components: the four industrial pins, their nuts, and the jounce bumper. The final bottom assembly consists of the bottom plate. This current design, seen in Figure 15, differs from the design presented in section 4.0 in the quick release mechanism used and the vibration dampening system used. The Gardena connector was replaced with the bayonet connector and the spring suspensions were replaced with a singular jounce bumper. Both of these design changes simplify the design and increase the manufacturability of the design. Further explanation can be found in section 5.1.



**Figure 15:** Rendered final design.

## 5.1 Differences from Concept Design

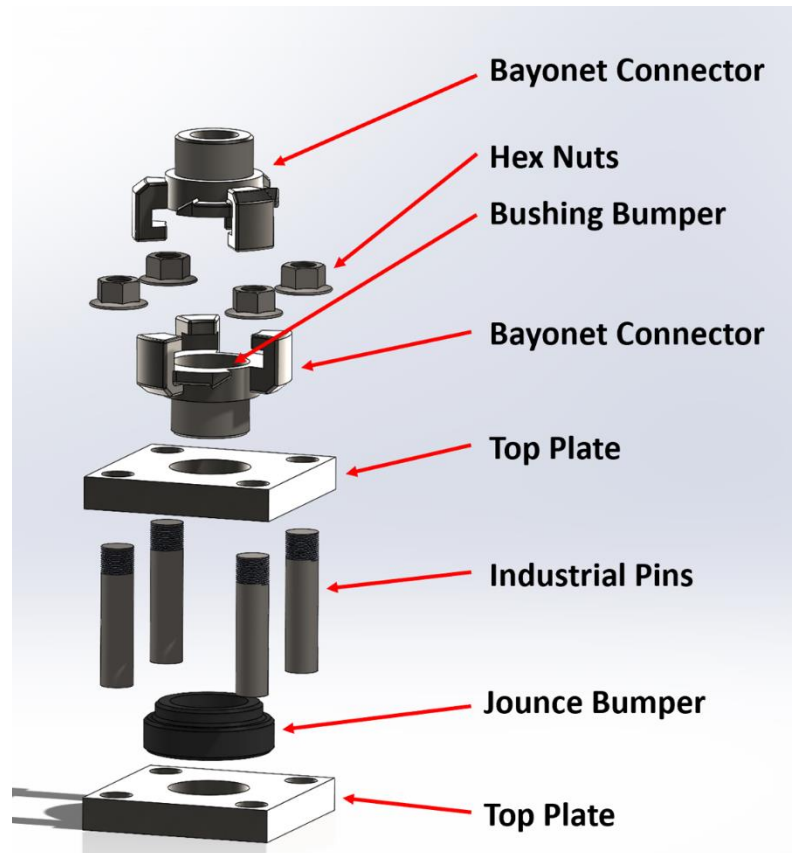
The previous design, explained in section 4.0, Concept Design, incorporated a Gardena collar for quick release and several spring suspensions for vibration dampening. After IDR, the Gardena collar was switched out with the bayonet locking mechanism seen in Figure 15. When the Gardena collar was first selected, it was desirable for its waterproofing, quick release, and apparent off-the-shelf availability. However, after further research it became clear that the Gardena was not available in the desired dimensions. Most available Gardena connectors were pricey and much smaller than desired. Any Gardena connector would have to be specially manufactured, which would quickly become complex and expensive. In contrast, the bayonet locking mechanism could be more easily casted. It is a sturdier design than the Gardena connector, with more flexibility with the dimensions and material. The bayonet connector is also quick release and with the embedded bushing it is waterproof, both important engineering specifications. While the bayonet connector cannot be purchased off-the-shelf, it is a simpler design than the Gardena connector and therefore more feasible to manufacture.

The second major redesign was regarding the spring suspension system laid out in section 4.3, Figure 8. The old design consisted of four spring suspensions to absorb vibrations and allow for larger bending loads. However, the spring suspension system presented a few significant issues, namely the creation of pinch points, the possibility of under-stiff springs causing instability, and difficulty procuring springs of the correct size. For these reasons, the system was replaced with a single, polyurethane, jounce bumper to sit centered between the top and bottom plate. This change allows the system to absorb vibrations without the issues raised by the spring suspension system. The final change to the design after the interim design review was to replace the four support rods, seen in Figure 11, with four

industrial pins. These pins will be press fit into the bottom plate rather than the top plate and will move vertically through clearance holes in the top plate. These pins will be secured with bolts.

## 5.2 Design Sub-Assemblies

The design, seen labeled in Figure 16, has three major subsystems: top assembly, absorption system, and bottom assembly. The top assembly's function is to connect to attachments, the absorption system absorbs vibrations to ensure steadier use of the attachments, and the bottom assembly attaches the overall system to the chassis of the robot.



**Figure 16:** Exploded view of concept prototype model

The top assembly consists of the top plate and the bayonet connector. The drawings for these can be found within the Drawing Package Appendix I at I-3 and I-4 respectively. The bayonet connector is the mating interface between the attachments, such as the robotic arm, and the main robot. Locking the two halves together forces the bushing into compression and is done by twisting the top half onto the bottom. It utilizes fins on each half, which interact with tracks on the opposite piece. The bushing within the bayonet locking mechanism pushes against the two mating surfaces of the locking mechanism, creating a tensile force on the fins of mechanism and preventing unwanted rotation. The drawing for this bushing can be found in Appendix I-5. The top plate will have the bayonet locking mechanism attached to it and will aid the absorption system by providing clearance holes for the industrial pins to move through as the system compresses and expands under loads and vibrations.

The absorption system consists of four industrial pins, four nuts, and one jounce bumper. The drawings for these can be found in Appendices I-6 and I-7, respectively. The jounce bumper will be between the top and bottom plates and will absorb vibrations to increase the stability of the attachments. The industrial pins will help to keep the system aligned, being rigidly press fit into the bottom plate and free to pass through the top plate. As the system compresses under loads, the jounce bumper absorbs loads and the top plate lowers further onto the industrial pins, made possible by the clearance holes in the top plate. To ensure the top plate does not slide off the top of the industrial pins, the hex nuts will be screwed onto the pins.

The bottom assembly consists of the bottom plate. This drawing can be found in Appendix I-8. As previously stated, the bottom plate will have the industrial pins press fit into it. This plate will then be welded onto the chassis. It will fasten the entire system to the chassis of the robot as well as add structural support.

### 5.3 Structural Prototype

Structural prototyping was completed in two different prototypes. One prototype is the 3D-printed bayonet locking mechanism and its corresponding bushing, seen in Figures 17 and 18. The second prototype consists of the top plate, bottom plate, industrial pins, the jounce bumper, and the nuts for the industrial pins. Seen in Figure 19 is the design without the jounce bumper and bayonet connector.



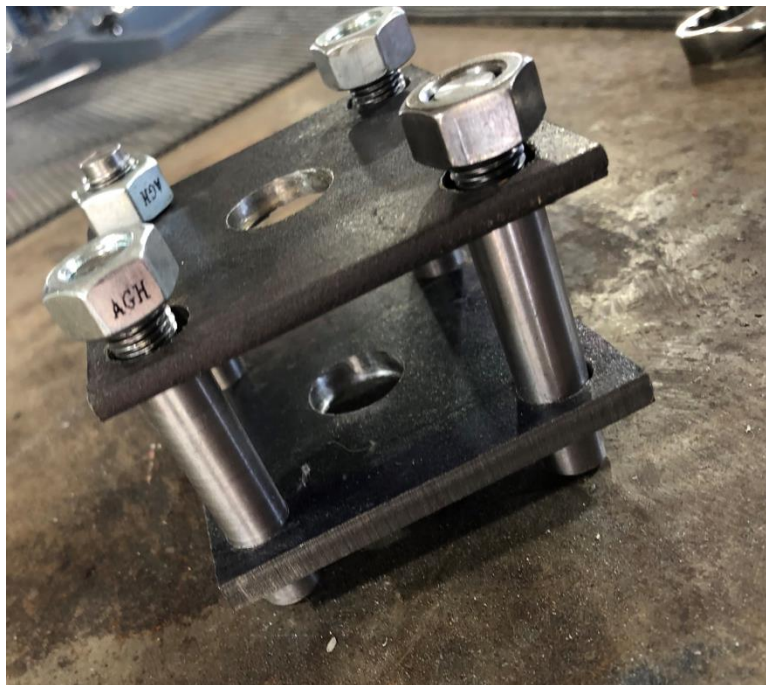
**Figure 17:** 3D-printed bayonet locking mechanism with both halves locked together.



**Figure 18:** Half of the bayonet locking mechanism.



The first iteration of the 3D-printed bayonet locking mechanism led to the discovery that the locking features of the bayonet locking mechanism may not have been large enough to stay in the locked position, the hole to pass power through was too small, and the three fins that go over the locking hook were too thin. The hook not being prominent enough to keep the lock in place is a concern because if the lock were to come undone during operation the attachment would be disconnected from the robot resulting in both the attachment and robot being stuck in a potentially hazardous location. The hole to pass power must be large enough for the power to easily pass through so there is no risk of the power cord getting pinched or severed, once again potentially leaving the robot and attachment in a hazardous location. The three fins that go over the locking hook cannot be too thin as this is where the cantilevered loads will converge and is a potential point of failure. With this, an updated bayonet locking mechanism was 3D-printed. The durability of the lock is now adequate with the larger locking hook, the power cord now has enough room to pass through without worry of pinching or severing, and the fins are thick enough to support the cantilever loads. With the bushing inserted into the bayonet locking mechanism the compression of this bushing is enough to keep the halves locked together. Using a custom bushing the force to compress and lock the bayonet will be optimized.



**Figure 19:** Structural Prototype with top plate, industrial pins, and bottom plate

The absorption system structural prototype was created to test if the cantilevered loads would create enough friction between the industrial pins and the top plate to inhibit movement between them. This is an issue because if movement cannot occur between them then the jounce bumper will not be able to absorb any vibrations. Through this prototype it was discovered that the holes for the pins would need to be milled for the final prototype due to the gradually widening diameter of the pins. The prototype, seen above, responded largely as expected when a load was applied. There was little to

no unwanted grinding between the pins and the clearance holes of the top plate. If larger loads on prototypes did cause interference issues in the future, a proposed solution would be to add lubricant.

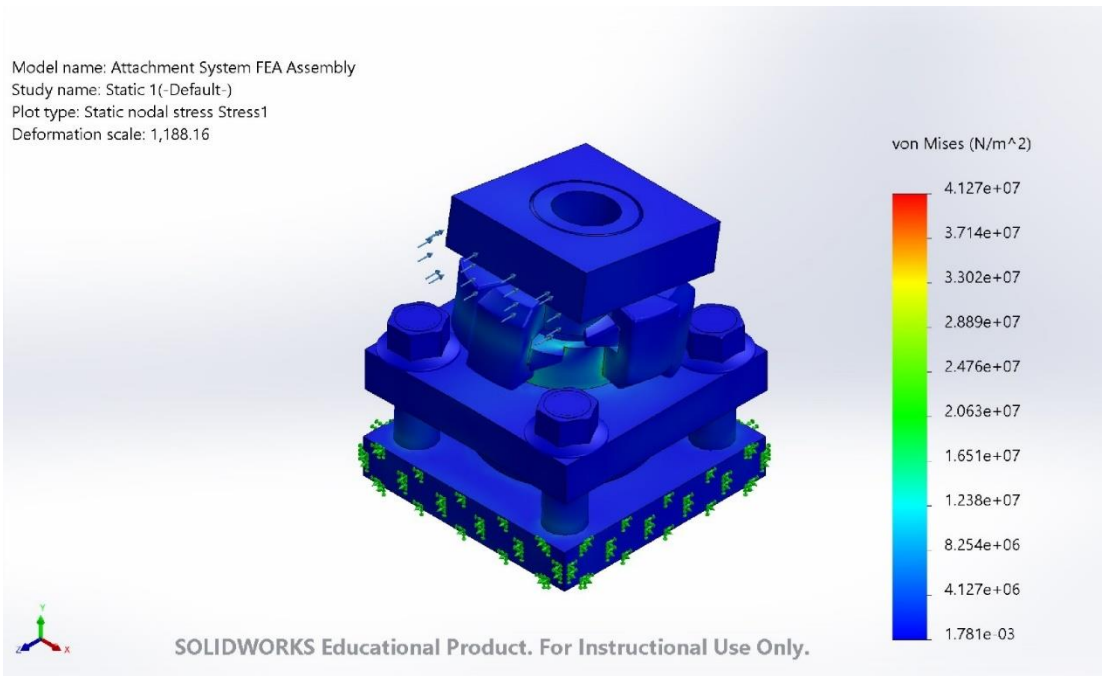
In order to test if using epoxy to secure the jounce bumper to the top and bottom plates will create a water-tight seal to IP65, standard epoxy was used to seal the remaining steel from cutting out the top and bottom plates. This resembled butt welding to metal plates together in a T shape. A garden hose was used as a water jet and sprayed onto the epoxy seal between the two plates. No water was able to pass through the epoxy seal confirming that the seal will be water-tight to an IP65 standard.

## 5.4 Meeting Engineering Specifications

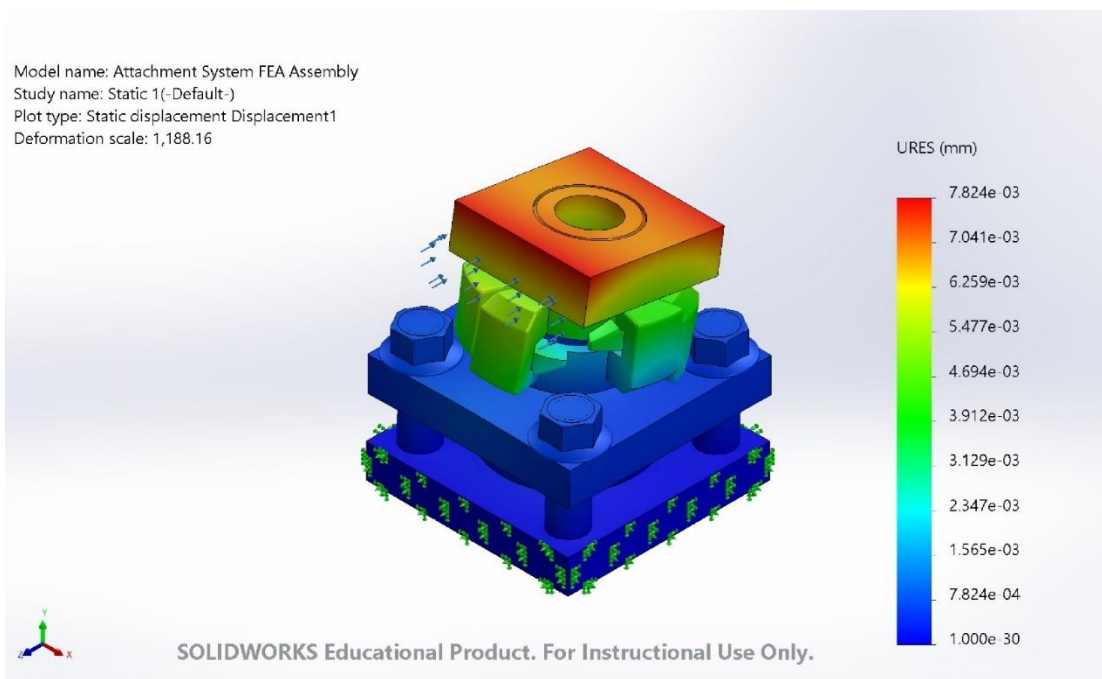
There are five main engineering specifications to be met with this design: withstanding the maximum moment and torque loads, remaining steady despite vibration, being waterproof to IP65, replacing attachments in under eight minutes, being able to pass the necessary power through to the attachments, and keeping prototyping costs under five hundred dollars. Each aspect of the design was chosen to fulfill one or more of these specifications. Finite element analysis, structural prototyping, and hand calculations were used to prove the design's ability to meet each specification. The currently completed analysis raises a few concerns, mainly the durability of the design through repeated rugged use.

The materials and geometry of the current design were selected in part to ensure the attachments points ability to withstand the maximum moment of 167 lbf-ft. The material of the plates, pins, and bayonet is steel. The plates and pins will be made of stainless steel, which has a yield strength of about 31.2 ksi. Carbon/low alloy steel will be used when casting the bayonet locking mechanism. These steels are less cost, able to be hardened, and weldable. Low carbon steels have an average yield strength of a little over 25 ksi. Finite element analysis of the design with these materials, shown in Figures 20-23 proves the ability of the design to withstand the maximum load. Additionally, the inclusion of fillets and chamfers on the bayonet connector, which can be seen in more detail in Appendix I-4, reduce stress concentration points and prevent points of failure. While the geometry and material of the current design was chosen to best prevent failure under the maximum moment, the analysis was used to prove or disprove these design decisions. Because the bayonet mechanism must be casted, a fully functional prototype was not feasible. As a result, much of the engineering evidence was provided by SolidWorks FEA. The FEA shown in Figures 20-23 shows the bayonet connector under the maximum loads of two different cases. These two different cases are a moment on the system from a perpendicular force and a torque load on the top cylinder of the bayonet connector piece. The maximum stress in each case remains well below the yield strength of the materials, providing a safety factor of about 5.5 and 12.5, respectively. It is also important to note that the presence of this max stress is not very prevalent in the colored displays of Figure 20 and Figure 22. This suggests that even though at least one particle point somewhere in the system may see this stress number, the overall areas in which this max stress number acts are too miniscule to raise concern.

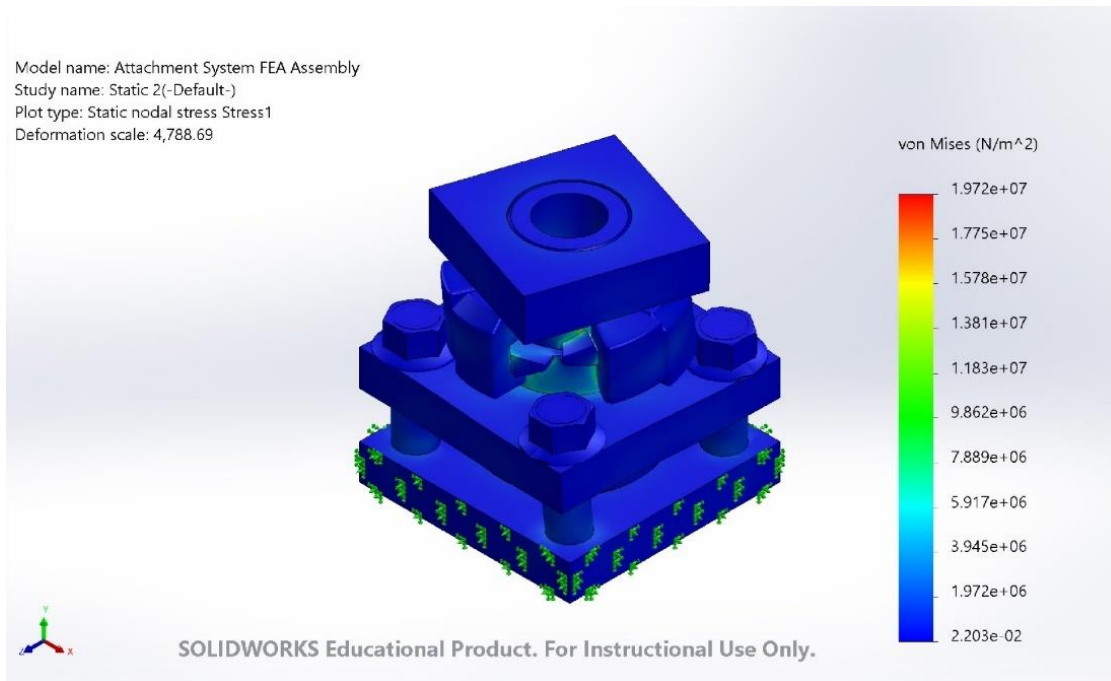
In addition to a maximum moment and torque load cases, a maximum axial load case was also tested with SolidWorks FEA. It was found that the effects of the axial load case not significant enough to report or raise concern. Further and more detailed FEA of all cases will later be conducted on a finalized complex model to officially gain accurate understanding of legitimate performance.



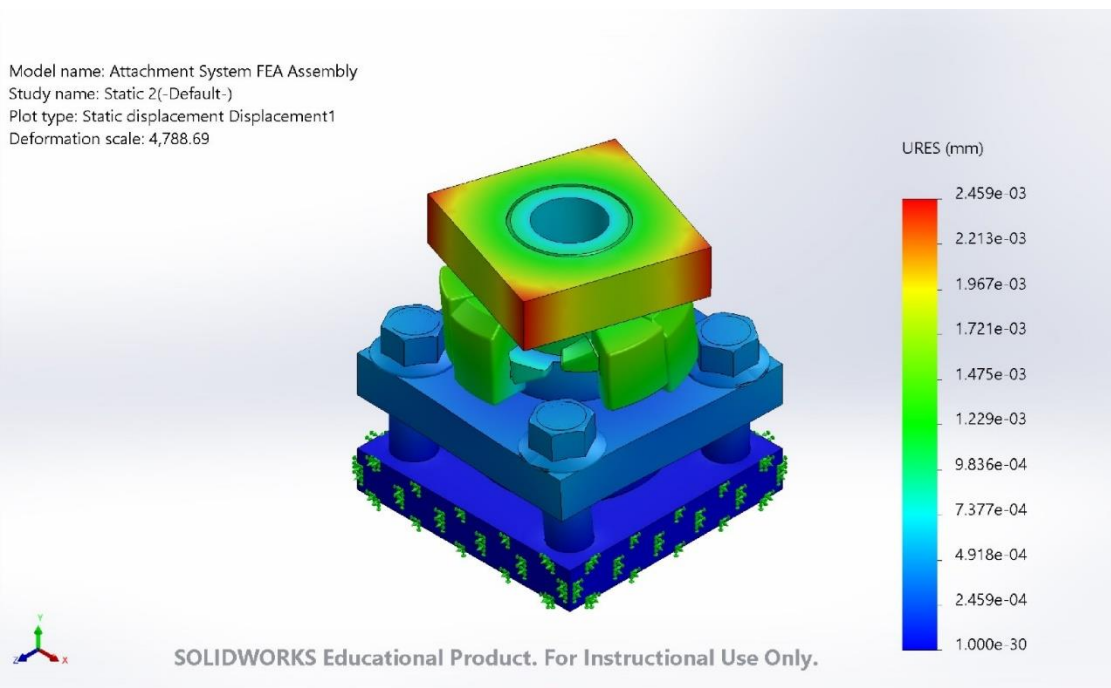
**Figure 20:** Moment Load Case (Stress FEA) – 150 lbf applied to front left face of force piece to create high moment on the system. Yielded max stress of 4.127e07 N/m<sup>2</sup> or 5.98 KSI



**Figure 21:** Moment Load Case (Displacement FEA) – 150 lbf applied to front left face of force piece to create high moment on the system. Yielded max displacement of 7.824e-03 mm or .0003 in.



**Figure 22:** Torque Load Case (Stress FEA) – 150 lbf-in. CW applied to the top cylindrical face of the top connector to create high torque on the system. Yielded max stress of 1.972e07 N/m<sup>2</sup> or 2.86 KSI



**Figure 23:** Torque Load Case (Displacement FEA) – 150 lbf-in. CW applied to the top cylindrical face of the top connector to create high torque on the system. Yielded max displacement of 2.459e-03 mm or .00009 in.

The second engineering specification, remaining steady despite vibrations, was completed through the industrial pins, jounce bumper, and the gasket within the bayonet mechanism. The industrial pins help to support the loads applied by any attachments and their motion. Finite element analysis of this design showed that the stresses present in the pins remained well below the materials yield strength, with a safety factor of around 30, as seen in Figure 20 and Figure 22. Majority of the stresses fell upon the bayonet connector pieces. The polyurethane jounce bumper, often used in vehicular suspension systems to prevent any bottoming out, will absorb vibrations. Because the jounce bumper and industrial pins are relatively easy to procure, much of the justification for this design was given by the structural prototype. Additionally, the jounce bumper is commonly used in vehicular suspension systems, providing additional support for the design. The gasket-like bushing bumper within the bayonet locking mechanism pushes against the two mating surfaces of the locking mechanism, creating a tensile force on the fins of mechanism (see Appendix I-5 for reference). The justification for this design comes from the structural prototype- the bayonet locking mechanism was 3D printed to test for fit and usability. Together, these three components reduce vibrations and unwanted motion, holding any attachments to the robot steady during use. Placing a camera on top of the structural prototype and moving the prototype to simulate use returned a relatively steady video, proving the design works.

The third specification, being waterproof to IP65, was met by epoxying the jounce bumper to the top and bottom plates and epoxying the electrical connectors and their wiring. Epoxy is a useful tool to prevent water ingress and is something commonly used in marine robotics. The design was tested using the structural prototype, by splashing water on the part of the design meant to be held together by epoxy.

The fourth specification, replacing attachments in under 8 minutes, was completed by the bayonet locking mechanism. The connector requires pushing the two mating faces together and twisting to attach or remove the attachment. The bayonet mechanism that was 3D printed for the structural prototype was easily detachable with minimum time and effort.

The fifth specification, the ability to pass necessary data and power through the connector to the attachment, is met by the inclusion of an electrical connector epoxyed into the middle of the bayonet connector and by passing the wire through the center of the jounce bumper into the chassis.

The only concerns with the proposed design moving forward are the ability of the top plate to slide freely over the industrial pins while experiencing the maximum load, the difficulty in milling the holes for the top and bottom plates to the specified tolerances, and the bayonet system staying locked with the maximum torsion applied. Efforts to fix these concerns have already been made and future testing will confirm that these are of no concern. In the future, with the access to better equipment, prototypes can be made with higher precisions.

## **5.5 Safety, Maintenance Considerations, & Cost**

To assess the safety and hazard considerations of this design, a Failure Modes & Effects Analysis (FMEA) and Design Hazard Checklist, in Appendix J and H, respectively, were completed. The FMEA is a process to review the design and improve upon it by looking at the ways the design might fail to perform the necessary functions. Once these methods of failure have been identified, the ways they might affect the customer, as well as method of preventing these failures were considered. From the FMEA, most of the potential modes of failure were related to the attachment points failing due to large dynamic loads

being applied. There is little concern of this failure causing injury as the robot is designed to go into areas in place of human first responders. To prevent this type of failure, preventative activities such as prototyping and extensive FEA have been completed. Another potential failure mode is the electrical connections failing due to pinching or water damage. This could cause injury, as exposed wires and conductive liquids might cause users of the robot to be shocked when attaching or detaching tools. This will be prevented by using a strong epoxy on the jounce bumper's points of contacts with the top and bottom plates as well as within the locking mechanism to secure the bushing. The Design Hazard Checklist is provided by Senior Project Advisors and is a comprehensive list of ways in which a design might pose safety risks to users. The completed checklist, in Appendix H, highlights hazards that are generally related to either the bayonet connector or the electrical connections. Major hazards for the bayonet are pinching and squeezing when connecting or disconnecting attachments and the connector potentially failing while humans are in proximity, causing the attachments to fall on users. Hazards related to the electrical connections come from pinching/ shearing causing exposed wires or water damage creating shorts. The preventative actions for these hazards can be found in the FMEA in Appendix J.

Maintenance and repairs for this design vary in complexity depending on which components wear out or fail. If the bayonet connector fails, a new one will have to be cast. There is no real way to repair it otherwise, as any cracking or deformation would seriously reduce the structural integrity of the design. Replacing the bayonet will be the most expensive repair. In a similar vein, the industrial pins will need to be replaced if any sort of deformation or cracking occurs. The press fit and epoxy securing the industrial pins into the bottom plate mean that removing any damaged pins will be difficult but possible. The pins are relatively cheap and can be bought individually, making replacements easy to acquire. Replacing either the top or bottom plate will be difficult in that both will have parts either welded or epoxied to them. Buying and manufacturing the plates is relatively easy. Any kind of deformation or warping to either plate will prevent the industrial pins from moving vertically through the holes in the top plate, as each pin must be correctly lined up with its respective hole. Any wear or damage to the jounce bumper would be a minor concern as removing and replacing the jounce bumper is an easy task. It would simply involve unscrewing the hex nuts, removing the top plate, breaking the epoxy seal of the jounce bumper with the top and bottom plates, and replacing the old bumper with a new one. The biggest issue would be if there were electrical wires being run through the jounce bumper into the bayonet connector. If this was the case, stripping and cutting the wires to remove the jounce bumper, and then re-soldering and heat wrapping the wires once the new bumper was put in is a viable solution.

The team decided to suggest casting the bayonet locking mechanism to Blueline Robotics. Due to the price of casting being dependent on the specific design, the quantity to be produced, machining required, and a timeline of when the locking mechanisms are needed to obtain a good estimate for the price of casting this part. Due to this, the bayonet locking mechanism was 3D printed for the final prototype. One spool of filament was required which costs \$26 on Amazon. The stock steel for the top and bottom plates for the final prototype was purchased from McMaster-Carr at \$39.19. The bushing for the locking mechanism was purchased from a skateboarding website for \$6. The four industrial pins were purchased from McMaster-Carr for \$3.64 per pin. The four 7/16-20 thread count hex nuts were also purchased here in SLO from Home Depot at 20 cents per nut. The Jounce bumper for the absorption system within the housing will be purchased from McMaster-Carr for \$11.01. The total price for the prototype will be around \$128.37 which leaves a lot of room for unforeseen costs as the stated

budget for the prototype is \$500. The indented bill of materials with these costs can be seen in Appendix I-1.

## **6.0 Manufacturing**

The entire attachment system is made up of parts widely varying in manufacturing complexity. Some parts were purchased off-the-shelf from different vendors, while some purchased components needed to be altered for assembly and function, other parts were produced within the Cal Poly machine shops, and some parts, namely the bayonet locking mechanism, are so complex they will need to be outsourced in the future. Due to the complex and expensive nature of outsourcing manufacturing processes for the bayonet locking mechanism, these complex components were 3D printed for the verification prototype used in the verification testing. These models allowed for functionality and mobility testing, but not strength testing. The outsourced manufacturing plan created for the bayonet locking mechanism has been looked over and verified by shop technicians with the intent to be pursued eventually by Blueline robotics.

### **6.1 Procurement**

Many of the components of this design were either ready-made stock pieces or stock material that was easily altered. Every component aside from the bayonet locking connector halves was manufactured from stock material or stock parts. The total procurement and manufacturing costs of both the structural prototype and the verification prototype were well within the \$500 budget.

The first part that was purchased and used as produced were the industrial pins. These pins were bought from McMaster-Carr at the exact size designed. The drawings for these pins can be found in Appendix I-6. McMaster-Carr has a broad selection of industrial pins with external threads made for a variety of applications at different specifications. These pins came with matching flange nuts.

The steel material used to create the top and bottom plates of the design were also purchased from McMaster-Carr. The plates are 6'x6' half inch thick, low carbon steel.

Lastly, the polyurethane bumper-like component was purchased from McMaster-Carr. For the bayonet locking mechanism, a bushing was purchased from a skateboard website.

### **6.2 Manufacturing**

The bottom plate was manufactured from 6'x6', ½ inch thick rectangular stainless-steel stock. The steps for the bottom plate were completed at the Cal Poly Mustang 60 Machine Shop and are as follows:

1. The stock piece was cut to 3 inches by 3 inches, as specified in Appendix I-8, using a circular saw or bandsaw.
2. The four industrial pin holes and the one center hole were added. All the holes were made using a manual mill to achieve the desired tolerance. The holes were milled to 1/2" and post-machine reamed to achieve the desired tolerance specified in Appendix I-8 of 29/64". Ideally, with access to a CNC mill, all features could be produced at a faster rate with higher accuracy. The material properties of the

stainless-steel plates made it necessary to drill each hole with multiple passes. When drilling, a slower speed and tapping oil were required to ensure the material was not heated to the point of hardening.

3. Once the holes were drilled, the plate was deburred using a deburring tool and inspected for tolerance achievement with digital calipers. After this step, the plate was complete for assembly. Figure 24 shows the plate with the drilled holes prior to deburring.



**Figure 24:** The top plate held in the mill vise.

4. The top plate was manufactured in the Cal Poly Mustang 60 Machine Shop in a similar manner to the bottom plate except with different hole sizing. The pin holes for the top plate were 0.5 inches in diameter to provide a clearance fit and the center hole was 1.20 inches in diameter. Otherwise, steps one through three were repeated for the top plate. If future manufacturing of these plates is done on a CNC, the different tolerances will have to be considered in a separate CNC code. It is noted that a drill size of 30/64" was used on a manual mill. Figure 25 shows the clearance of the holes in the top plate.



**Figure 25:** The top and bottom plate with pins press fitted. Does not include the bayonet connector, jounce bumper, or nuts.



5. The jounce bumper procured from McMaster-Carr was altered in the Cal Poly Machine Shop by removing one inch from the top of the bumper. It was cut using a hand-held battery powered saw.

### 6.3 Assembly

The assembly was completed in the Cal Poly Machine Shop. The assembly of the design started from the bottom up.

1. The industrial pins were press fit into the  $\frac{29}{64}$ " holes in the bottom plate by pushing them in by hand, using Loctite metal adhesive for additional strength. Figure 26 shows the industrial pins press-fitted into the bottom plate.



**Figure 26:** The bottom plate with jounce bumper set in place

2. The polyurethane bumper was placed onto the bottom plate, lining up the hole through the bumper with the center hole through the bottom plate. The bumper was secured to the bottom plate around the center hole using epoxy adhesive. The epoxy was applied such that the entire circumference of the mating surface of jounce bumper with the bottom plate was sealed with no gaps. This provided a watertight seal. Figure 26 shows the jounce bumper in place on the bottom plate.

3. A coating of epoxy was applied to the top surface of the jounce bumper that would contact the top plate. This was done in a manner similar to step two, above, which epoxied the jounce bumper to the bottom plate. The top plate was then placed onto the industrial pins such that the pins fit through the four clearance holes and the top plate rested on the jounce bumper. Figure 27 shows the top plate in place, resting on the jounce bumper, with the industrial pins threaded through.



**Figure 27:** The top plate is placed on the assembly.

4. The bayonet connector piece was permanently fastened to the top plate by setting it into the center hole. Once set, the bayonet connector piece was sealed using epoxy along the top surface of the plate, ensuring a watertight seal.

5. Lastly, the polyurethane bushing was fixed into the bayonet connector piece that is secured to the top plate using epoxy adhesive. The placement of the bushing within the bayonet locking mechanism can be seen in Figure 28.



**Figure 28:** The unattached bayonet connectors separated to show the bushing.

## 6.4 Outsourcing

The bayonet turn-locking connector pieces were designed with the long-term goal of casting them. They will be made from casted stainless steel. For the scope of this project, it was determined that outsourcing this component was not feasible or necessary immediately. Instead, the pieces were 3D printed for the visual representation and to determine that they were correctly sized.

## 6.5 Challenges

There were many unexpected challenges in manufacturing a verification prototype. In the critical design review phase, the plates were going to be manufactured using a CNC mill. Unfortunately,

it was impossible to find Cal Poly shop technicians willing to take on this project. The solution was to manually mill the necessary holes. This was fine in theory- however, in practice the stainless-steel material destroyed a lot of tool bits and took a very long time to manufacture. Beyond the two plates, there were significant challenges faced in finding a way to manufacture the bayonet locking mechanism. Like the top and bottom plates, the original plan was to CNC it however, the machine shop technicians advised against it. The next plan was to have the sponsor use their connections to 3D print the locking mechanism with inlaid carbon fiber. Unfortunately, it was determined that due to the shear loads and the direction of the carbon inlay, the carbon fiber would not provide any additional strength. To have a completed prototype in time for the DVPR signoff that portrayed a correct visual representation, a standard 3D printer was used to manufacture the bayonet locking mechanism.

## 6.6 Final Budget

The goal was to keep the overall cost of parts, manufacturing, and assembly under \$500. The cost for each part used throughout the manufacturing process is broken down in Table 9.

**Table 9:** Budget of project and bill of materials

Project Budget						
Description		Qty	Cost (\$)	Ttl Cost (\$)	Source	More Info
Lvl1	Lvl2					
Top Assembly						
-	Bayonet Lock (filament)	1	26	26	Amazon	3D printing filament
-	Bayonet Lock (Metal Rod Stock)	1	57.51	57.51	Mc Master-Carr	item 89535K71
-	Top Plate	1	14.01	14.01	McCarthy Tank and Steel	6"x6"
-	Bushing	1	6	6	rootsoutdoornc.com	1" inner diam, .35" outer diameter, .5" thick
Absorption						
-	Industrial Pins (Functional Proto)	4	3.92	17.96	Mc Master-Carr	item 92281A417
-	Industrial Pins (Final Proto)	4	4.49	17.96	Mc Master-Carr	item 92281A421
-	Nuts	4	0.2	0.8	Home Depot	7/16-20 off the shelf
-	Jounce bumper	1	11.01	11.01	McMaster-Carr	item 9306K21
-	Adhesive	1	5.97	5.97	Home Depot	Metal Adhesive for press fits
Bottom Assembly						
-	Bottom plate	1	14.01	14.01	McCarthy Tank and Steel	6"x6"
-	Bottom/Top Plate Stock (Final Proto)	1	39.19	39.19	Mc Master-Carr	item 6620K116
Paid Operations						
-	Top/Bottom Plate Machining	1	N/A	N/A	Cal Poly machine Shops	Shop Tech (quote pending)
-	Bayonet Lock machining	1	N/A	N/A	Maglio CNC Prototyping	Local Shop (quote pending)
Total:		13		184.42		
Budget:	500.00					
Budget Remaining:	315.58					

Through part procurement, manufacturing, and assembly a total of \$184.42 was spent. This is well below the allotted \$500 showing that this design is very feasible. Due to two different iterations of prototyping, steel for the top and bottom plates was purchased on two separate occasions. In the bottom assembly section of Table 9, the Bottom/Top Plate Stock (Final Proto) was the steel used for the verification prototype. This price will increase when manufacturing of the top and bottom plates is done using a CNC mill and the bayonet locking mechanism is cast.

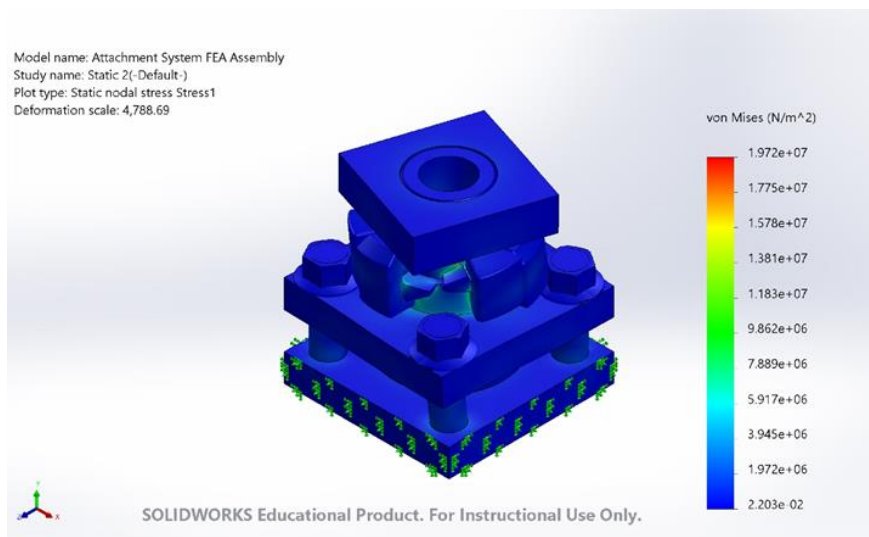
## 7.0 Design Verification

This section details the Design Verification Plan (DVP) developed to ensure that the final design meets all the engineering specifications listed in Table 6. Each test described in the following sections was developed to ensure that specific components and sub-assemblies met their desired functional criteria. Much of the quantitative data for the DVP will come from FEA owing to the difficulty casting the bayonet locking mechanism for prototyping.

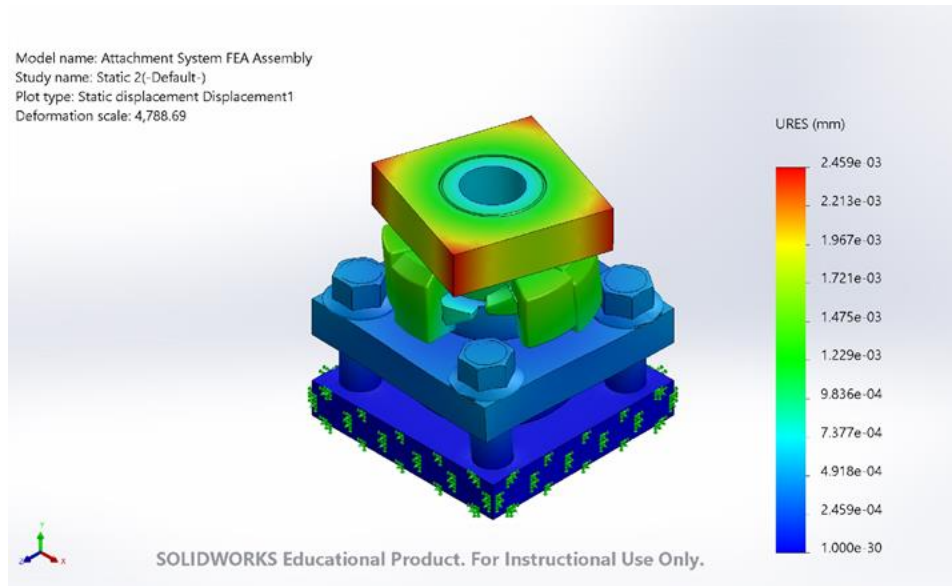
### 7.1 Test #1: Bayonet Locking Mechanism FEA

To test whether the bayonet locking mechanism will fail under the given load cases an FEA analysis was conducted. This determined the critical points of the locking mechanism and if any areas are too thin. The FEA was conducted under three load cases: cantilevered load accelerating horizontally at 2 radians per second, cantilevered load accelerating vertically at 2 radians per second, the impact force of the robot tipping over onto the arm attachment, and the axial force of 50lbs on the system from heavy attachments. SolidWorks was used to conduct this FEA analysis. This is further outlined in the DVPR in Appendix K. To pass this test, the parts maximum displacements should not exceed .002in and the safety factor with material strengths and the max stresses should not be less than 5.

In the Solidworks assembly for the entire system, a new static study was created. The bottom plate was defined as fixed where it would weld to the robot chassis. The top bayonet connector had a torque applied to the part where the attachment would be fixed. This torque was calculated through dynamics hand calculations of the 3 given load cases seen in Appendix A. With the way this study was created, it isolated a maximum load case of the arm rotating horizontally on the attachment system to really test its design. The exaggerated deformation and display of the stress and displacement analyses are seen in Figures 29 and 30.

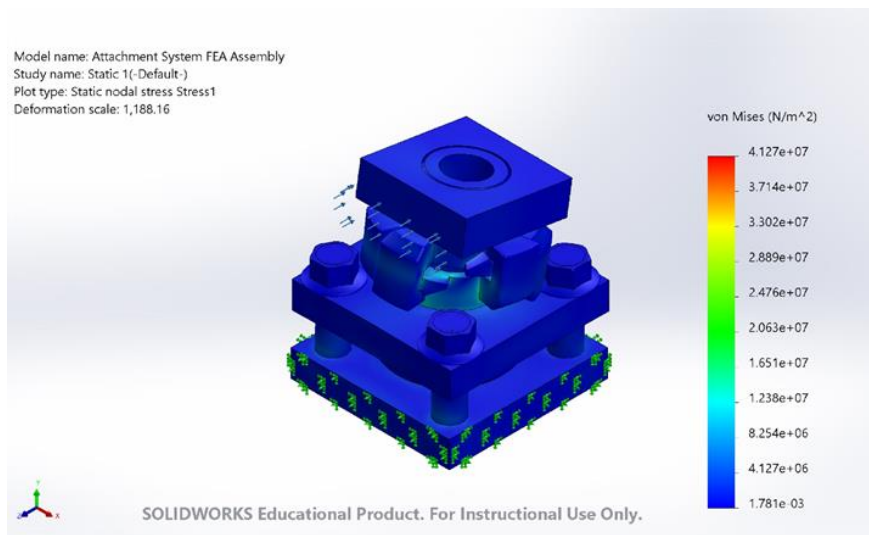


**Figure 29:** Exaggerated deformation and color display of stress location in clockwise torsion load case.

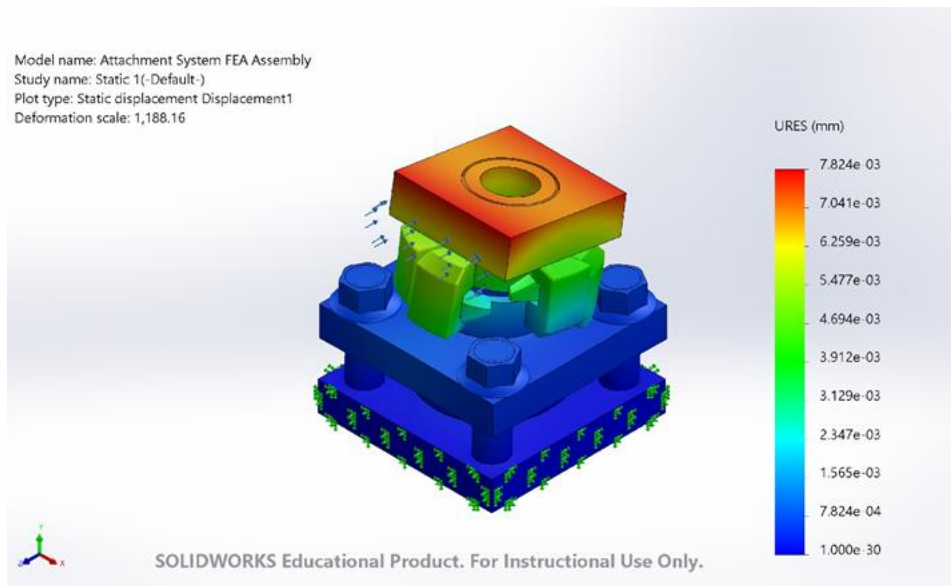


**Figure 30:** Exaggerated deformation and color display of displacement location in clockwise torsional load case.

To simulate the robot arm rotating vertically and the arm tipping over and experiencing an impact force, the next static study was of the system experiencing a moment at the connection point. This was achieved by again fixing the lower bayonet connector into the top plate, and then applying a horizontal shear force onto the top bayonet connector where the attachment is fixed. The value of this shear force corresponds to the calculated moment in the dynamics hand calculations of Appendix A. The exaggerated deformation and display of the stress and displacement analyses are seen in Figures 31 and 32.

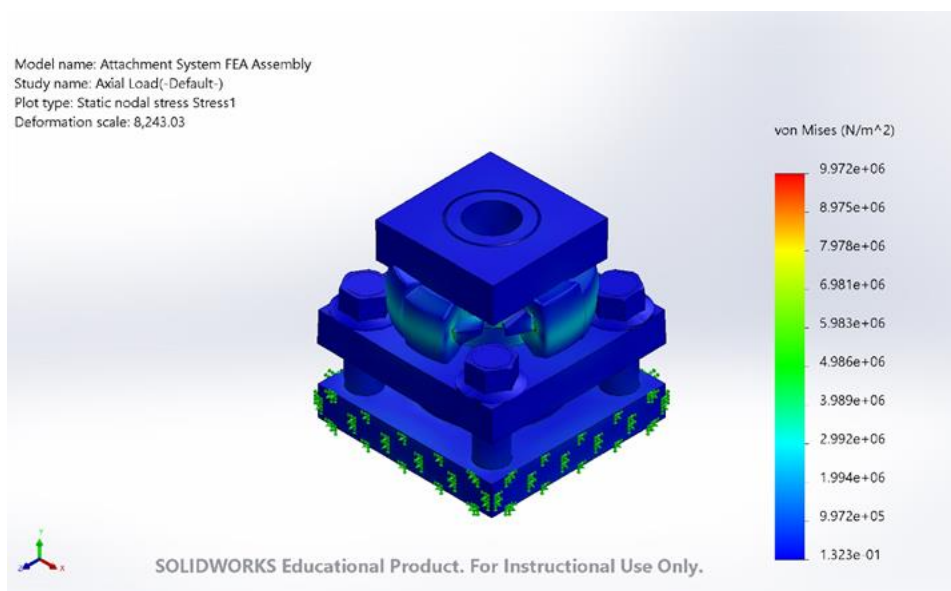


**Figure 31:** Exaggerated deformation and color display of stress location in moment load case.

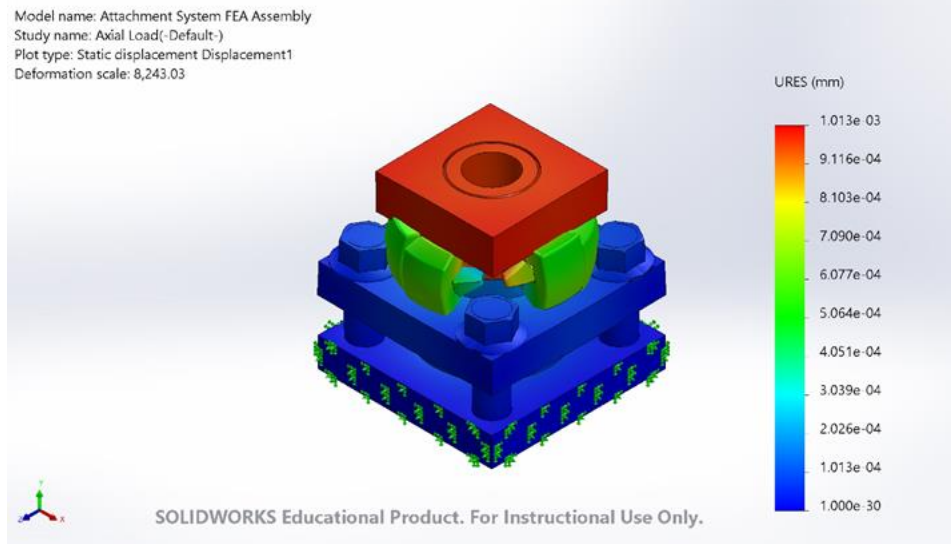


**Figure 32:** Exaggerated deformation and color display of displacement location in moment load case.

Lastly, to test the axial force of attachments on the connectors, the top plate was fixed, and the top bayonet connector had a downward axial force acting where the attachments would be fixed. This resulted in the system being “squished”. The exaggerated deformation and display of the stress and displacement analyses are seen in Figures 33 and 34.



**Figure 33:** Exaggerated deformation and color display of stress location in axial load case.



**Figure 34:** Exaggerated deformation and color display of displacement location in axial load case.

After conducting these complex FEA load cases, many conclusions for multiple tests could be stated. Overall, the results pass the desired performance tests that were set out for the design. Max stresses and displacements occurring in the bayonet connectors can be seen in Table 10. Safety factors proved to be more than reasonable, and displacements resulted in miniscule movement. It is important to note that when looking at the deformed state model in Figures 31-34, the deformation visual is about 8,000-12,000 times more deformed than the actual max displacements. Additionally, there seems to be a lot of displacement in the axial load case, however, this is the design at work with the bushings and jounce bumper compressing slightly due to the downward forces. This max displacement value is still essentially zero.

**Table 10:** Results of bayonet connector design test

	Min. Stress [psi]	Max. Stress [psi]	Min. Displacement [in]	Max. Displacement [in]	Safety Factor Stress	Safety Factor Displacement
Axial Load Case	.002	1446	3.937e-32	3.988e-5	24	51
Moment Load Case	.258	5986	3.937e-32	0.0003	5.8	6.67
Torsion Load Case (CCW)	.032	2860	3.937e-32	9.681e-5	12.2	21
Torsion Load Case (CW)	.032	2860	3.937e-32	9.681e-5	12.2	21

## 7.2 Test #2: Top and Bottom Plate FEA Analysis

The top and bottom plates were also looked at through an FEA analysis under the same three load conditions in Test #1. This analysis will determine possible points of failure and maximum deformation. It is critical that the maximum deformation is known to keep the housing correctly aligned so the jounce bumper can operate properly. This test is outlined in more detail in Appendix K. To pass this test, the parts maximum displacements should not exceed .002in and the safety factor with material strengths and the max stresses should not be less than 5.

In the Solidworks assembly for the entire system, the same FEA studies were used. This time the results in the plates would be observed for this test. If the Bayonet connectors can withstand and support the system alone, it is believed that in cooperation with the plates and the pins the system will be even more successful overall. The design verification provides for redundancy with the goal of attaining higher overall factors of safety. The bottom plate was again defined as fixed where it would attach to the chassis of the robot. The top bayonet connector had a torque applied to the part where the attachment would be fixed. This is the same torque that was calculated through dynamics hand calculations of the 3 given load cases seen in Appendix A. The exaggerated deformation and display of the stress and displacement analyses are seen in Figures 29 and 30.

To again simulate the robot arm rotating vertically and the arm tipping over and experiencing an impact force, the next static study was of the system experiencing a moment at the connection point. This was achieved by again fixing the bottom plate as if welded to the robot chassis, and then applying a horizontal shear force onto the top bayonet connector where the mock attachment is fixed. The value of this shear force is the same one used previously that was calculated from the corresponding moment in the dynamics hand calculations of Appendix A. The exaggerated deformation and display of the stress and displacement analyses are seen in Figures 31 and 32.

Lastly, to again test the axial force of attachments on the plates, the bottom plate was fixed, and the top bayonet connector had a downward axial force acting where the attachments would be fixed. The exaggerated deformation and display of the stress and displacement analyses are seen in Figures 33 and 34.

The plates in the design passed their FEA test with flying colors. As designed, majority of the load cases stresses are experienced elsewhere in the design other than just the plates. With that, max stresses and displacements for the plates can be seen in Table 11. As expected, the top plate displaced slightly vertically with the jounce bumper compressing. Although it displaced a little bit, it is nowhere near enough to be noticed by the human eye.



**Table 11:** Results of the plate FEA design test

	Min. Stress [psi]	Max. Stress [psi]	Min. Displacement [in]	Max. Displacement [in]	Safety Factor Stress	Safety Factor Displacement
Axial Load Case	.002	289	3.937e-32	1.196e-5	104	167
Moment Load Case	.26	2395	3.937e-32	6.161e-5	12.5	32
Torsion Load Case (CCW)	.032	1715	3.937e-32	2.904e-5	17.5	69
Torsion Load Case (CW)	.032	1715	3.937e-32	2.904e-5	17.5	69

### 7.3 Test #3: Industrial Pin FEA Analysis

The industrial pins underwent an FEA analysis under the same three load cases stated above. Like the top and bottom plate FEA analysis, this was run to determine potential points of failure and the maximum deformation that occurred. Learning the deformation of the industrial pins is very critical because if any of the industrial pins deform, the alignment of the housing will be off, and the jounce bumper will not be able to operate. This test is outlined in more detail in Appendix K. To pass this test, the parts maximum displacements should not exceed .002in and the safety factor with material strengths and the max stresses should not be less than 5.

This time, stresses and displacements were observed and verified within the pins for each load case. The bottom plate was again defined as fixed where it would attach to the chassis of the robot. The top bayonet connector had a torque applied to the part where the attachment would be fixed. This is the same torque that was calculated through dynamics hand calculations of the 3 given load cases seen in Appendix A. The exaggerated deformation and display of the stress and displacement analyses are seen in Figures 29 and 30.

To again simulate the robot arm rotating vertically and the arm tipping over and experiencing an impact force, the next static study was of the system experiencing a moment at the connection point. This was achieved by again fixing the bottom plate as if welded to the robot chassis, and then applying a horizontal shear force onto the top bayonet connector where the mock attachment is fixed. The value of this shear force is the same one used previously that was calculated from the corresponding moment in the dynamics hand calculations of Appendix A. The exaggerated deformation and display of the stress and displacement analyses are seen in Figures 31 and 32.

Lastly, to again test the axial force of attachments on the pins, the bottom plate was fixed, and the top bayonet connector had a downward axial force acting where the attachments would be fixed. The exaggerated deformation and display of the stress and displacement analyses are seen in Figures 33 and 34.

The pins proved to perform to a very satisfactory degree. They indeed did pass this test well. The max stresses were minimal and the displacements essentially non-existent. This is great news since the pins are imperative to the absorption systems function. They must stay undeformed, but still provide structural rigidity to the assembly. Numerical results of stresses and displacements found in the pins from the FEA are listed in Table 12.

**Table 12:** Results of the pins FEA design test

	Min. Stress [psi]	Max. Stress [psi]	Min. Displacement [in]	Max. Displacement [in]	Safety Factor Stress	Safety Factor Displacement
Axial Load Case	.002	1.45	3.937e-32	3.988e-8	38620	51282
Moment Load Case	.26	2394	3.937e-32	3.081e-5	23.4	65
Torsion Load Case (CCW)	.032	2002	3.937e-32	1.940e-5	28	105
Torsion Load Case (CW)	.032	2002	3.937e-32	1.940e-5	28	105

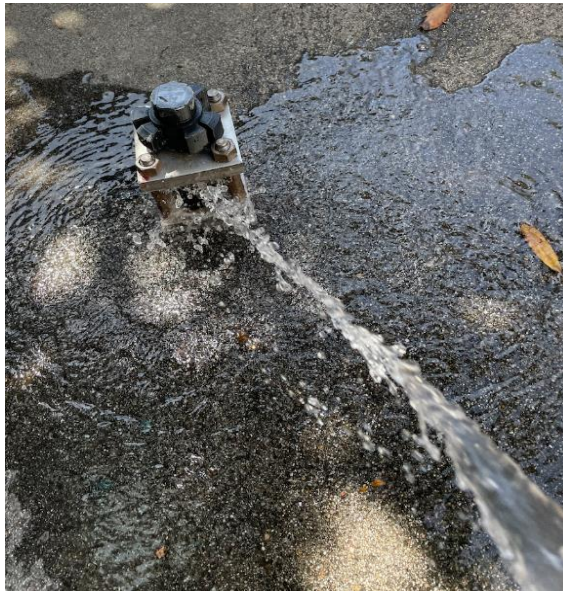
#### 7.4: Test #4: Absorption System Testing

To test if the jounce bumper is absorbing some of the vibrations, a phone with an accelerometer application was placed onto the top plate of the housing. While the application was running, the top plate was subjected to vibrations. Another trial was run without the jounce bumper. The two tests were then compared to see if the data with the jounce bumper active had lower amplitudes of vibration. For this test, the prototype and a phone with an accelerometer application was needed. This test was conducted indoors on a desk and can be conducted in any indoor area. This test is outlined in more detail in Appendix K. The results of this test showed that the jounce bumper was not successful in absorbing vibrations. The amplitudes of vibrations were nearly identical between the two tests with and without the jounce bumper active. The reason that the jounce bumper was not effective in absorbing vibrations is due to it having too high of a stiffness. The vibrations that the housing was subjected to were too small to make the jounce bumper compress. The difficulty with selecting an appropriate jounce bumper stiffness is due to the 50-pound axial load due to the robotics arm attachment that will be placed on to the attachment system. The jounce bumper must be stiff enough to minorly compress under this axial load but also be not too stiff to absorb the vibrations. Another difficulty that arose during this test was finding appropriate equipment to properly test the system from absorptions. The results of this test are further outline in Appendix K.

#### 7.5: Test #5/6: Watertight to IP65

To test if the design is water-tight to an IP65 standard, a waterjet was used to test the epoxy seals. There are three epoxy seals that were tested, they are located where the absorption jounce bumper meets the top plate, where the same jounce bumper meets the bottom plate, and where the bushing is embedded into the bayonet locking mechanism. For this test, a hose was sprayed around the

entire epoxy area for all three epoxy locations as seen in figures 35 and 36. After this was completed, the inside of the jounce bumper was checked to see if any water got through as seen in figures 37 and 38. This test was conducted outdoors as it caused water splashing and can be conducted in any outdoor area. This test was run five times for each epoxy seal, and is outlined in more detail in Appendix K. All three epoxy seals succeeded in keeping water out of the inside of the jounce bumper for all five trials. From this it was determined that the epoxy seals keep the inside of the attachment system watertight to an IP65 standard. The results of this test are further outline in Appendix K.



**Figure 35:** Watertight test of epoxy seals between the jounce bumper and the two plates



**Figure 36:** Watertight test of epoxy seals between the bushing and bayonet locking mechanism.



**Figure 37:** Checking to see if the epoxy seals between the jounce bumper and the two plates kept the inside of the jounce bumper dry.



**Figure 38:** Checking to see if the epoxy seal between the bushing and bayonet locking mechanism succeeded in keeping the inside of the bayonet locking mechanism dry.

## 7.6 Test # 7: Time to Attach and Release

Using the 3D printed bayonet locking mechanism, multiple trials of connecting and disconnecting it were run. These trials were all timed and an average time to attach and release was calculated. This test was conducted indoors at a desk and can be conducted in any indoor area. These trials and their average values are shown in Table 13. This data was then used to perform an uncertainty

analysis and an error propagation. This test is outlined in more detail in Appendix K. The goal was to have this average time to attach and detach be under 8 minutes. Through testing an average time of 1.65 seconds and an average detach time of 1.65 seconds was found. This is well under the allotted 8 minutes and so it was concluded that the attachment system succeeds in being quick release. The results of this test are further outline in Appendix K.

**Table 13:** Timed trials and averages of attach and detach times.

Trial	Attach Time (s)	Detach Time (s)
1	1.99	1.59
2	1.97	2.09
3	1.58	1.65
4	1.32	1.47
5	1.53	1.64
6	1.39	1.59
7	1.51	1.65
8	1.49	2.00
9	2.03	1.56
10	2.04	1.41
11	1.74	1.58
12	1.50	1.65
13	1.49	1.55
14	1.48	1.52
15	1.43	1.42
16	1.69	1.78
17	1.75	1.64
18	1.82	2.23
19	1.60	1.32
20	1.72	1.65
Average	1.65	1.65

**Uncertainty Analysis:**

The population means ( $\mu$ ) for both the attach and detach time data from the mean of a finite sample ( $x$ ) with size of (n) use equation 1.

$$\mu = \bar{x} \pm \frac{ts}{\sqrt{n}} \tag{1}$$

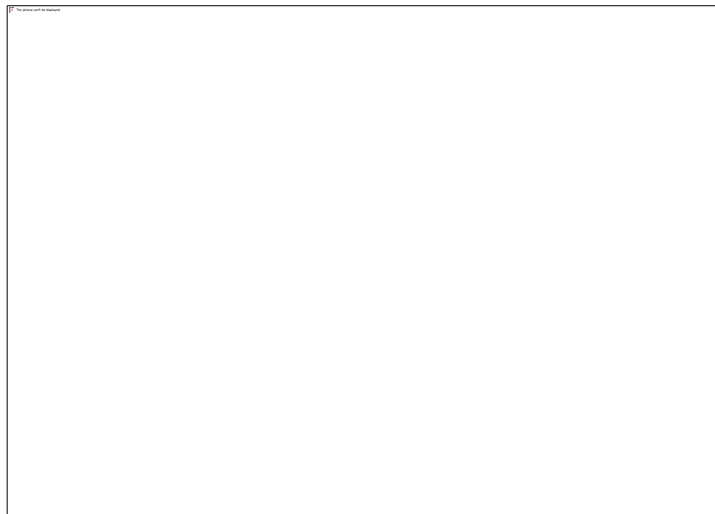
With a sample size of 20, the t values for each case are both equal to  $t = 1.328$  for this analysis using a 90% confidence interval. The sample standard deviation  $s$  was also calculated using a sample size  $n = 20$ . This was calculated using equation 2.

$$s = \left[ \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2 + \right]^{1/2} \tag{2}$$

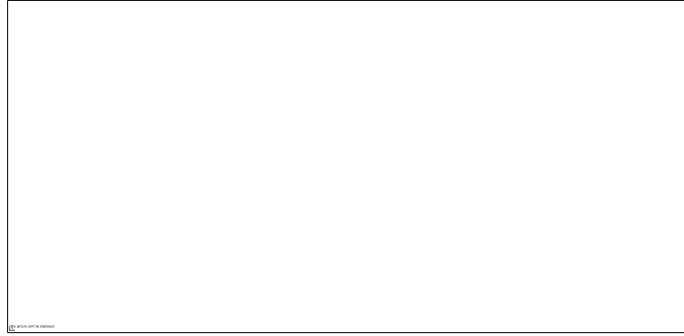
The results of the 90% confidence interval uncertainty analysis for the time to attach is  $1.65 \pm 0.065$  (s). For the time to detach the results are  $1.65 \pm 0.067$  (s).

### 7.7 Test # 8: Passing Power Through the System and Ensuring Wires Will Not Get Damaged

To test if the power will be able to pass through attachment system without any concern of pinching or severing, a physical test was run. This test required a cable of the same diameter of the power cord Blueline plans to use and the prototype. The cable was physically passed through the bottom plate, top plate, and bayonet locking mechanism and visually inspected to see if the cable had room and was not in danger of being pinched or severed. This test was conducted indoor on a desk and can be conducted in any indoor setting. This test is outlined in more detail in Appendix K. The cable was successfully passed through the attachment system. With the cable passing through the attachment system, a 25-pound weight was placed onto the locking mechanism of the attachment system to resemble the axial loads due to the attachments, as shown in Figure 39. Ideally a larger load of 50-pounds would have been used as this is the weight of the robotic arm attachment that Blueline will use however, the bayonet locking mechanism was 3D printed out of ABS plastic which would not have supported a 50-pound load. After 10 seconds the weight was removed, and the cable was taken out of the attachment system to be visually inspected as shown in Figure 40. The cable showed no signs of being pinched or crushed. From this it was determined that the attachment system can pass power from the chassis of the robot to the attachments and the power cord will not get pinched or crushed. The results of this test are further outline in Appendix K.



**Figure 39:** 25-poung weight placed on top of the attachment system while power cord is being passed through.



**Figure 40:** Power cord is visually inspected to ensure no pinching or crushing occurred.

## 7.8 Summary and Suggestions

Overall, all criteria were tested and only absorbing vibrations did not pass. This is better outlined in Table 14.

**Table 14:** Summary of Tests

Spec #	Specification Description	Requirement or Target (units)	Specification Source	Verification Prototype Pass/Fail
1	Withstanding the three loading conditions (bayonet locking mechanism)	Factor of safety >5	sponsor	Pass
1	Withstanding the three loading conditions (plates)	Factor of safety >5	sponsor	Pass
1	Withstanding the three loading conditions (industrial pins)	Factor of safety >5	sponsor	Pass
2	Vibration Absorption	Jounce bumper presence reduces vibrations	Sponsor	Fail
3	Ingress Protection	Watertight to IP65	EN 60529	Pass
4	Quick Release	Separation of tool from design in < 8 minutes	Sponsor	Pass
5	Power	Cables pass with no interference under loadings	Sponsor	Pass

While only one test did not pass its criterion, there are a few suggestions that will help all tests to pass, or to pass with higher margins. For testing if the absorption system absorbs vibrations an accelerometer and shake table in a vibration's should be used. It is also recommended that a jounce bumper with less stiffness be used and tested as it is believed that the jounce bumper used is too stiff to absorb most of the vibrations. For the top and bottom plates, it is suggested that they be manufactured using a CNC mill. This will improve accuracy and save time. The bayonet locking mechanism should be cast and physically tested against the load cases to confirm the FEA.

## 8.0 Project Management

The overall design process revolved around three main phases: design, build, and test. These three phases spanned over a 10-week period over Cal Poly's fall, winter, and spring quarters. The design phase was comprised mainly of defining the problem that needed to be solved, along with researching both existing and competitive products. This then led to multiple design concepts which were later refined into a final design. With this, a Preliminary Design Review (PDR) took place in the fall quarter. The build phase started off with more design and CAD analysis which then led to part selection. With this, a risk assessment was then conducted, allowing the start to building the finalized design. This phase ended with a Critical Design Review (CDR) in the winter quarter. The testing phase started off with more building which went until the design had been built fully. Once built, the product was tested under each criterion given by Blueline Robotics. With the tests concluded, this Final Design Review (FDR) was written. Throughout these three phases, there were many tasks that needed to be completed. A breakdown of every task in a Gantt chart form can be found in Appendix L. Key deliverables are shown in Table 15, along with the dates by which they were completed.

**Table 15:** F32 Key Deliverable Timeline

Deliverable	Description	Due Date
Scope of Work	Outline of the entire project.	10/13/2020
Preliminary Design Review	Initial review of the design solutions.	11/12/2020
Interim Design Review	More informed review of the design solutions.	01/14/2021
Critical Design Review	Detailed review of design solution including costs, analysis, and updated solution.	02/12/2021
Manufacturing and Test Review	Review manufacturing and testing methods that will be used in building the product.	03/11/2021
DVPR Sign Off	A logical testing sequence will be thoroughly planned out.	05/18/2021
EXPO	Finalized product will be presented along with final design, build, and testing processes for peer feedback.	05/28/2021
Final Design Review	Provide sponsors with a finalized review of the design as well as the finished product.	06/04/2021



## 9.0 Conclusions and Recommendations

Overall, the purpose of this document is to justify the final design and the verification prototype against the given criteria. Provided in this document were items from the scope of work, the preliminary design review, the interim design review, and the critical design review. The task presented by Blueline Robotics was as follows: Blueline needs a way to allow their robot to be fitted with a variety of tools to ensure it can be used for a multitude of missions and situations. This system's needs must be achieved quickly and easily for "in the field" moments. This attachment point needs to be able to support cantilevered loads while moving in multiple directions. Additionally, this device must be watertight to an IP65 standard and be fully functional in harsh environmental conditions. Finally, the cost of the final prototype and design should stay below the constraint from Blueline of \$500. The original design presented in the preliminary design review was altered after the interim design review. The reasons for the change stemmed from the cost and complexity of manufacturing custom parts. The final design set forth in this document removed the components that caused issues, namely that Gardena connector and the spring suspension system. The final design utilizes a simpler quick release mechanism and a simple jounce bumper rather than the complex spring system of the previous design. The final design was tested against all the criteria ensure it will meet Blueline's standards. The prototype meets or exceeds all the criteria except for absorbing vibrations. It is suggested that a jounce bumper with a lower stiffness be used to absorb more vibrations, and that this new absorption system be tested in a proper vibrations lab with an accelerometer and a shake table. Additionally, the top and bottom plates should be manufactured using a CNC mill to provide a higher degree of accuracy and save on time. Lastly, the bayonet locking mechanism should be cast with stainless steel and welded onto the top plate. The finished prototype should then be physically tested against the expected load cases to verify the FEA. To properly use the attachment system a user manual is outlined in Appendix M.

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## **Appendices**

**Appendix A: Preliminary Analysis of Load Cases**

**Appendix B: Quality Function Deployment Chart (House of Quality)**

**Appendix C: Ideation Section Results**

**Appendix D: Pugh and Weighted Matrices**

**Appendix E: Final Concept Design Weighted Decision Matrix Rating Explanation**

**Appendix F: CAD Drawing Isometric View of Prototype**

**Appendix G: Hand Calculations for Spring Stiffness**

**Appendix H: Design Hazard Checklist**

**Appendix I: Drawing Package**

**Appendix J: Failure Modes & Effect Analysis (FMEA)**

**Appendix K: Design Verification Plan (DVP)**

**Appendix L: Project Management Gantt Chart**

**Appendix M: User Manual**

## Appendix A: Preliminary Analysis of Load Cases

Seen below is some preliminary analysis done for a minimum load case on the attachment system's connection point. It must sustain the impact force of the robot tipping over onto the arm attachment producing a moment on the attachment system. It must also sustain a 25lb cantilever load on the 4-foot arm accelerating horizontally and vertically at 2 Rad/s creating torques on the system. This analysis is just preliminary and helps us define a starting point in terms of strength and tier of the design.



**Figure 1:** Scan of preliminary analysis moment load case for the attachment system connection point.



**Figure 2:** Hand calculation for resulting torque on the attachment system from load case.

**Appendix B: Quality Function Deployment Chart (House of Quality)**



**Appendix C: Ideation Section Results**

Appendix C-1: Brain-dumping ideation section results.



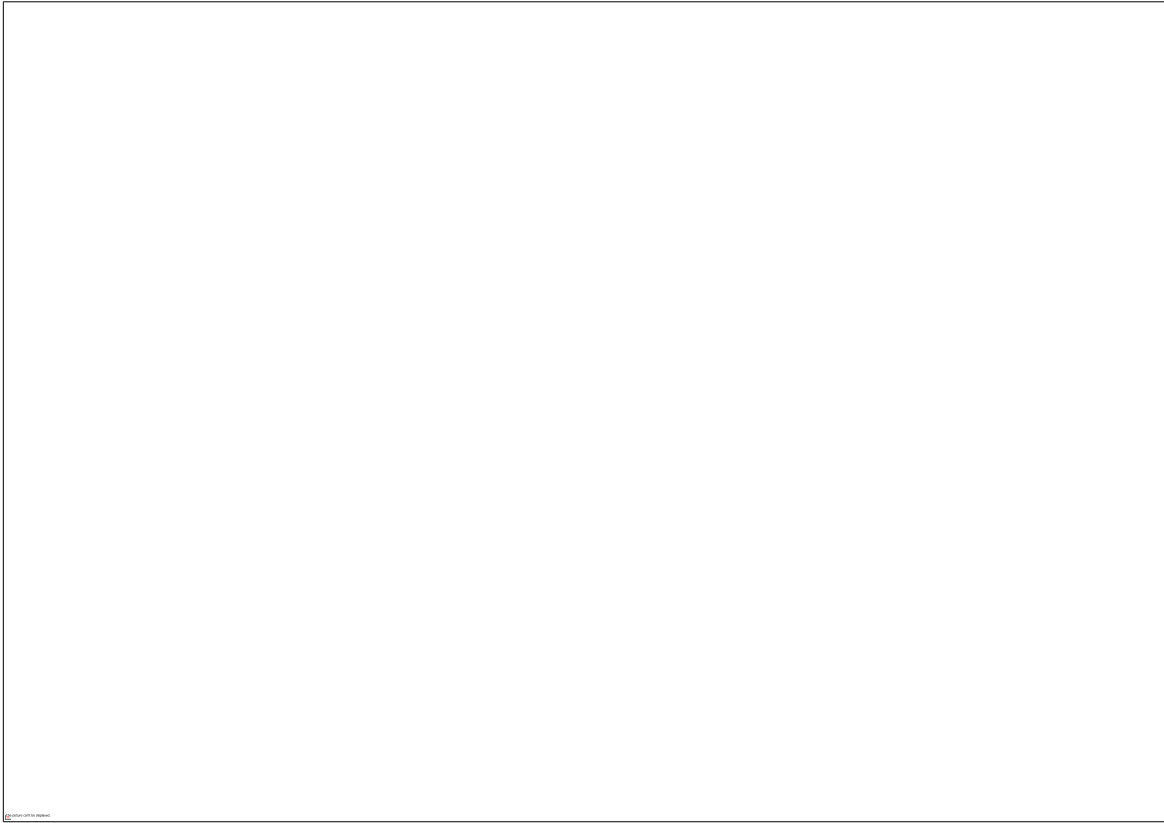


Appendix C-2: Brain-walking ideation section results



**Appendix D: Pugh and Weighted Matrices**

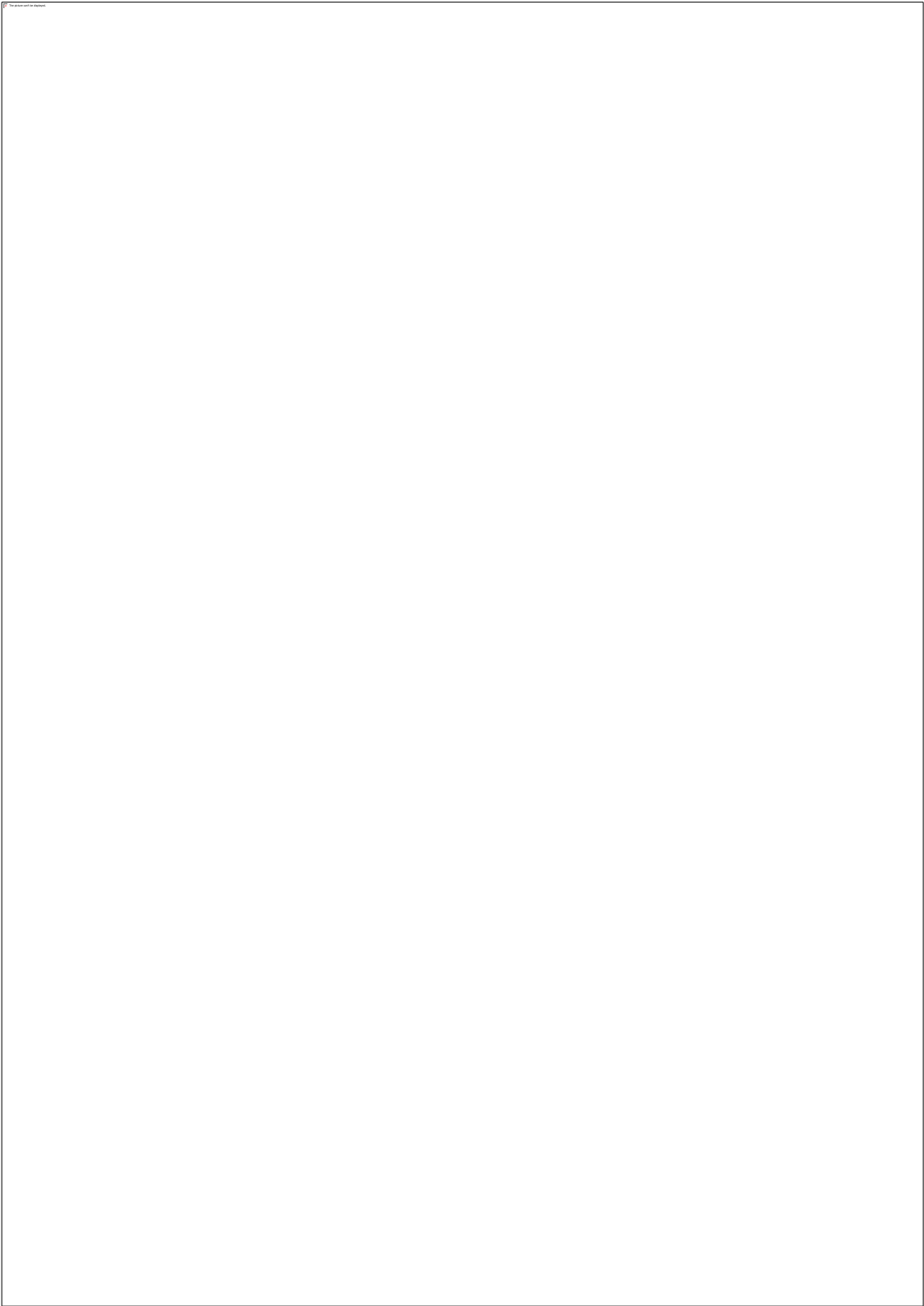
Appendix D-1: Pugh Matrix for supporting Dynamic Load



Appendix D-2: Pugh Matrix for Absorbing Vibration and providing Damping



Appendix D-3: Pugh Matrix for Actuation

A large empty rectangular box with a thin black border, intended for a Pugh Matrix. The box is currently blank, with no text or data inside.

Appendix D-4: Pugh Matrix for Watertight.



The image shows a large, empty rectangular box with a thin black border, intended for a Pugh Matrix. The box is currently blank, with no text or data inside.

Appendix D-5: Pugh Matrix for Universal Attachment Point



Appendix D-6: Weighted Decision Matrix



## Appendix E: Final Concept Design Weighted Decision Matrix Rating Explanation

Final Concept Design Weighted Decision Matrix Rating Explanation

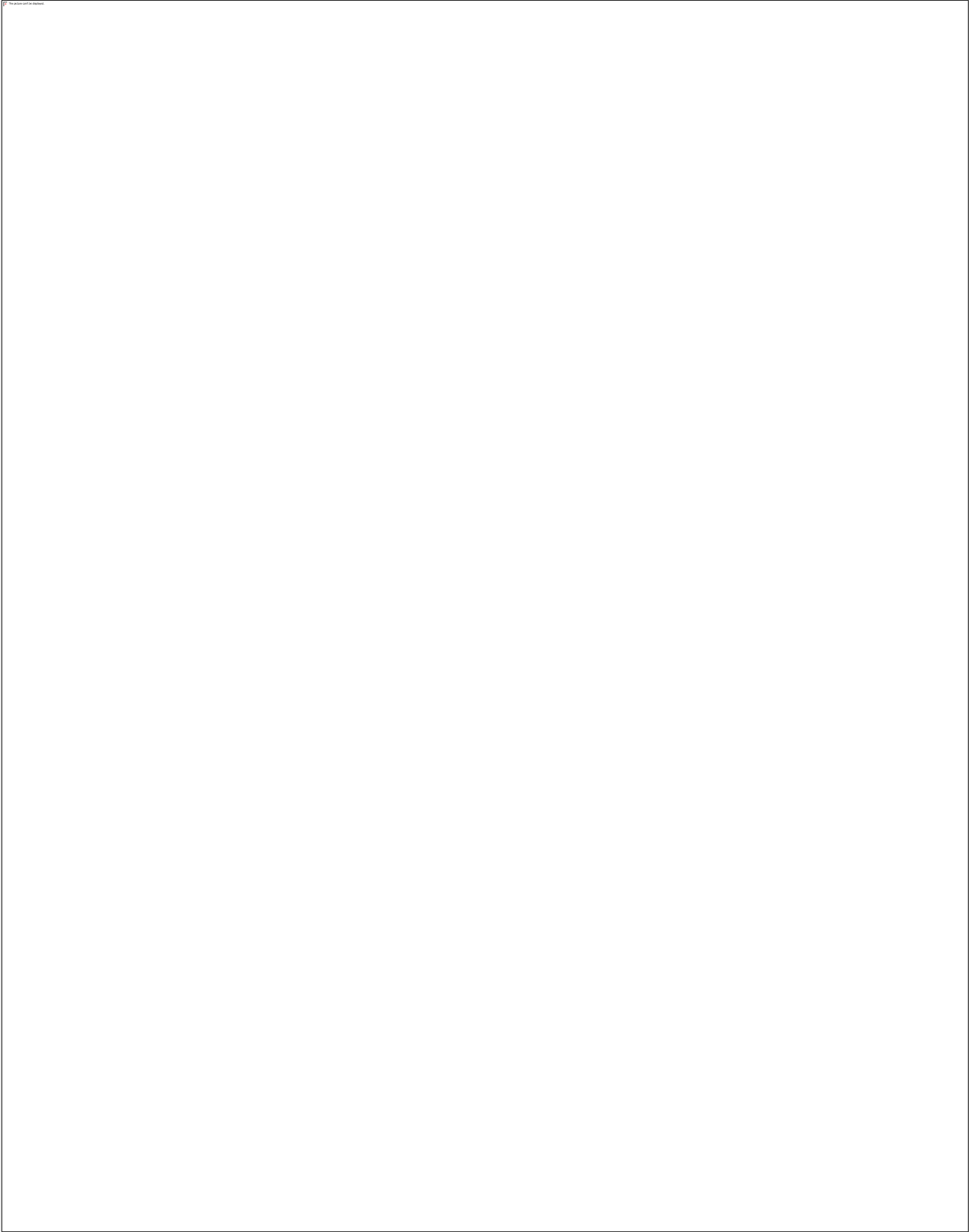
<b>Exchange Criteria</b>	<b>Exchange Criteria Weighted Value</b>	<b>Notes</b>
<i>Able to withstand cantilever load of 25lb w 4ft arm</i>	23	Collar material/dimensions can be altered to increase strength
<i>waterproof to IP65</i>	22	O-rings prevent water and solid particle ingress
<i>Prototype under \$500</i>	15	Complexity of Gardena collar and suspension system is undesirable and potentially expensive
<i>Able to interface with multiple attachments</i>	11	Internal electrical connections can be swapped and/or designed to be universal
<i>quick release, under 5 min</i>	8	Gardena collar allows for quick release
<i>pass necessary power/data through</i>	9	Internal electrical connections allow for data/power passing
<i>survive rough/rugged environments</i>	5	Flexibility in collar, suspension system design to make more robust
<i>stretch- rotating</i>	5	Current design does not allow for rotation- further modifications necessary
<i>flexibility in choosing material</i>	2	Current design provides material flexibility



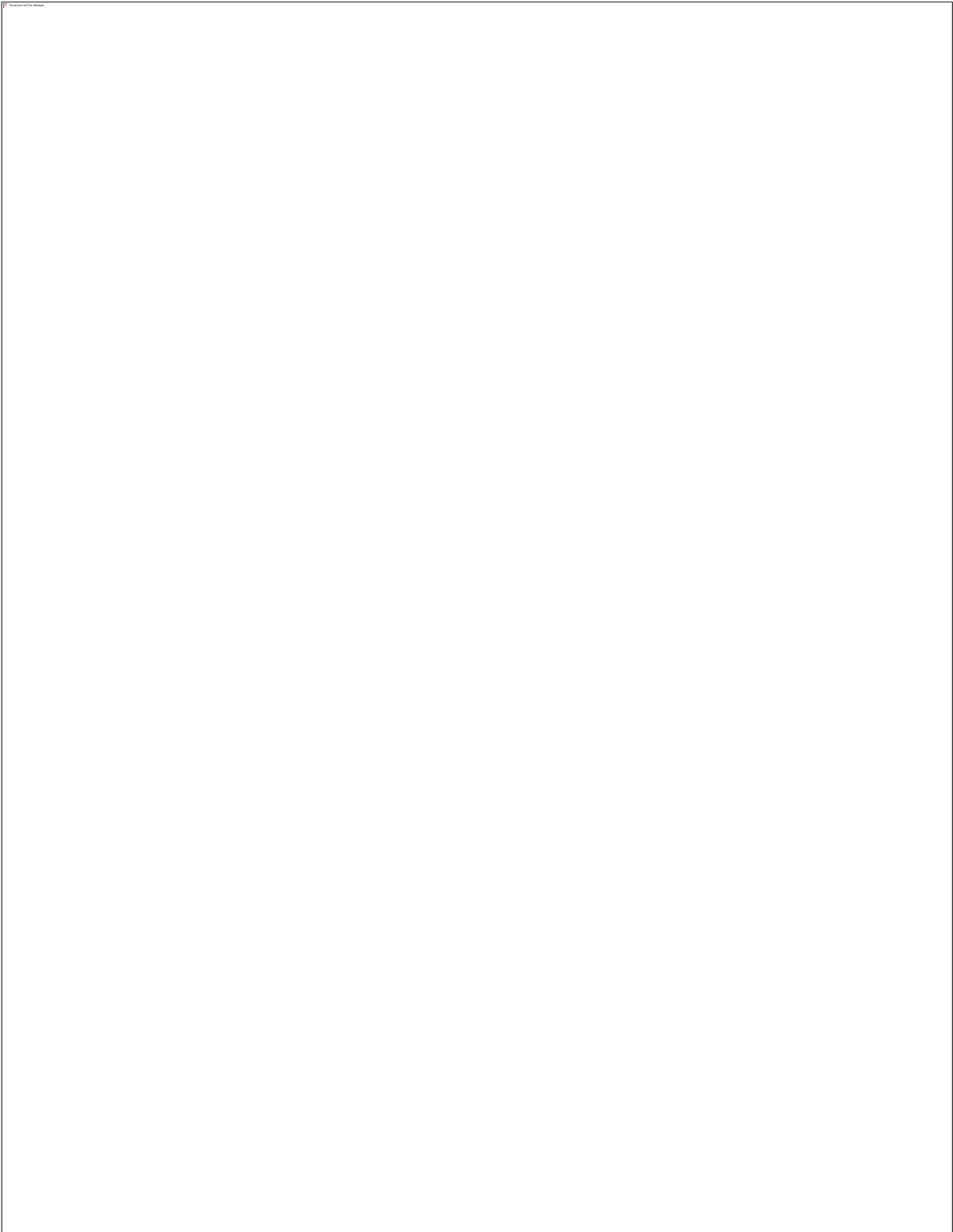
**Appendix F: CAD drawing isometric view of prototype**



**Appendix G: Hand Calculations for Spring Stiffness**





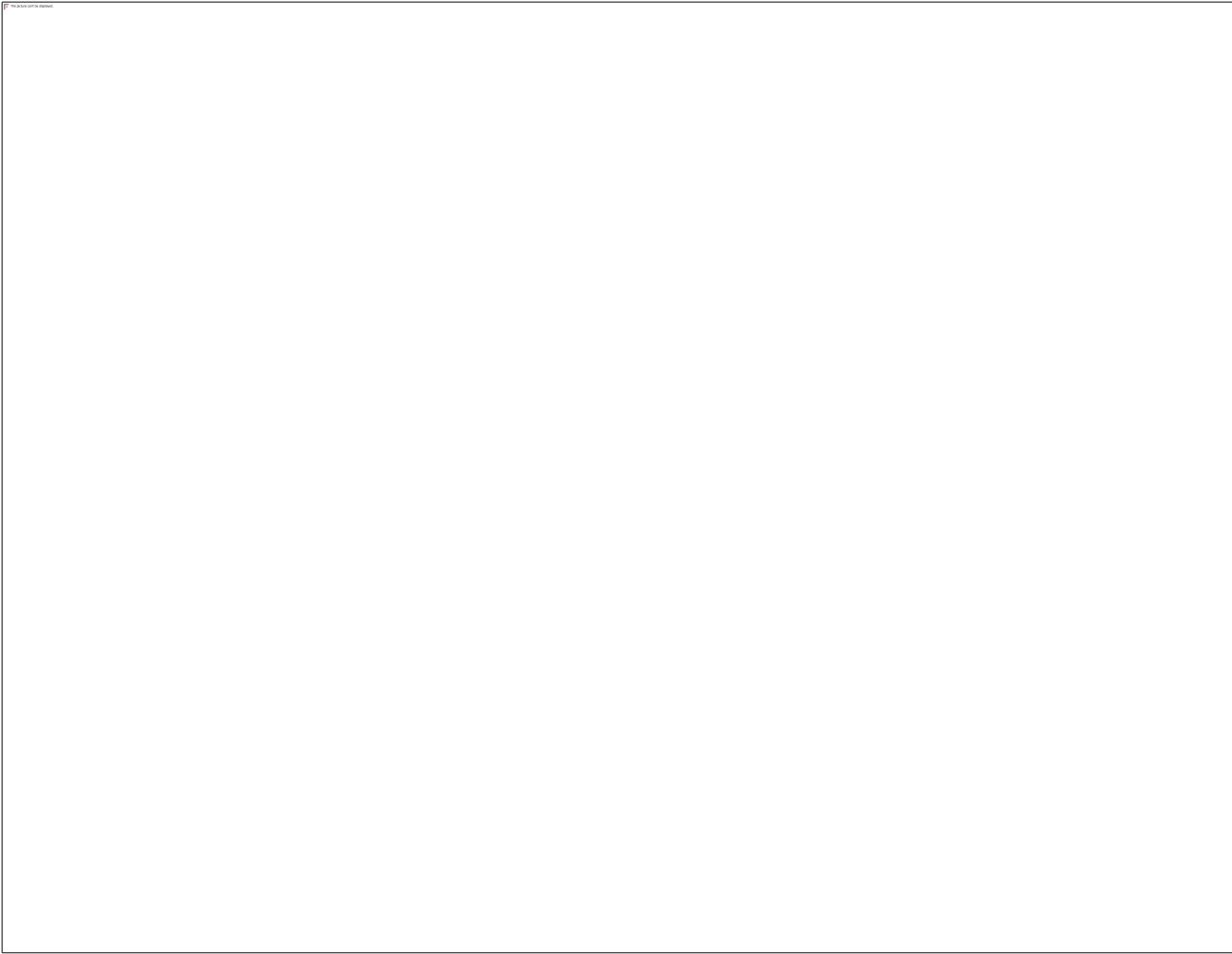


**Appendix I: Drawing Package**

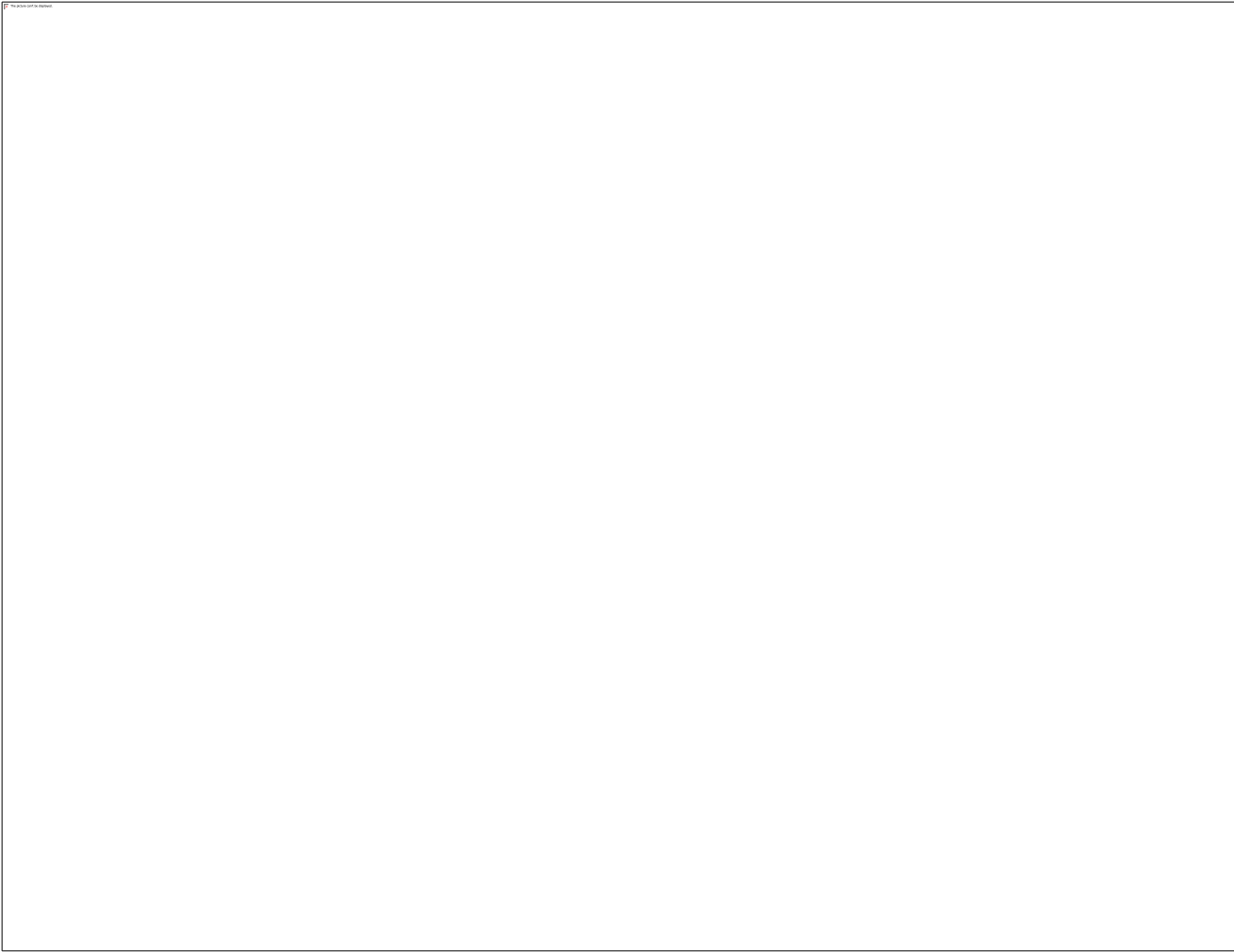
Appendix I-1: Indented Bill of Material



Appendix I-2: Exploded View of Assembly



Appendix I-3: Drawing of Top Plate (#1120)



Appendix I-4: Drawing of Bayonet Connector (#1110)





Appendix I-5: Drawing of Bushing (#1130)



Appendix I-6: Drawing of Industrial Pin (#1210)



Appendix I-7: Drawing of Jounce Bumper (#1230)



Appendix I-8: Drawing of Bottom Plate (#1310)



## Appendix J: Failure Modes & Effects Analysis (FMEA) part 1

Failure Mode	Effect	Severity	Occurrence	Detection	RPN	Control Plan
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**Failure Modes & Effects Analysis (FMEA) part 2**

A large, empty rectangular box with a thin black border, intended for conducting a Failure Modes and Effects Analysis (FMEA). The box is currently blank, providing space for the user to input their analysis.

**Appendix K: Design Verification Plan (DVP)**



**Appendix L: Project Management Gantt Chart**



**Figure R.1:** Printed out project management Gantt chart.

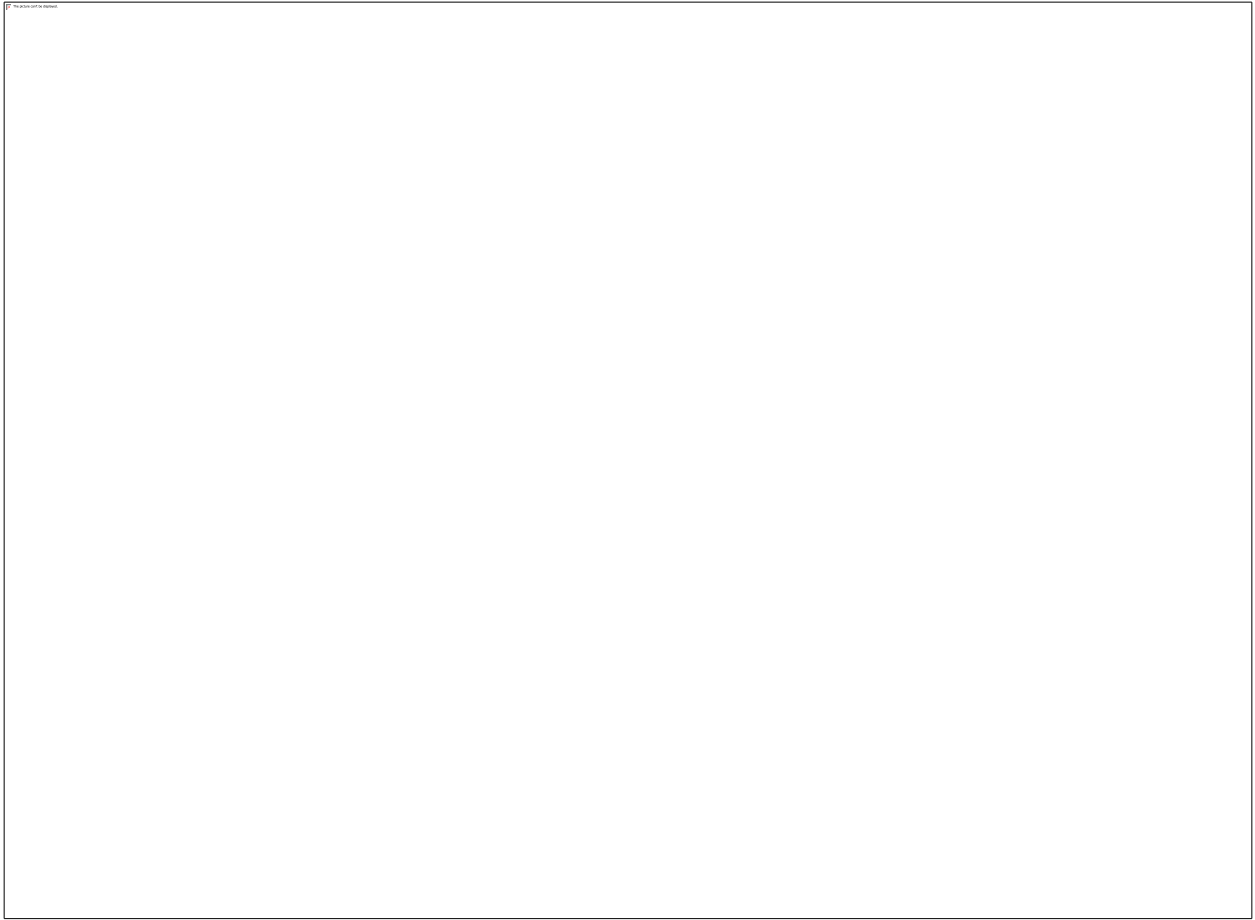




**Figure R.2 Continued:** Printed out project management Gantt chart.



**Figure R.3 Continued:** Printed out project management Gantt chart.



**Figure R.4 Continued:** Printed out project management Gantt chart.

## Appendix M: User Manual

### Hazards and Required PPE

There is no PPE equipment that is required to operate the robot modular attachment system. Potential safety hazards include pinching of hands and fingers as well as hair or loose clothing getting caught when operating the robot modular attachment system. When attaching the two halves of the bayonet locking mechanism, they first get pushed together, compressing the bushing inside the bayonet locking mechanism that is welded to the top plate as shown in Figure 1. When pushing these together, it is important to be careful that hands, fingers, long hair, or loose clothing are not in-between the two halves of the bayonet locking mechanisms as this will cause pinching of the hands and fingers and long hair or loose clothing to be caught. After pushing the two halves together and compressing the bushing, the bayonet locking mechanism that is welded to the attachment in use will be turned clockwise to lock the two halves together. While turning, it is important to make sure that hands, fingers, long hair, and loose clothing are not on the rails where the sliding takes place or pinching of the hands and fingers and long hair or loose clothing getting caught can occur. The rails can be seen in Figures 1 and 2. Proper hand placement for attaching and detaching the attachment system are shown in Figures 3.

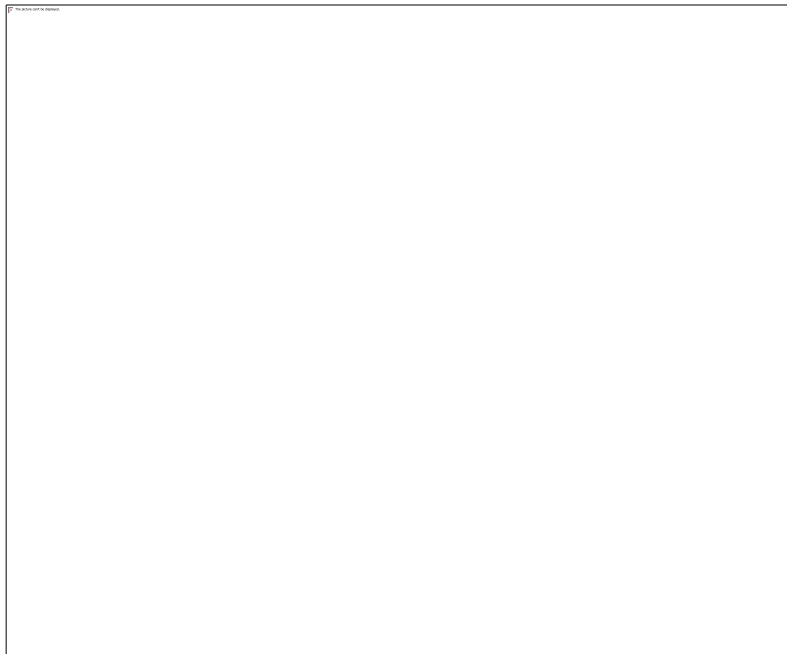


Figure 1

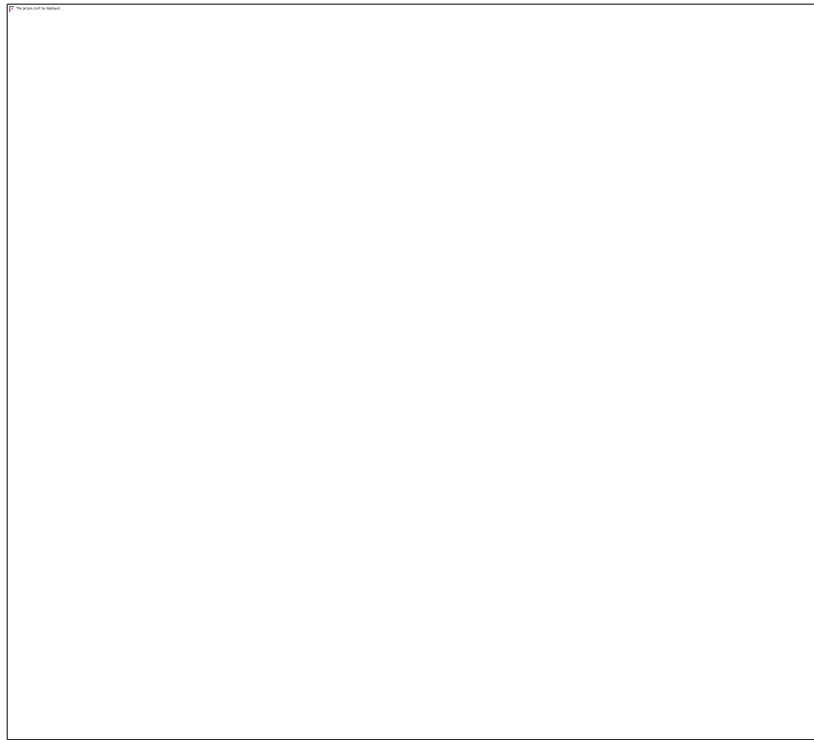


Figure 2

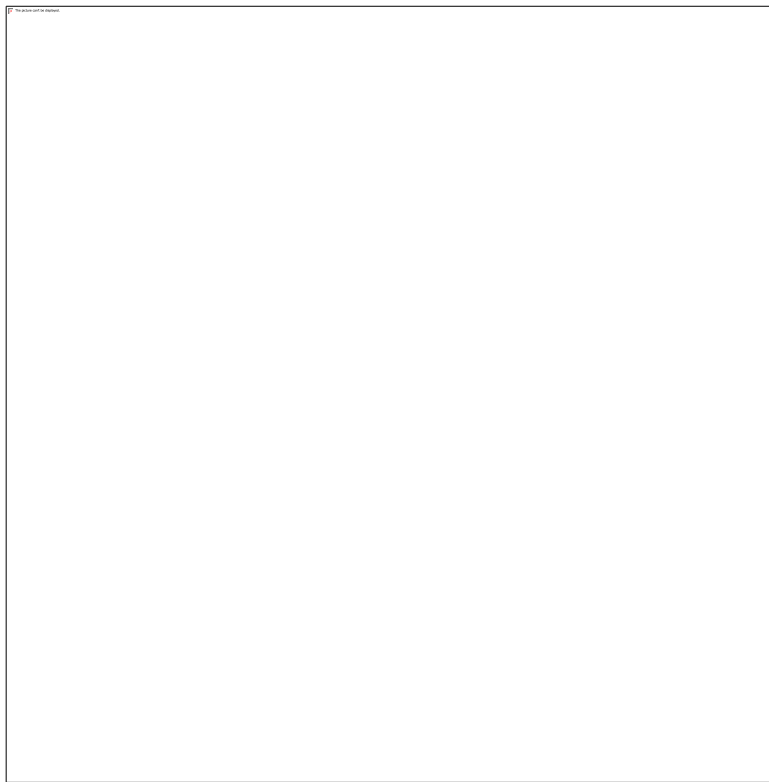


Figure 3

## Operational Steps

The modular attachment system shall function as a stand-alone system. The only operational steps for an operator to complete is attaching and detaching the variety of attachments via the bayonet connector pieces. This process is outlined as follows:

1. Align the bayonet connector on the attachment with the insert slots on the chassis bayonet connector.
2. Ensure the connectors are clear of all debris, hair, loose clothing, or loose appendages. Press connectors together until the overhangs of the fins are passed the singular locking thread notch. Here, ensure that there is a tight compression between the bushings and a solid electrical connection through the system onto the attachment. Avoid pinching fingers.
3. While the connectors are firmly pressed together begin to turn and lock the connectors into place. Turn the attachment bayonet connector all the way clockwise until the fins lock into the thread notch and touch up against the next fin.
4. With all fins locked and engaged, the connectors can be released, and the system should be rigid and operational.
5. Repeat these steps in reverse order when removing an attachment.

## Repair Procedures

There are two components that could lose their effectiveness through wear and tear. The first component is the jounce bumper, and the second component is the bushing. In order to replace these components please use the following steps.

**Jounce Bumper:** If the jounce bumper split/failed, one repair solution may be:

1. Use a chisel and hammer to separate the epoxy from the top and bottom plates while leaving it connected to the broken jounce bumper.
2. Remove the nuts using a crescent wrench and slide the top plate off the industrial pins.
3. Remove the jounce bumper from inside the industrial pins.
4. Use sandpaper to remove any leftover epoxy still attached to the top and bottom plates.
5. Place new jounce bumper inside the four industrial pins making sure that the hole passing through aligns with the holes in the top and bottom plates.
6. Place the top plate back over the industrial pins and screw the nuts back on so threads are showing above the nut.
7. Use epoxy to seal the circumference of the jounce bumper to the top and bottom plates, making sure that there are no gaps in epoxy. Let epoxy set for 24 hours to achieve maximum strength.

**Bushing:** If bushing cracks or comes loose

1. Use a screwdriver to pop the bushing out of the bayonet locking mechanism. This will require force as the bushing is sealed with epoxy to the bayonet locking mechanism.
2. Use sandpaper to remove any leftover epoxy in the bayonet locking mechanism.
3. Use epoxy to seal the new bushing into the bayonet locking mechanism, making sure that the hole through the bushing aligns with the hole in the top plate. Let epoxy set for 24 hours to achieve maximum strength.

**Part Required for Repairs:**

- Hammer
- Chisel
- Sandpaper
- Epoxy
- Crescent Wrench
- Screwdriver
- Jounce bumper
- Bushing

**Recourses for Help**

For help with ordering parts and unclarity in operating and repair procedure please contact Blueline Robotics. Reasons to call Blueline Robotics may include: the top plate being unable to freely slide over the industrial pins, the bayonet locking mechanism was received damaged or not whole, or the seals around the jounce bumper and bushing are broken.

- Resources: Blueline robotics
- Troubleshooting guide:
  - Checking that the top plate can slide up and down pins to make sure pins are aligned
  - Checking the bayonet locking mechanism is whole and undamaged, ie. if something warps it may not detach.
  - Check to make sure there's no water inside the locking mechanism/ the epoxy seals are undamaged ie if there's water damage it might hurt the electronics

## Maintenance Guidelines

- Checking the epoxy seals around the jounce bumper and bushing every two months to make sure the seal is intact and reapply epoxy if needed.
- Make sure that when the no weight is applied to attachment system the paint lines on the nuts match those on the top plate. Use a crescent wrench to adjust if needed.
- Inspect the jounce bumper for cracks every two months and replace the jounce bumper if any cracks are visible.
- Inspect the fins on the bayonet connectors for fatigue or cracks every 2 months.
- Ensure wiring and electrical connections are always intact.