SPRING LOADED CAMMING DEVICE

Final Design Review

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Statement of Disclaimer

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Abstract

Spring loaded camming devices or "cams" are used in traditional rock climbing as a means of active fall protection. Climbers place cams in cracks and fissures in the rock wall. The cam's lobes press against the walls, locking it in place, anchoring the climber in case of a fall. Currently, there is a lack of large cams on the market. Only two small companies produce cams that are usable in cracks 6.5 inches wide and larger, however their designs are either too heavy and/or lack features to be comfortable. We are a group of mechanical engineering students at Cal Poly San Luis Obispo, and at the beginning of this project we aimed to design, manufacture, and test a large active fall protection device that improves on the currently available designs. Primarily, we wanted our design to be lightweight, strong, and have a semi-flexible stem. Due to the COVID-19 outbreak and campus closure in March 2020, we were forced to adapt and modify our goals to be achievable while we continued to work remotely. Since we did have access to Cal Poly facilities, we built a single camming device instead of the planned ten and were unable to tensile test the final cam. Even so, we feel that the testing results obtained from this prototype will be able to guide future iterations. The Final Design Report summarizes the background and market research we conducted, explains our objectives of the project, outlines and justifies the design concept, describes our final prototype and how we manufactured it, and details the formal testing procedure required to validate our calculations as well as provides recommendations for moving forward. We found that the prototype met all specifications but for the weight limit. It costs less than $130 per cam to manufacture, is usable in the targeted 6-9 inch range of rock crack widths, and has a flexible stem as requested by the climbing community. The final weight of the cam is 1135 g, which is a bit above our maximum desired weight of 900 g. We are confident that this design has the capability to take significant weight off the design with continued tensile testing.

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1 Introduction

Traditional (trad) climbing is a style of rock climbing in which the climber carries and places protective equipment to secure them from hitting the ground, and then removes all gear when they complete the route. These types of climbs are done outdoors on natural rock walls, where no preset bolts exist. We focused on active protection devices, which must be actuated by the user. Active devices are placed into cracks and holes in the rock. The end in the crack expands to press against the walls of the rock, while the other end clips to the climber's rope. An example of an active device is a spring-loaded camming device (cam), shown in **Error! Reference source not found.**., which consists of multiple lobes that rotate inwards while the device is being placed into the crack and expand to the size of the crack once the climber releases the trigger.

Figure 1. A typical spring-loaded camming device being used to anchor this climber to the rock in case they lose their grip. [1]

Smaller camming devices typically have a flexible stem between the anchoring lobes and the climber's rope to allow the device to bend around edges of rocks without causing permanent deformation or breaking off. The current trad gear market lacks large camming devices for cracks that the climber can fit their entire body into and are also a high enough quality where the climber can feel confident in their safety. Current designs are cumbersome, heavy, and/or lack a flexible stem, making climbing harder and placement options more limited. Therefore, our goal for this project was to design, build, and test a product that improves upon previous large protection devices. Specifically, we aimed to produce a lightweight, strong, and flexible cam that can be used for large cracks. This project is being externally sponsored by Myles Wittman, a Production Manager at Outdoor Research, who is also a passionate rock climber.

The Final Design Review is divided into eight sections:

Background
In the Background section, we summarize the research we conducted during in the ideation and initial design phase. This includes insights from interviews with rock climbers, an analysis of current products and patents, a collection of technical articles detailing the different aspects of spring-loaded cam design and testing, and rock-climbing industry standards that our design must comply to.

Objectives
Here we state and detail the goals and deliverables of the project. We address the specific problem we aim to solve, the wants and needs of the climbing community, the Quality Function Diagram (QFD) process, as well as our design specifications and how we are measuring them.

Concept Design
In the Concept Design section we detail our final design concept and the controlled convergence strategies and thought processes we used to formulate it.

Final Design
Here we walk through our final design description and analysis by component. This section also includes cost analysis for our verification prototype.

Manufacturing
In the Manufacturing section we outline the machining and assembly processes of the subassemblies, the total cam assembly, and provides our recommendations.

Design Verification
In the Design Verification section we have detailed all testing procedures that are necessary to verify functionality of the cam.

Project Management
In the Project Management section we discuss the path taken to complete the project. It also highlights unique manufacturing and prototyping methods used and lists all purchases made.

Conclusions
In the Conclusion we reflect on our achievements and shortcomings, discuss what we learned, and give our recommendations for the continuation of this project.

2 Background

The background section summarizes the market research we conducted. It is important to thoroughly understand the desires of rock climbers, our target audience, for their protective equipment. Therefore, we interviewed our rock climbing peers and more experienced trad climbers to determine their opinions of the large cams currently available. We also gathered information on company patents that are potentially useful as well as related research other engineers have completed.

2.1 Summary of Meeting with Sponsor

Mr. Wittman is a Cal Poly Mechanical Engineering alum working in Los Angeles at Outdoor Research. He is very passionate about climbing and has experience in placing large gear when trad climbing. He also owns a lot of active protection gear and uses it frequently.

During our first meeting with Mr. Wittman, we agreed that the current market lacks ideal pieces on the market to be used for protection against large cracks. He requested that we build as many initial prototypes of the cam as possible, and also provided useful feedback for what he likes about the gear that he owns; he prefers for his gear to have adjustable webbing that he can clench between his teeth while he adjusts his holding position on the wall, to have a locking mechanism so that the piece is not fully splayed out while he carries it up the pitch, be as lightweight as possible while providing a sturdy hold, and to have a good friction pattern machined on the outside of the metal lobes [2].

2.2 Summary of Interviewing Climbing Colleagues

To better understand the wants and needs of a range of climbers, we interviewed a handful of friends who frequently use traditional climbing gear. The information that we gathered from these interviews was very interesting and may lead to a shift in the focus of our design. One design consideration that we considered to be critical was the stem flexibility; however, the climbers that we interviewed considered the flexible stem to be non-critical. They instead focused on ergonomics, a locking mechanism that can be locked and unlocked with one hand, overall size, weight, and the cams usable range [3], [4], [5], [6], [7]. To better understand our customer wants and needs we will conduct a survey and a series of focus groups throughout our product development. This will help us narrow down our design considerations and develop a better product.

2.3 Survey to Target Market

We distributed a survey to rock climbers at the local climbing gym to get a better idea of the wants and needs of our specific audience, because trad climbing is so specific. We sent the survey to our own climbing peers as well as asked the local climbing gym to post it on their social media account. We got a total of 32 responses from people, 13 of whom are primarily trad climbers who seek off-widths. Most people do not seek out trad climbing more often than any other form of climbing. The range of experience of our audience was very wide, varying from one year to twenty years. We asked the participants what mattered most, to them, when selecting active protection. As can be seen graphically in Figure 2, most people would prioritize strength before weight when purchasing a piece and would prioritize holding power over durability.

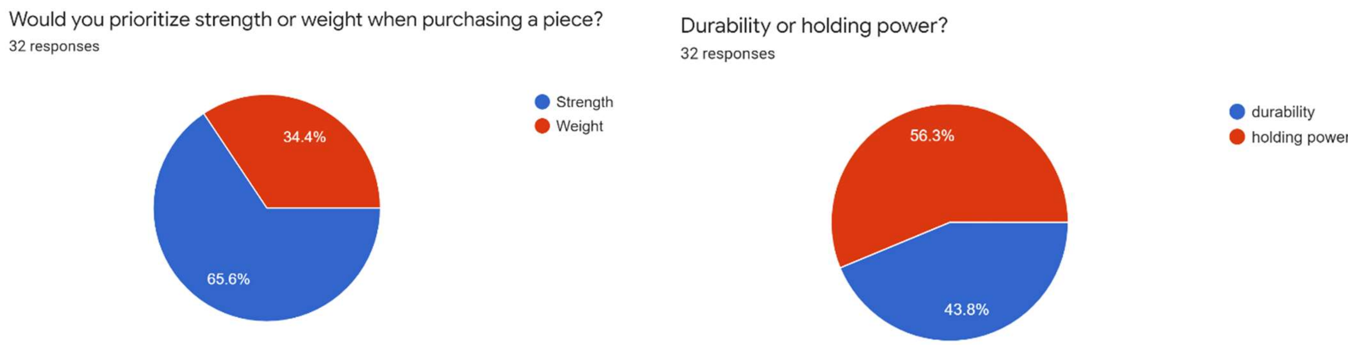


Figure 2. Graphical summary of the specification priorities of the target audience.

Multiple people mentioned that it is crucial to have a camming piece that is easy to use because the climbers experience extreme fatigue in their arm muscles during long routes. In general, smooth deployment and quick insertion into cracks makes for a good device.

2.4 Discussion of Existing Designs

To understand the current market environment and advances in the technology of rock-climbing protection devices, we researched existing designs and patents on similar devices used for fall protection. Significant results from the design search are shown in Table 1, while the patent search results are shown in Table 2. Many companies have patents on specific features of their cams, so we need to be cautions not to implement features that have been previously patented in case we would like to market and sell our final design. Table 3 lists the current standards that are regularly adhered to for similar products.

Table 1. Current products on the market.

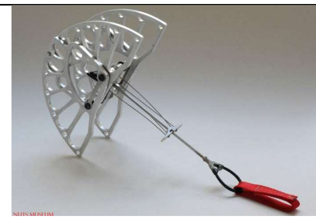
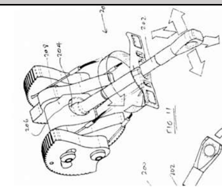
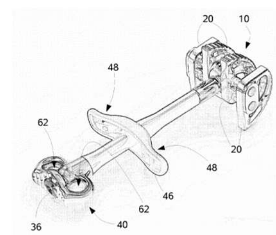
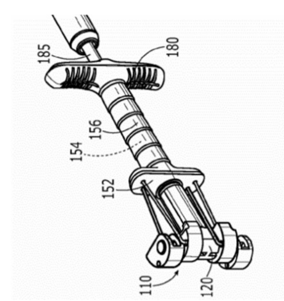
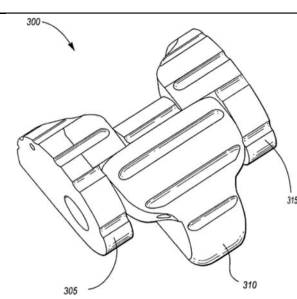
Company Name	Product	Description	Picture	Reference
Valley Giant	VG9	• Large camming device with flexible, u-stem and single-axle • Rated to 18kN • Range of 6-9 in. • Weighs 920 grams.		[8]
Merlin	8	• Large camming device with rigid, single stem and double-axle design. • Rated to 9 kN. • Range of 6-9 in. • Weighs 570 grams.		[9]
Black Diamond	C4 Camalot #6	• Large camming device with flexible single stem and single-axle design. • Rated to 14 kN. • Range of 4.5-7.7 in. • Weighs 530 grams.		[10]
Trango	Big Bro #3	• Large expandable tube chock • Rated to 12 kN. • Range of 7.5-12 in. • Weighs 338 grams.		[11]
Kong	Gipsy #6	• Large triangular folding cam • Rated to 18 kN. • Range of 4-8 in. • Weighs 488 grams.		[12]

Table 2. Table of patent search results

Patent Name	Patent Number	Key Characteristics	Drawing	Reference
Camming Devices	US 6,679,466 B2	• 4 lobe Wild Country Cam • Double-axle cam with slots to prevent over rotation • Stem can rotate about the lobes of the cam		[13]
Protection device for use in climbing	11152652.1	• 4 lobe DMM Cam • Double-axle with bias springs to keep cam in extended position • Steel cable stem wrapped in plastic sleeve • Concave plastic trigger activation bar		[14]
Camming Device Stem	US 9,302,154 B2	• Black Diamond camming device • Steel cable stem • Retraction sleeve nested within independent sleeves to protect from wear • Also allow retractions even when under an outside load.		[15]
Active Camming Device Surface	US 7,275,726 B2	• Black Diamond Camming surface • Both concave and convex faces of the lobes • Non flat camming surfaces increase stability • Provide increased connection points with the rock		[16]

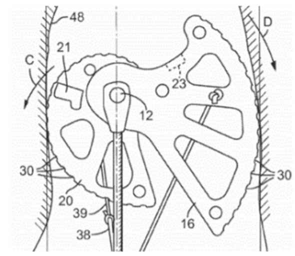
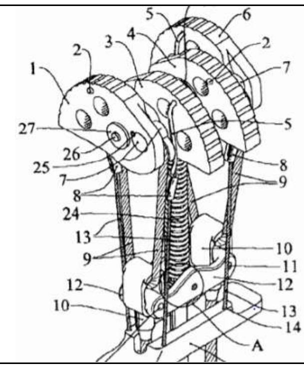
Patent Name	Patent Number	Key Characteristics	Drawing	Reference
Mechanical Climbing Aid of the Cam Type	US 7,802,770 B2	• 4 Lobe Metolius Mountain products cam. • Asymmetrically sized cams to reduce interference between cam lobes • Logarithmic spiral shaped cam lobes • Single-axle cam with a U-shaped stem		[17]
Cam Device for Climbing	US 7,014,156 B2	• 4 Lobe single-axle Totem Cam • Load generated by falling acts on the lobes instead of the shafts • Each set of two lobes are individually rated for falls		[18]

Table 3. Industry Standards

Organization	Safety Standard Number	Description	Reference
UIAA	UIAA 125	The UIAA is the leading standard for climbing gear. UIAA 125 applies specifically to frictional climbing anchors such as cams. A certification body that uses the EN 12276:2013 standard.	[19]
European Standards	EN 12276:2013	The European Standards for climbing gear. Development of this standard was made in conjunction with UIAA 125. This is the standard to use when testing.	[20]
CE	N/A	A certifying body for products that meet health and safety standards that are to be sold in the European Economic Area (EEA).	N/A

2.5 Relevant Technical Literature

Since rock climbing is not a widespread sport, and crack climbing is even more niche, it was somewhat difficult to find technical articles directly related to spring loaded camming devices. When we were unable to find articles related to rock climbing and camming devises, we attempted to find analogous research in other engineering fields. We focused on four areas of interest: methods of testing the strength of the cam, friction analysis, methods to inhibit buckling in the stem, and the mechanics of spring-loaded camming devices.

Cam Strength Testing

The Safety of Rock Climbing Protection Devices Under Falling Loads describes the method that a team from the University of Bath used to test the strength of climbing anchor nuts under falling loads [21]. The team set up a testing rig comprising of an anchor bolt held up by support jaws and a weight which drops using a release mechanism. A load cell connects the weight and the anchor and monitors the force experienced by the anchor bolt during the drop process. The research team tested multiple weights, fall factors (the ratio between the rope length and the fall height), whether consecutive drops influence the anchor nut's strength, as well static loading tests using an Instron tensile testing machine. They found that the anchor nuts often failed just beyond their rated loads and failed by either the steel rope ripping or the upper wall shearing.

Testing of Rock Climbing Anchors discusses the current faults in the testing of chemically-bonded rock climbing anchors in soft rock [22]. In accordance the European Standard EN959 the current method is setting an anchor within a concrete block, fixing the block in place, and loading the anchor in both shear and in tension. The authors argue that the concrete does not act like the rock found on most outdoor climbing walls and the current standards are geared towards mechanical anchors, not chemically bonded anchors. They suggest creating cylindrical concrete tubes with imbedded rock. The anchors are set in the center of the rock. The researchers found the results more realistic to previous field tests.

Friction Analysis

Hughes Gauge: a new method for measuring coefficient of friction aims to improve on current methods of measuring friction, such as the drag sled [23]. The problem with the drag sled is that the towing force will never be in co-planar with the friction, causing a moment and changing the force distribution in the contact patch. Instead, Hughes intends to correct this shortcoming by leaning into it and using an object's tipping point to determine its coefficient of friction. In concept, if one can find the tow height between the object sliding and the object tipping, coefficient can be determined. We may use this method to determine which lobe pattern has the greatest coefficient of friction.

Inhibit Stem Buckling

In *Novel Design of Valve Stem to Eliminate Buckling,* a team of engineers found that valve stems were buckling under load and getting jammed [24]. To solve the problem, they designed the valves to contain cavities allowing the stem to bend elastically while still maintaining its strength. The team used iterative simulations in ANSYS to finalize the design.

Rock Climbing Camming Device Mechanics

Although not a scholarly article, *An Elastic Model of Holding Power of Spring Loaded Camming Devices Used as Rock Climbing Anchors*, *CAMS-A Technical Review*, and *Totem Cam Mechanical Principles* are too valuable of resources not to mention [25], [26], [27]. The webpages walk through the basic physics behind camming devises, including how to calculate the cam's contact area and the maximum force before a cam shears out of the crack, providing us a head start on our design analysis.

3 Objectives

The Objectives section formally defines the problem that we intend to solve as well as the criteria we intend to use to assess the validity of solution concepts and designs. In addition to quantifying the desires of the target audience, this section defines the extent of the product which we aim to design and build and to quantify the design specifications. We found it critical to define the scope of the project before proceeding to the concept design phase as it is easy to lose sight of our objectives during the ideation and prototyping.

3.1 Problem Statement

Rock climbers need a versatile protection device that can be carried and placed in cracks as they climb up the wall, but the current market lacks devices that are both easy to place and lightweight. Therefore, our goal is to make an active rock-climbing anchor that improves upon the current designs. We aim to design, construct, and test a camming device for use in large cracks that is lightweight, strong, and comfortable for the climber to use.

3.2 Boundary Diagram

The boundary diagram shown in Figure 3 shows what we aim to include in the design of this project.

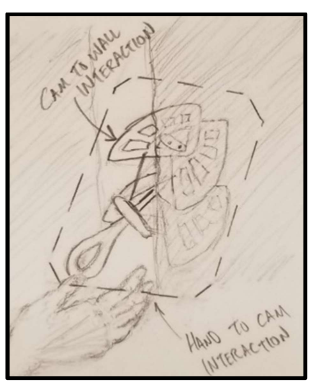


Figure 3. Boundary diagram which shows the scope of the project.

Important things to note are the interaction between human and machine; the device is actuated by the user pulling a finger trigger which moves the cam against the resistance of a torsional spring. Another key interaction is that between the camming lobes and the rock wall. The frictional patterns on the outside of the lobes contacts the rock and creates an outward and downward force against the rock, which in turn exerts an equal and opposite reaction to protect the climber against falls.

3.3 Wants and Needs

To completely understand the problem, our team considered the wants and needs of the customers of this product. First, we compounded a list of customers which included rock climbers, manufacturers, and any retailer or company that would sell this device. For each of these customers we brainstormed the wants and needs of each group for the product, as shown in Table 4.

Table 4. Customer Wants and Needs.

Wants/Needs	Explanation
Lightweight	The device needs to be lightweight or a rock climber might decide not to use it and instead leave in on the ground.
Large Usable Range	Because every rock and crack are different the usable range must be large to allow a wide variety of uses in different cracks.
Flexible Stem	When the device is put in a crack the stem may be bent around the edge of the crack and the device cannot permanently deform with this bending.
Bite-able	When taking the device off the harness and putting it into the crack the device must be able to be put in the mouth to adjust hand placement so placing the device is possible.
Locking mechanism	While on the harness a rock climber wants the device to lock into its smallest position, so it does not get in their way while they are climbing.
Durable	The device muse be durable to have a long life and make sure the it does not fail after a singular use.
Holding Power	The device must be “confidence inspiring,” such that the climber feels comfortable taking a fall with the device protecting them.
Affordable	The device must be affordable for a climber or they would not purchase and used the device.
Ergonomic	The device must be comfortable and easy to use to make placing it as easy as possible in dangerous situations.

3.4 Design Specifications

We will compare and test our designs using the specifications presented in Table 5. We identified three high-risk specifications: the cam's tensile strength, the cam's weight, and buckling resistance of the stem. The primary design challenge of the project is to balance creating a cam strong enough to inspire user confidence, but also light enough so it is not overly taxing to climb with. Since the two specifications are in direct competition, we determined them to be high risk. The stem bending is also a high-risk specification because the stem needs to be long enough to accommodate the full range of motion of the trigger mechanism, which is longer than a typical camming device due to the cam's larger range. However, the risk of buckling increases with the length of the stem. Once again, we have conflicting specifications, and we will need to perform analysis to best optimize the two. We chose to not adjust these high-risk parameters to keep our product competitive and marketable.

Table 5. Specifications Table

Spec Number	Specification Description	Requirement/ Target	Tolerance	Risk	Compliance
1	Tensile Strength	14 kN	Min	High	Testing, Analysis
2	Cost	$130	Max	Medium	Analysis
3	Weight	900 g	Max	High	Analysis, Inspection
4	Range	6-9 inches	6 inches Min No Max Limit	Low	Inspection
5	Bending Deformation	90 degrees	Min	Low	Analysis, Inspection
6	Stem Buckling	No Buckling	Y/N	High	Analysis, Inspection

3.5 Quality Function Development Process

A Quality Function Development (QFD) table was used to help quantify the importance of the project wants and needs, and their related specifications. To start the table our team listed the customers and each of their respective needs for the device. We then benchmarked other products on the market to see how well they fit the needs of the customer. We created specifications for the device and recorded the correlations between each specification. From the perspective of potential users, we ranked the importance of each customer desire on a scale of 1-

10, 10 being very important to each group of users. Using these values, a relative weight was calculated for each of the device specifications, which helped us decide what the most important design considerations are for the design of the device. The consumer wants and needs, ranked in order of importance, are tabulated along with the corresponding engineering specifications, tolerance, risk, and method of measuring compliance. According to our QFD Chart, the most important specifications to meet are the cost, bending deformation, and stem buckling targets. While we agree that cost is an important specification, we disagree that the bending deformation and stem buckling specifications are more important than tensile strength and weight requirements. The tensile strength of the cam is critical to user safety and the specification that dictated the shape and sizing of all the components. Also, if a cam is too heavy the user is less likely to bring it on the climb. Both weight and tensile strength are critical to the function of the device, while the flexible stem is not. The full QFD table can be found in Appendix A: Quality Function Development Table.

4 Concept Design

Figure 4 depicts a rudimentary SolidWorks model of our chosen concept design. The trigger and the locking mechanism lack detail in in the model. However, we created this model to better understand the relative location of the individual components of the device. The following Concept Design section walks through the process we used to generate possible solutions and choose our design direction.

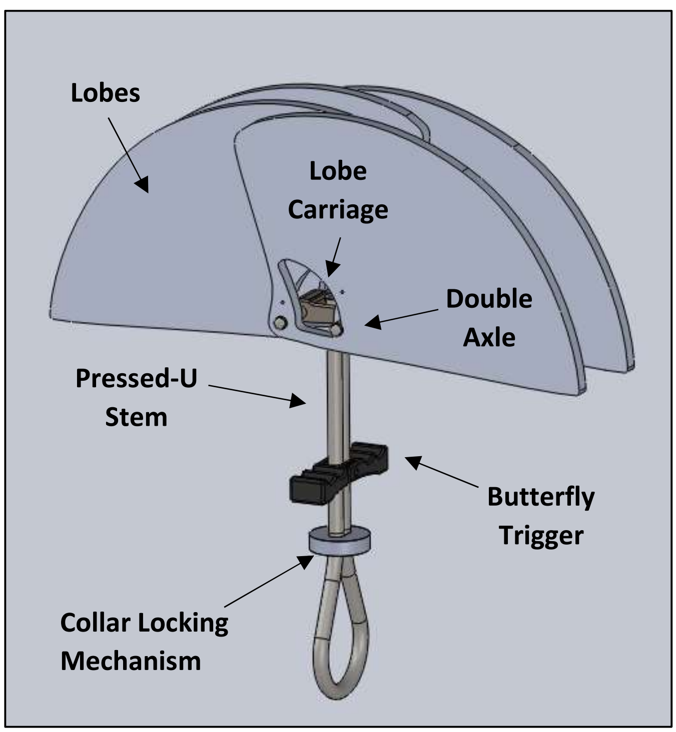


Figure 4. Preliminary CAD model of our chosen concept direction.

4.1 Ideation Process

The ideation phase was completed in three separate sessions. Our team participated in the first ideation session, which we used to develop as many ideas as possible. During this session we brainstormed ideas for individual functions of the cam, such as expanding to fit the crack and holding the climber. During the second session we developed ideas for the following components of a climbing cam: stem, locking mechanism, lobe shape, and trigger mechanism. We conducted the last ideation at the local climbing gym, where we invited climbers of all experience levels to brainstorm new ideas for the stem, locking mechanism, lobe shape, and trigger mechanism. This was very helpful because it allowed us to gain new ideas from people that would use our final product. For a full list of our ideas please See Appendix B: Idea Bank. We used the ideas from the ideation sessions to build functional prototypes, seen in Figure 5.

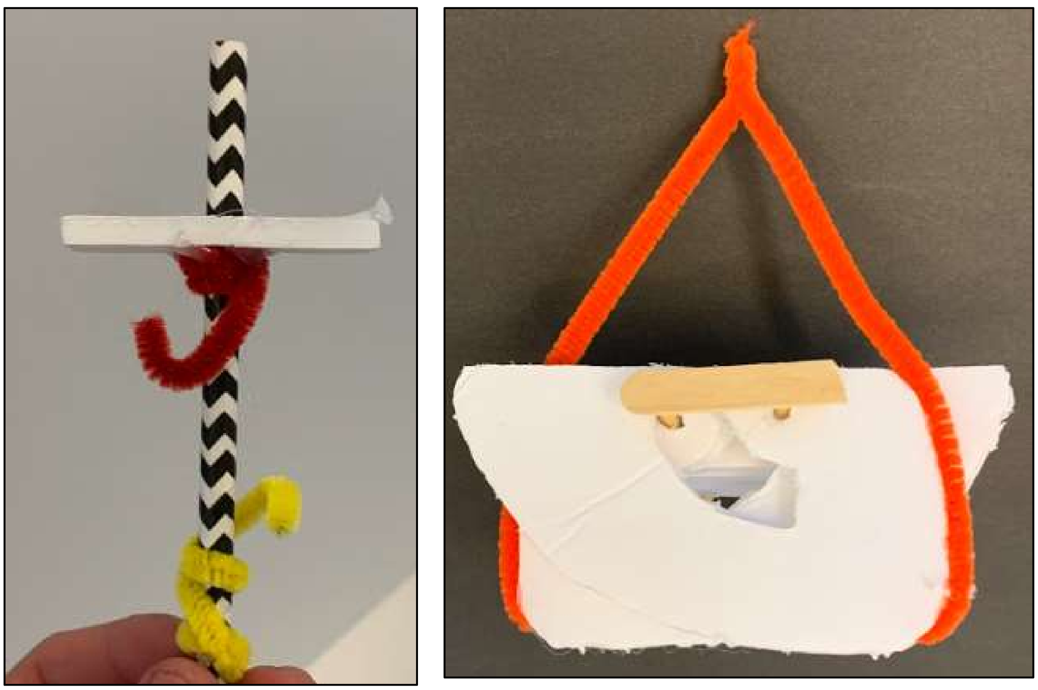


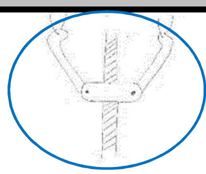
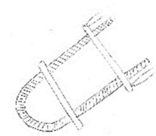
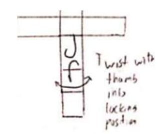
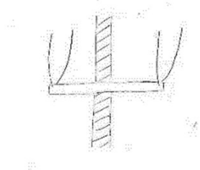
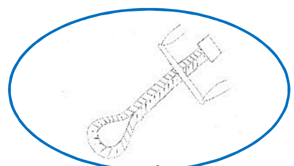
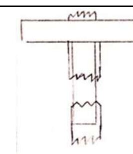
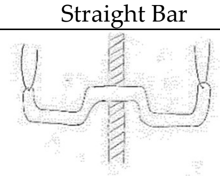
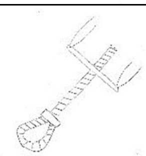
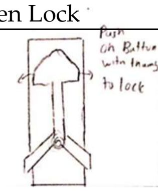
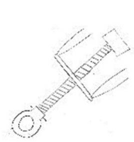
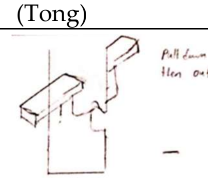
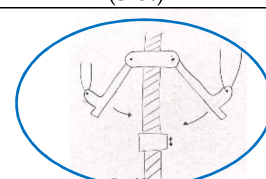
Figure 5. Two prototypes built from craft supplies. We built the prototypes based upon ideas from the ideation sessions.

The functional prototypes were made of simple materials such as cardboard, string, and hot glue. We made many prototypes with the goal of this session being to investigate the feasibility and functionality of our ideas that we had brainstormed.

4.2 Initial Concept

After compiling all our ideas from ideation, we used Pugh matrices, which can be found in Appendix C: Pugh Matrices, to help us converge upon the best ideas for each of the aspects of the cam. The Pugh matrices compare each of the ideas against a one concept set as a datum, and they are rated on how well they solve the customer wants and needs as seen in Table 4. By analyzing the outputs of the Pugh matrices, we were able to find the solutions that best solved the wants and needs for each respective part of the cam. To combine the individual component concepts into a full cam design, we used a morphological table seen in Table 6.

Table 6. Morphological Table Showing Design A Configuration

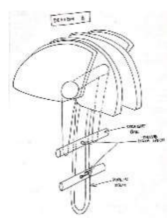
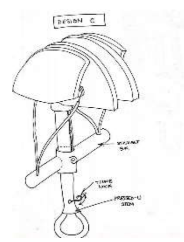
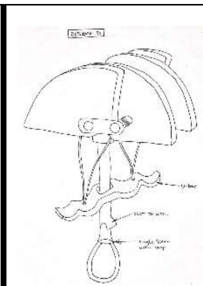
Trigger Mechanism	Stem Design	Locking Mechanism
 Butterfly Trigger	 Pure U	 Twist Lock
 Straight Bar	 Pressed U	 Pen Lock
 U-Bar	 Single Cable with Loop	 Thumb Press Lock (Tong)
	 Single Cable without Loop	 Lateral Finger Bar (Slot)
		 Collar (With Butterfly Trigger)

The morphological table allowed us to combine the best solutions from the Pugh matrices into many unique full cam designs that we could compare in our weighted decision matrix. This method yielded five top design options which we felt were the best combinations of the component concepts. The five designs that were determined using this method are the initial concepts of the cam.

4.3 Concept Selection Process

The weighted decision matrix uses the criteria and weighting determined in our house of quality to compare each concept to our customer requirements. Each of the designs was given a rating on how well they satisfy each of the criteria. The criteria weight and the ratings were multiplied together to generate a relative success of each criteria. All these normalized successes were summed for each design to decide which design meets the criteria the best. The weighted decision matrix is shown in Table 7.

Table 7. Weighted Decision Matrix

		 **Design A**		 Design B		 **Design C**		 Design D		 Design E	
Criteria	**Weighting**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**
Size	4	5	20	1	4	3	9	3	9	5	20
Ergonomics	3	3	9	3	9	4	12	5	15	3	9
Ease of Manufacturing	3	3	9	5	15	4	12	2	6	1	3
Aesthetics	1	3	3	2	2	3	3	4	4	4	4
Totals			**41**		36		**38**		34		36

We used four criteria to determine our best design: size, ergonomics, ease of manufacturing, and aesthetics. Size is the overall volume of the cam. Besides the cam's lobes, we want to minimize the size and profile the cam's triggers, stem, and carriage as to save weight and increase portability. Ergonomics is how comfortable is the cam to use. Many of the other large cams do not form to the user's hand and require the user to stretch their hands to actuate the trigger. We do not want the user to have to strain themselves while using our cam. Ease of manufacturing is a measurement of how confident we are in our ability to construct the design. We would like to keep the design as simple as possible to reduce manufacturing cost and ease maintenance. Aesthetics is the marketability of the design. Our design needs to stand out from other cams on the market, and make users feel confident in our product.

4.4 Detailed Description of Selected Concept

After completing our weighted decision matrix, we found that Design A best fit the criteria. As seen in Figure 6, Design A consists of a four-lobe double-axle lobe design which will allow for the largest expansion range of the cam. This design also has a butterfly trigger mechanism. This trigger mechanism has two trigger bars that rotate about a fixed point on the stem.

Figure 6. Drawing of Design A, which features a butterfly trigger, a pressed U stem, and a rotating collar lock.

At the end of each of the trigger bar there is a cord that connect the lobe to the trigger mechanism. When the climber pulls down on the trigger bars they will rotate, and the cam lobes will contract. The primary advantage of this system is that a small distance moved by the fingers translates into a large travel of the cam lobes. In a more traditional, translational trigger system, due to the larger lobe size, the triggers need more space to travel, requiring the user to uncomfortably stretch their hands. With the butterfly trigger, the user does not need to stretch their hand as the trigger's pivot point is stationary relative to the stem. This also allows us to reduce the size of the stem, which helps save weight and the portability of the device.

The locking mechanism on this concept is specifically designed to work with the butterfly trigger. This locking mechanism will consist of a twisting collar lock that will have slots that match with tabs on the trigger bars. When the triggers are fully contracted the tabs will slide into the slots in the collar, and the lock can be activated by spinning the collar with the user's thumb. This will offset the slots and tabs, so the lobes stay in their fully compressed state.

We built a prototype to test the feasibility of the butterfly trigger mechanism, and this can be seen in Figure 7.

Figure 7. Concept Prototype for butterfly trigger mechanism

This prototype proved that the butterfly trigger is feasible, and the following offered valuable lessons moving forward. First, we learned that the placement of the trigger along the stem will have a large effect on the comfort of the device. Similarly, the attachment points on the lobes will influence the contraction of the lobes. More prototyping will be needed to find the best positions for attaching the butterfly trigger mechanism to the cam.

4.5 Preliminary Analysis

We must conduct analysis to properly size our cam's components. These components are the axles, carriage, lobes, and the stem. The shape of the carriage and the lobes will be optimized using finite element analysis (FEA) beginning in January. To ensure that we obtain accurate FEA analysis, we needed to start with proper loading cases. Using Figure 8, we found that when a 14 kN force was applied (T) at a 13-degree camming angle (α), the reactionary force was 15.6 kN. Similarly, for a 14 kN force applied at a 16-degree angle, the reactionary force was 12.7 kN. This provides us with the cam lobe loading as well as the shear force that will be applied to the axles.

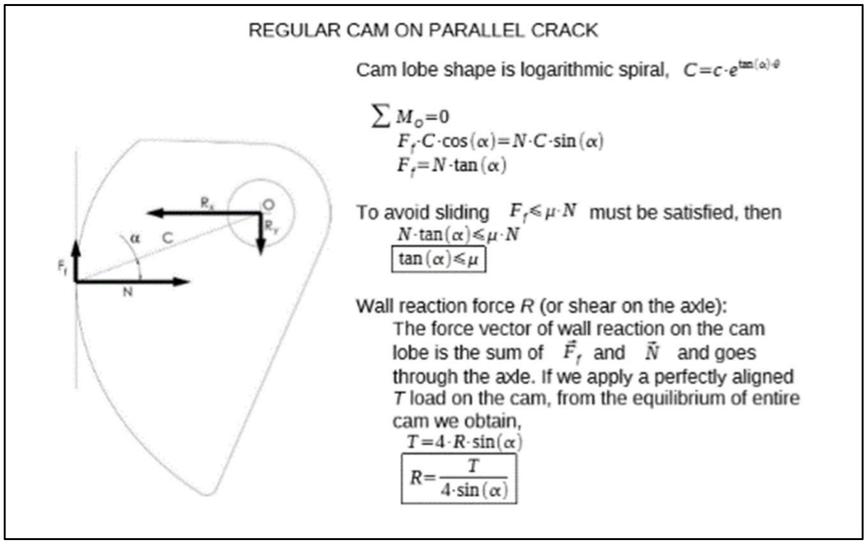
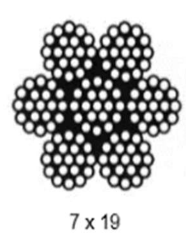


Figure 8. Calculation used to find the reaction forces acting on the cam lobes [27]

We also needed to find the minimum wire cable stem thickness. Using Figure 9, we found that a 3/16" diameter cable would be sufficient for a 14 kN (3147 pounds) loading.



Diameter In Inches	7 X 19 GALVANIZED CABLE	
	Approx. weight per 1000 Ft. in pounds	Breaking strength in Pounds*
3/32	17.4	1,000
1/8	29	2,000
5/32	45	2,800
3/16	65	4,200
7/32	86	5,600
1/4	110	7,000
5/16	173	9,800
3/8	243	14,400
7/16	356	17,600

Figure 9. Strength of wire rope based on diameter [28]

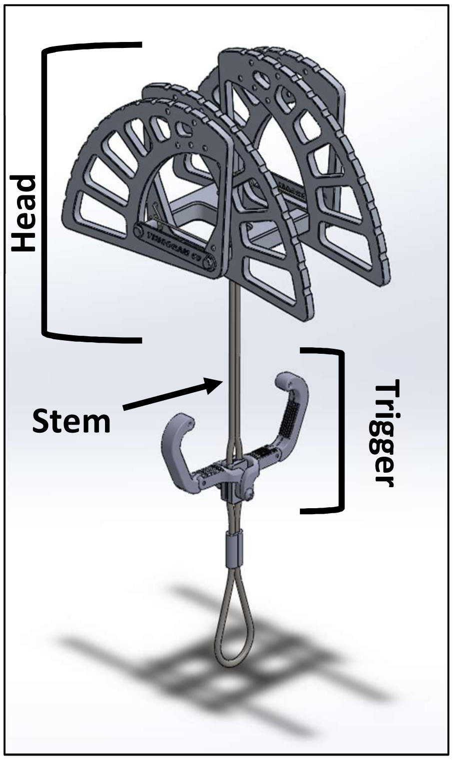
4.6 Risks, Challenges, & Unknowns

Going into this project, we knew that a major challenge of the cam would be that we would need to use Finite Element Analysis (FEA) heavily during the detailed design of the lobes. We aimed to make the lobes as lightweight as possible while maintaining the 14 kN strength specification. We learned how to use Abaqus to perform FEA in tandem with the timeline of this project. We also anticipated the need to design a custom fixture or jig for tensile testing.

In terms of risks that would affect the user, we acknowledge the risk that is posed to the climber when they are using this device. While our primary goal is to keep the climber safe while they are placing the gear, the climber does accept a risk when they decide to take on a trad route. Aside from the obvious safety hazard here, other possible risks to the user are that it is possible that they could pinch their fingers between the rotating cam lobes, that the spring being too stiff could prevent the user from being able to actuate the trigger during a climbing route if their arms are fatigued, and that if the device is improperly placed the cam can fail to hold them under the impact of their fall. All these safety risks mentioned will be made very clear to the user of this device using the instruction manual that we intend to produce by the exposition. These safety risks are tabulated in Appendix D: Design Hazard Checklist, after the completion of a hazard checklist is documented.

5 Final Design

The design of the cam is a two-axle carriage with four contracting/expanding lobes and a dual rotating trigger mechanism. We used mechanical analysis to justify the sizing and material choice for the structural components, but many of the ergonomic components cannot be justified with analysis alone. For this reason, we tested our prototype for ease and comfort of use, but because of the delays and closures due to COVID-19 we were not able to implement any of the findings from our ergonomic tests. The complete cam SolidWorks model as well as the manufactured cam is shown in Figure 10.



(a)

Figure 10 (a). Final Design Assembly
Note: Trigger Cords not Pictured

(b)

Figure 10 (b): Manufactured Final Cam

The cam consists of three subassemblies (the head, stem, and trigger subassemblies) connected at one main junction (the carriage). The head subassembly consists of the lobes, axles, springs, axle linkages, and fasteners. The stem subassembly consists of the stem, stem cap, and sleeves. The trigger subassembly consists of the triggers, fasteners, and trigger cord. Figure 11 illustrates the position of the head and the triggers during different stages of activation.

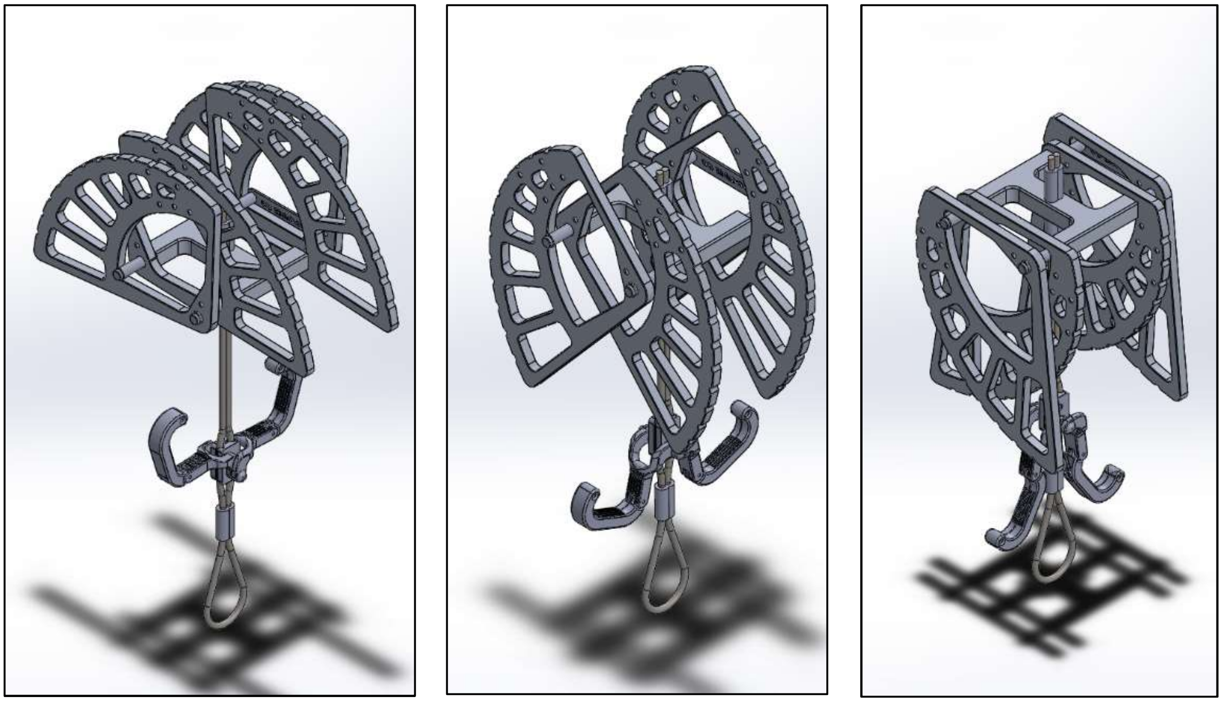


Figure 11. From Left to right: unactuated, partially actuated, fully actuated

The lobes are machined from 6061-T6 Aluminum and pivot around the axles which are turned down to size from 17-4 PH stainless steel stock. Torsional steel springs maintain the expanded position of the lobes when the device is not actuated and sits on the axle along with snap rings to maintain the axial position of the lobes. The carriage houses the axles as well as the wire cable stem. A future goal of ours is to is to cut out as much weight as possible from the carriage while meeting the structural requirements for the cam. Moving forward, the exact geometry of the carriage would be guided using analysis from FEA. The stem, which is made of 3/16" 1x19 Stainless Steel Aircraft Cable, is crimped on both sides of the carriage using swages. The triggers activate the lobes via 2.75 mm accessory cord that are glued into the lobes.

5.1 Lobe Design and Analysis

Camming devices that are on the market are cut to have a logarithmic curve, and significant research exists to support that there is no reason to deviate from this standard. Therefore, we are also using a logarithmic lobe profile, shown in Figure 12.

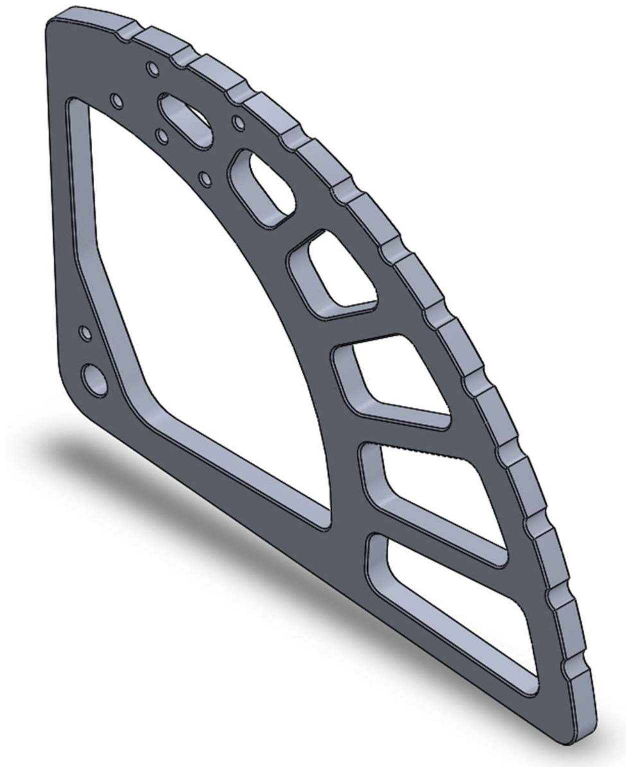


Figure 12. Final Lobe Design

The logarithmic curve allows the camming angle to be consistent regardless the placement of the cam. This allows for the forces in the axle to be the same for any placement position of the camming device. For our device, we decided to design a lobe with a camming angle of 15 degrees. With this camming angle, and an applied load of 14 kN on the stem, the force on the lobe due to the crack that it is placed in is 13.52 kN. In addition to choosing the shape of the cam, we determined a starting thickness of the cam by completing a buckling analysis. We modeled the lobe as a short rectangular column and found that the thickness of the cam lobes needed to be 0.52 inches, based on Euler buckling theory. Detailed calculations can be seen in Appendix E: Hand Calculations**.** Upon reflection, we realized that our 0.52-inch thick lobes were much thicker than those found on other cams on the market. To further optimize the lobe, we created a finite element model of a lobe using Abaqus, as seen in Figure 13.

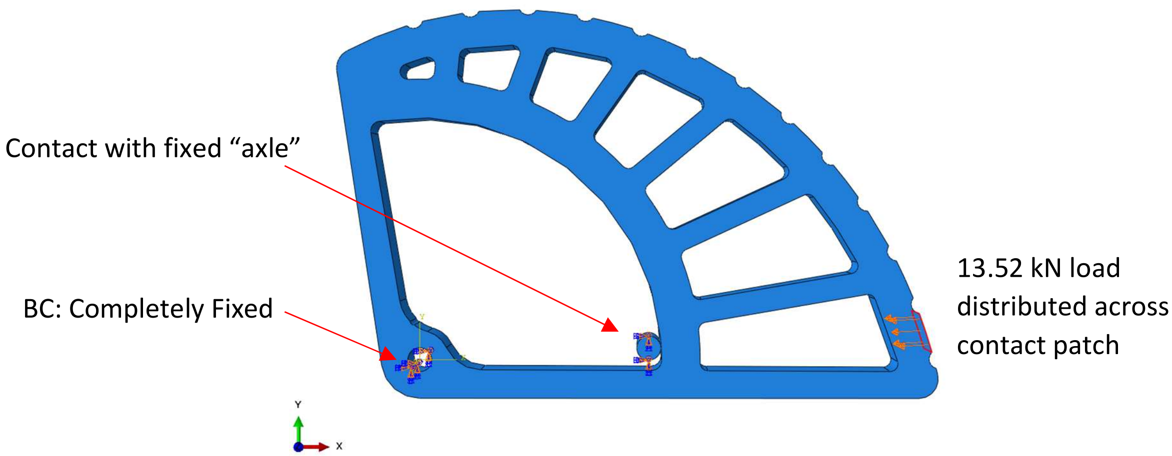


Figure 13: Lobe Abaqus Model

We started our finite element analysis by performing a convergence study to determine the best mesh size and mesh type. We determined that linear hexahedral elements with a global mesh size of 2-mm worked best, as it is a good balance between computation time and accuracy. We also found that at the current lobe thickness, the lobe's maximum principle stress is less than 6061's yield strength, giving us confidence that it will not yield under load. The lobe's von-mises stress distribution can be seen in Figure 14, and the convergence study can be found in Appendix F: Lobe FEA Convergence Study .

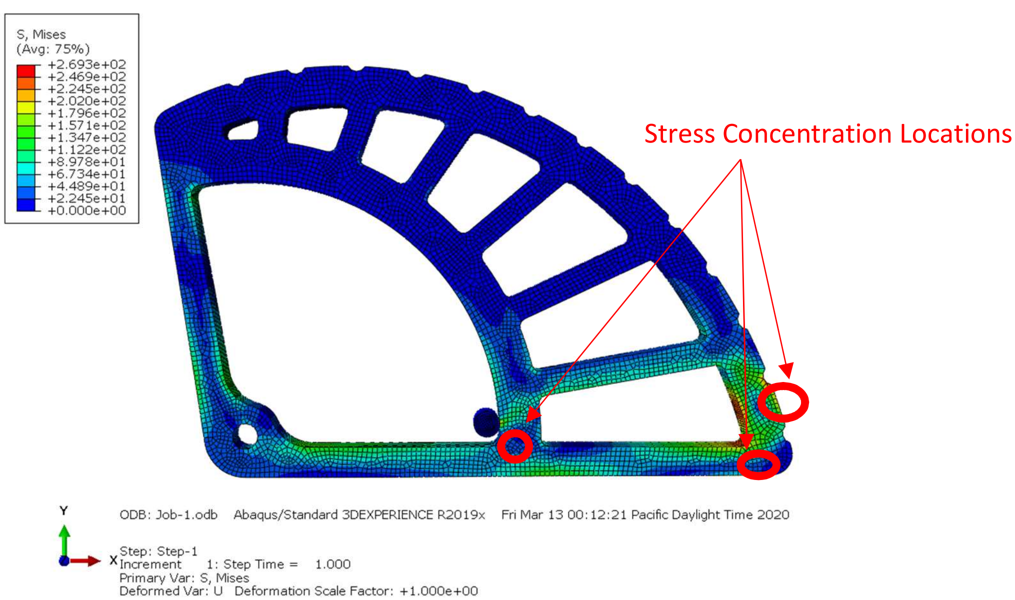


Figure 14: Von Mises Plot (Global Mesh Size: 1.5 mm, Linear Hexahedral Elements)

Once we determined what mesh we wanted to use, we then performed a linear buckling analysis. Interestingly, Abaqus would not allow us to use a contact with a linear buckling step. To get around this limitation, we paired the contact interaction to an initial static analysis step, then added a subsequent buckling step with a load of 1 N/mm^2. Normally, the eigenvalues from the linear buckling analysis describe the load scaler causing the part to buckle. With our two-step approach, however, this made the eigenvalues represent the added load needed to buckle the lobe. We found that the lobe would reach its first mode of buckling with an added load of about 298 N/mm^2 or another 52.77 kN, as seen in Figure 15. In other words, the lobe would yield before it would buckle.

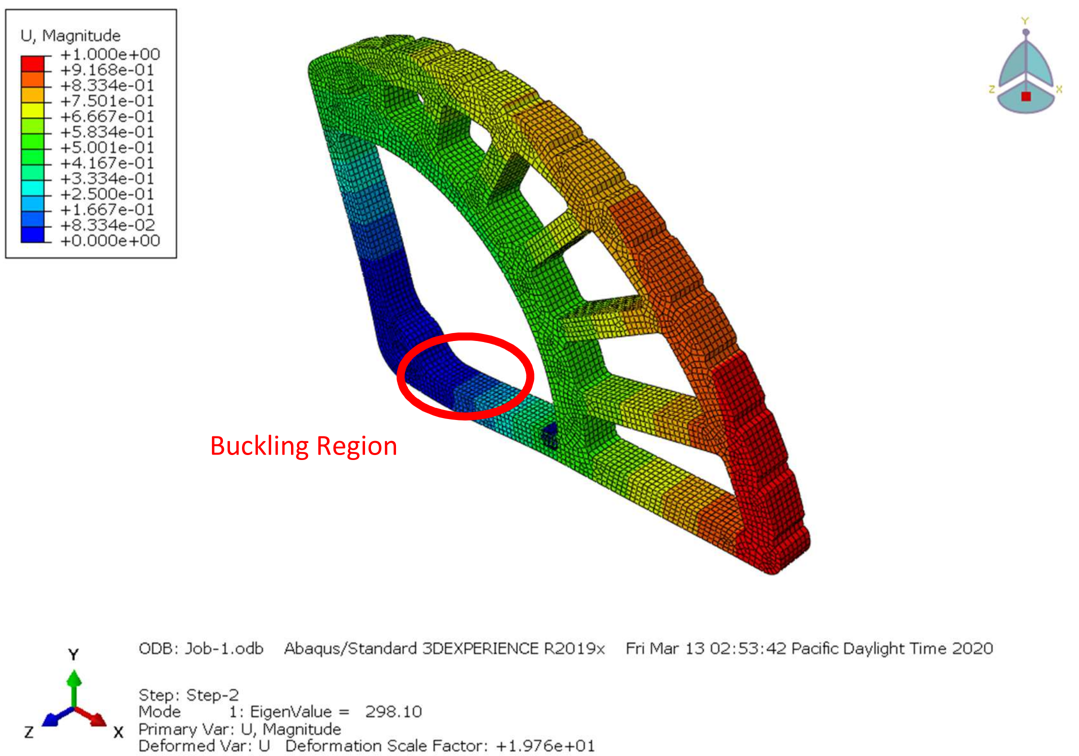


Figure 15: First Linear Buckling Mode

We then tested the model at five different thicknesses: our original thickness 13.21 mm, 11.5 mm, 10 mm, 8 mm, and the thinnest lobe currently on the market 6 mm. We performed the same two-step buckling process as before, making sure to change the surface traction load since the contact patch area changes. Figure 16 graphically summarizes our results for the minimum lobe thickness.

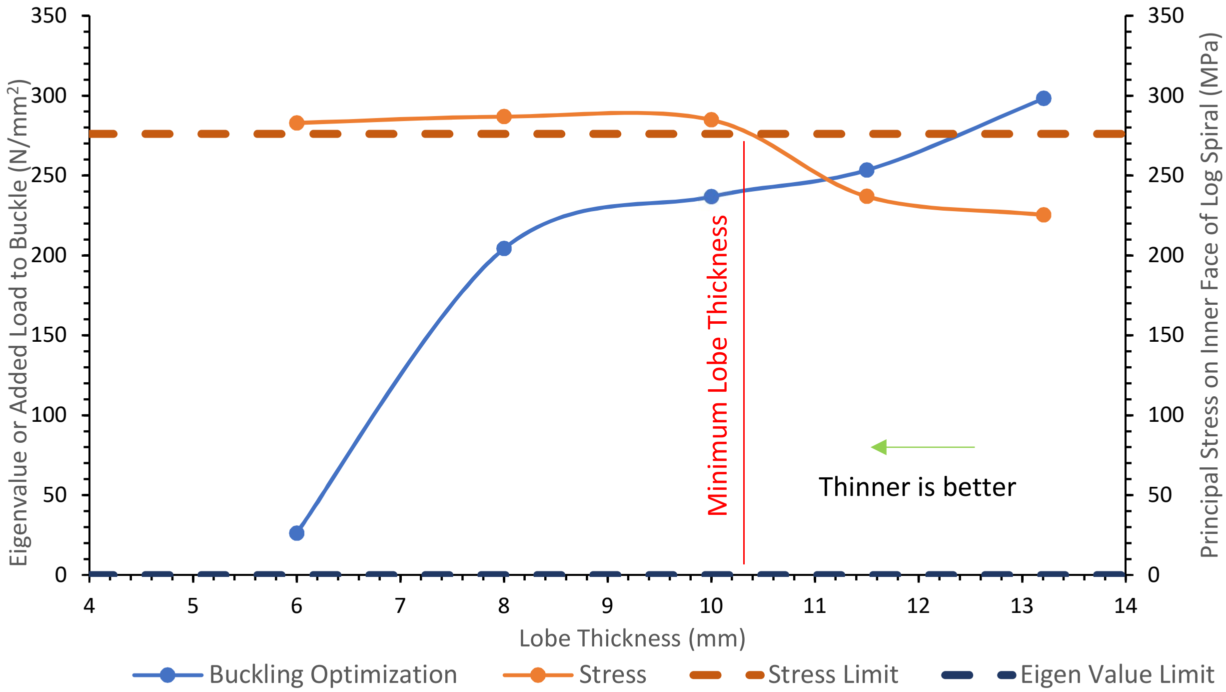


Figure 16: Lobe Thickness Optimization Plot

As expected, as we thinned the lobe, the principal stress increased, and the buckling eigenvalue decreased. None of tested thickness are likely to buckle, still having positive eigenvalues. But for thicknesses 10 mm and less, the simulation predicts the lobes would begin to yield under the 13.52 kN load. Thus, our minimum lobe thickness is approximately 10.6 mm or 0.4 in. We were skeptical of this result, as most other large cams' lobes are about 0.3 in thick. So, for our verification prototype, we manufactured lobes that are 0.3 in thick, in line with other cams on the market. We intended determine if the new thickness would fail under load using a tensile test, however, due to COVID-19, we did not have access to the campus testing facilities, and thus were unable to determine if the thinner lobe thickness is viable.

5.2 Carriage Design and Analysis

The carriage is the interaction point between the stem and the lobes, making it the main hub of the camming device. The carriage, shown in Figure 17, is made from 6061 T6 Aluminum, and is based upon similar cams that are on the market

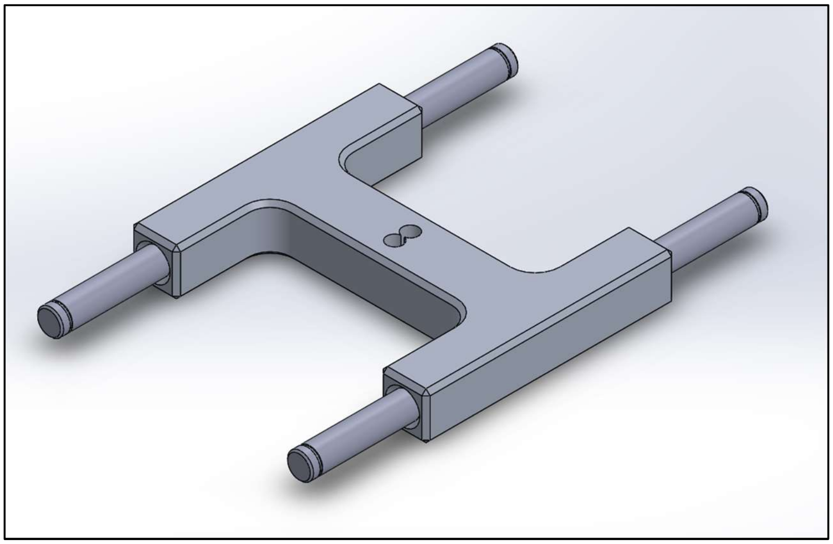


Figure 17. Carriage with Axles

The carriage was optimized using finite element analysis. The FEA model used symmetry boundary conditions because the loading about the carriage is symmetrical. Because of this only half of the carriage was analyzed in Abaqus. This allowed us to save time while running the analysis of the carriage and simplified the boundary conditions into fixed boundary condition where the carriage is cut in half. The FEA analysis can be seen in Figure 18 and Figure 19.

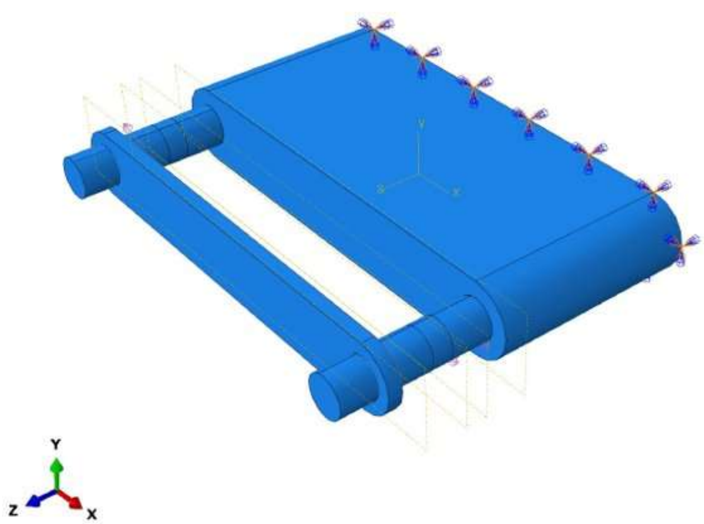


Figure 18: Carriage FEA Model Showing Load and Boundary Conditions

We found that the stress in the axle in the FEA model are higher than the yield strength of the 17-4 PH stainless steel. We were never able to figure out why this was the case, but we think it may have to do with the lobes taking more of the loads as the axles get pushed apart. However, the main use of this FEA model was to look at the stresses in the carriage. The stresses in the middle of the carriage are very low, and the material is not needed. We tried to optimize the carriage and remove material in the carriage and the following model was found.

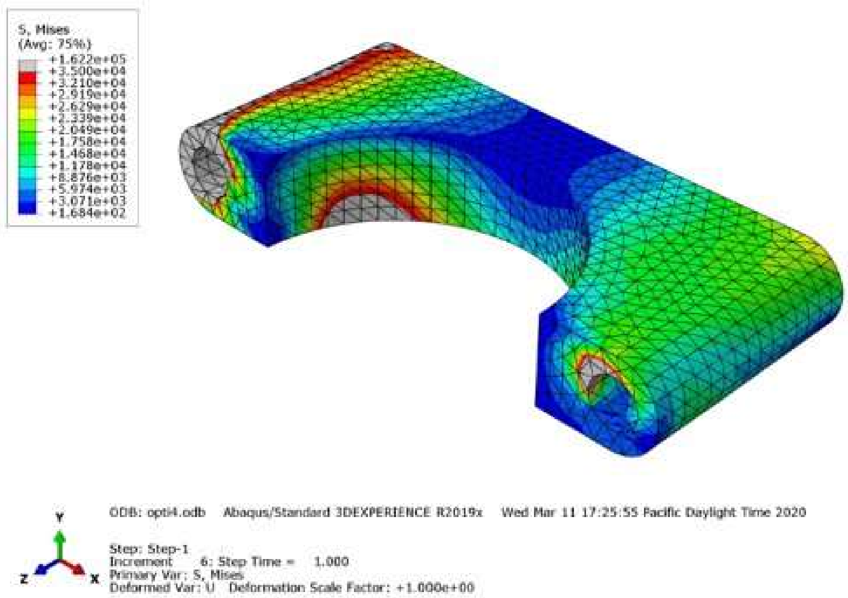


Figure 19: FEA of Carriage with Reduced Center

This model showed that the material in the center of the carriage is not needed because it sees such a low stress. Although the stresses in our model are very high, they show the correct stress distribution of the stresses in the carriage and axle. This stress distribution validates our decision to remove material in the center of the carriage, but more testing is needed to completely verify the design.

5.3 Axle Design and Analysis

The axles will be made up of 5/16″ 17-4 PH stainless steel. In Abaqus we represented our axle as a cantilever beam with a fixed end at the carriage. We decided to run a conservative analysis where the axle was modeled as a cantilever beam with a point load from a single lobe. This analysis led to an axle diameter sizing that was much larger than comparable cams on the market. This led us to redesign our model in order more accurately describe the physical cam. To do this we included an axle linkage that distributed the load between both axles, shown in Figure 20.

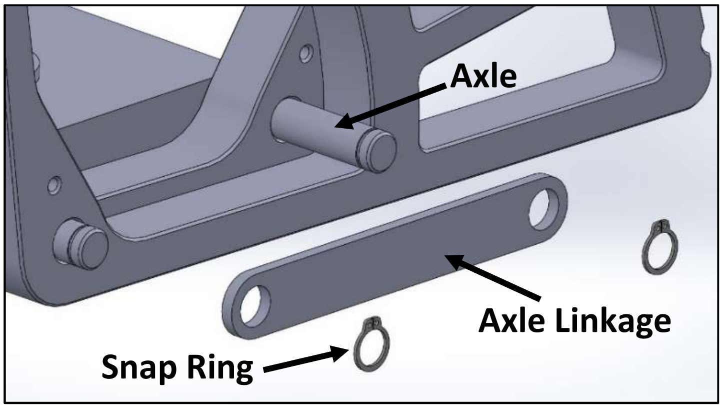


Figure 20. Axle Linkage and Snap Rings

This allows the horizontal forces from opposing lobes to cancel out so the only force on the axle was the vertical force. This led to an axle sizing that was comparable to other cams at 0.325 inches. Although the axle we choose is smaller the calculations indicate, the analysis is still a conservative approach, and our chosen axle is comparable to other camming devices.

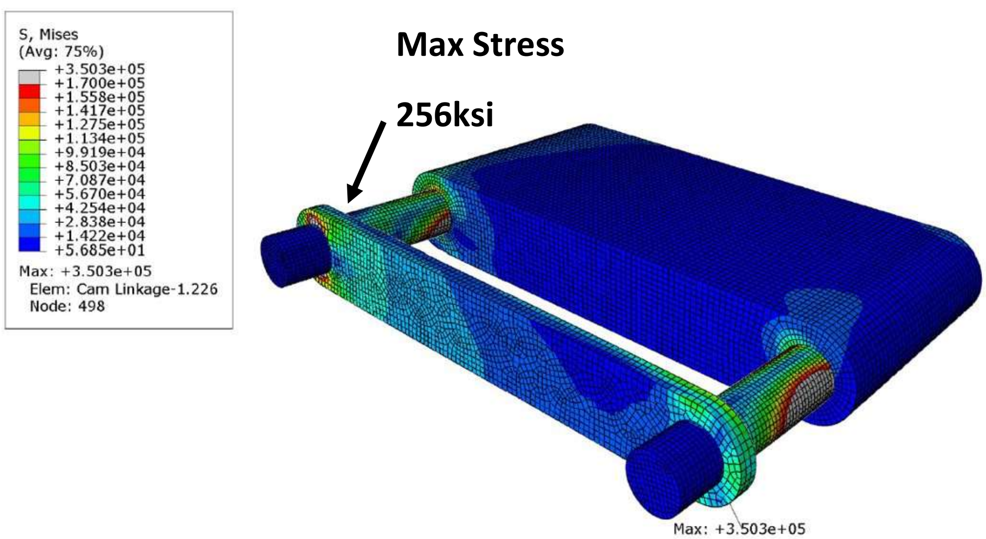


Figure 21: Von Mises Stress FEA of Carriage, Axles, and Axle Link

To further model the system, we ran an FEA analysis on the axles and the end caps to minimize the size of the axle to reduce weight. Through this analysis we found that the max stress in the axles was 265 ksi which is greater than the yield strength of the axles. Although this is the case, we believe that there are other interactions that are happening between the lobes and the axles which are not modeled in this FEA analysis. We justify our decision for an axle size of 0.325

inches based off other similar cams on the market. The axle still needs verification from testing, and our planned tests can be seen the design verification section. A complete calculation for the axle system can be found in Appendix E: Hand Calculations.

5.4 Stem Design and Analysis

The stem will consist of a wire cable with a sleeve, looped back once to form the thumb loop at the bottom of the cam. We selected 3/16" type 302/304 stainless steel aircraft cable. For the structural prototype we ordered 7x19 cord and 1x19 cord because they have different flexibilities, but both meet our strength requirement for the stem. After the prototype was completed, we found that the 7x19 cable did not provide enough stiffness. Because of this our final design is 1x19 cable wrapped in tape to eliminate any pinch points in the stem. To connect the stem to the carriage we will use three swages as seen in Figure 22.

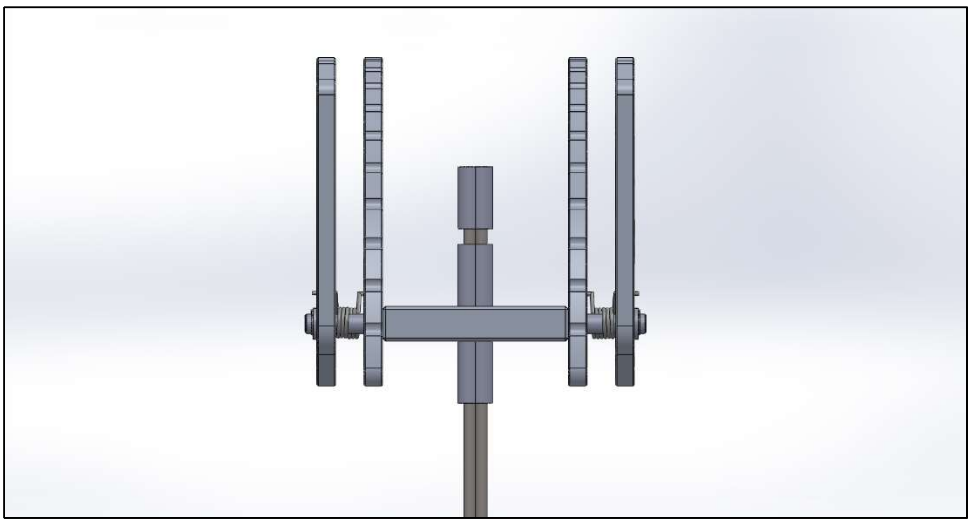


Figure 22. Three swage carriage connection

We plan to use three swages to test the effectiveness of the swages for connecting the stem to the carriage. If the swages slip while tensile testing, we will need to implement a different mechanism to connect the carriage and the stem.

5.5 Trigger Design and Analysis

For the trigger design, we implemented rapid prototyping. The triggers are 3D printed using ASA filament. To determine the general sizing, we constructed rudimentary prototypes using poster board, and produced a SolidWorks model to be used for printing. We 3-D printed several triggers of different dimensions and affixed them onto the structural prototype. We began with a single hinge trigger, but through ergonomic testing we found that they would not fully contract the lobes when actuated. To alleviate this problem, we have altered our design to implement a double hinged mechanism, shown in Figure 23,

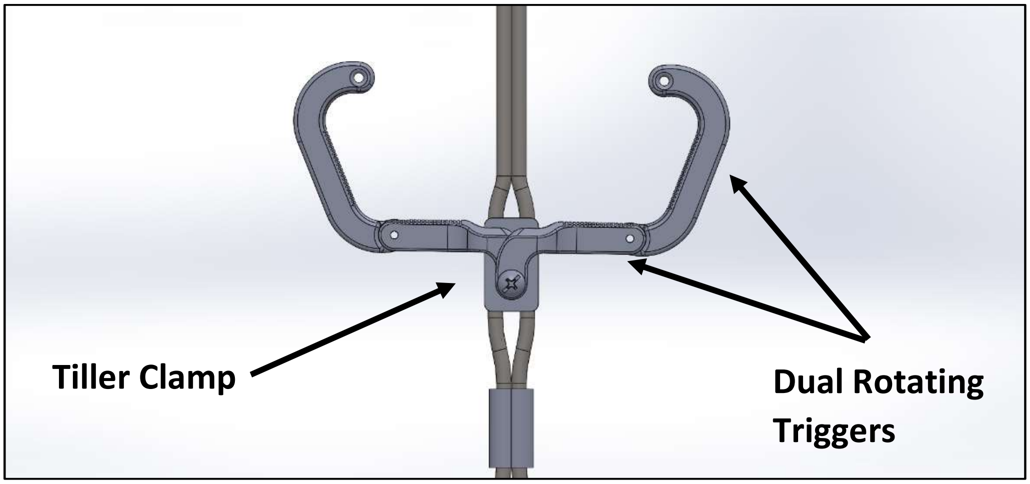


Figure 23. Trigger Assembly

This double hinge will allow the cam to fully contract while still maintaining ease of use. The double hinge will allow for extra activation of the lobe without increasing the size of the triggers. The triggers are connected to the stem with a tiller clamp. This allows us easy interchangeability and the ability to test different positions for the triggers as seen in Figure 24. The triggers are connected to the lobes with a 2.75 mm Accessory Cord. We chose 2.75 mm Accessory Cord because of its flexibility and durability.

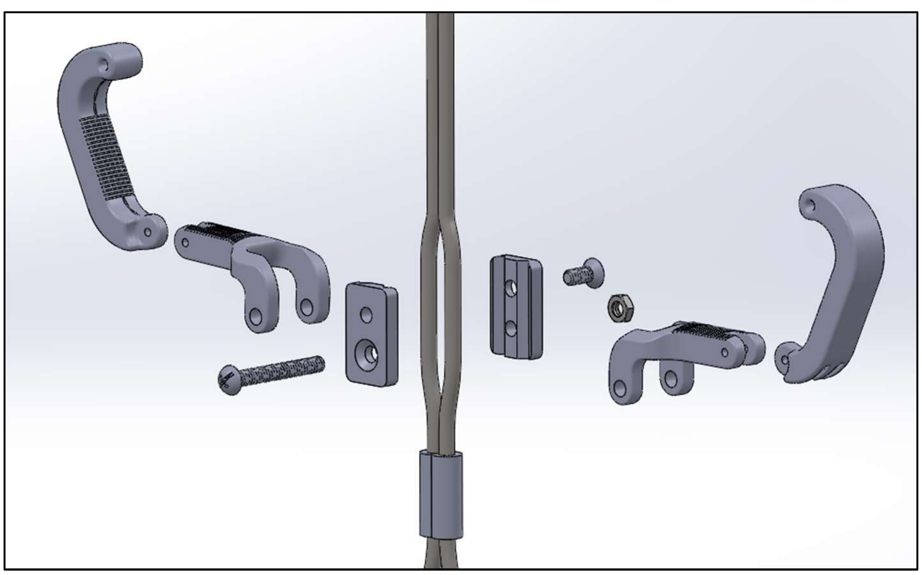


Figure 24. Exploded Trigger Assembly

5.6 Cost Analysis by Component

Prior the COVID-19 pandemic, our goal was to build 10 prototypes: 5 for iteration, 1 for each of us, and 1 for our sponsor. Since we anticipated constructing multiple prototypes, to save, we bought the aluminum for the lobes and carriages in bulk, which greatly reduced the cost per cam. We consulted Professor Trian Georgeou of Cal Poly's Industrial Manufacturing Engineering Department to find out where Cal Poly purchases their metal stock, and he informed us that Coast Aluminum was the best supplier to meet our needs. Coast Aluminum is located out of Fresno, California and can deliver the material directly to Cal Poly within two days of our order.

The most expensive item for this project is the bar stock aluminum for the cams' lobes. Each lobe is approximately 8 inches in length, so we need 2.75 feet of bar stock the four lobes on each cam. Coast Aluminum sells aluminum stock in 12-foot lengths. Thus, for our planned 10 cams, we needed 3 lengths of aluminum, which is $325.08 in total.

The other item we ordered from Coast Aluminum are the aluminum bar stock for the cams' carriages. Each carriage is approximately 3.5 inches in length; thus, we need about 3 feet for the ten cams, leaving 9 feet of extra stock. However, the 12 feet of aluminum bar stock will cost $175.67, which is a great price, as to purchase just 3 feet from other suppliers like OnlineMetals.com would cost over $100.

Since our other fabricated components are smaller in size, we do not need to purchase material in bulk. For our stem cables, purchasing the steel cable from Lexco Cables, which was recommended to us by Myles Wittman. The stem cables will cost us about $43.38 total for the 15 feet of cable necessary for ten cams. Both The 17-4PH stainless steel and the for the cams' axles and the 6061-aluminum round stock for the cable-caps were purchased through OnlineMetals.com, costing $104.76 and $11.56, respectively. The 14-gauge, 304 stainless steel sheet metal for the axle linkages came from MetalsDepot.com with a total price of $39.95. The 0.047 in diameter music wire we used for the axle springs were purchased from Amazon for $50.80. Finally, through Innovation Sandbox, our triggers were completely free, allowing us to make a couple iterations for no cost.

The last of components such as the snap-rings, tiller-clamps, and wire compression sleeves did not require any further manufacturing or modification and will be purchased either from Amazon or McMaster-Carr. For a simplified breakdown of the costs of each component, please refer to Table 8. A more comprehensive summary that includes supplier contact information and shipping time is in Appendix G: Complete Cost Table. For ten cams, the total cost is $804.13, or $80.13 per cam, which is well below are target price of $130.

Table 8. Reduced Cost Table

Subassembly	Part Number	Component	Supplier	Total Cost
Carriage	100	Carriage	Coast Aluminum	$175.67
Head Assembly	210	Axles	Online Metals	$74.05
	220	Lobes	Coast Aluminum	$325.51
	230	Axle Linkages	Metals Depot	$43.07
	240	Axle Springs	Amazon	$8.14
	250	Snap Rings	McMaster-Carr	$16.72
Stem Assembly	310	Stem Cable	Lexco Cable	$41.38
	320	Swage	McMaster-Carr	$52.55
	330	Electrical Tape	Home Depot	$4.75
Trigger Assembly	410	Trigger A	Innovation Sandbox	$0.00
	420	Trigger B	Innovation Sandbox	$0.00
	430	Trigger Cord	Amazon	$24.67
	440 + 450	Tiller Wire Clamp + Flathead Screw	Amazon	$34.96
	460+470	Through Screw + Nut	Home Depot	$2.36
			Total:	$804.13

To help pay for the material costs, we submitted a proposal to the Mechanical Engineering Student Fee Allocation Committee (MESFAC) to gain funding for our iteration prototypes. Fortunately, on February 7th, MESFAC granted us $835.40, providing us the funds we need for the metal stock and other materials.

Unfortunately, due to COVID-19, we were unable to complete the manufacturing for the first cam that we began during winter quarter. The remaining machining included the carriage, axles, and axle links. Since we did not have access to campus spring quarter, we decided to outsource the last of the machining to Rogue Engineering. The last of the machining cost $349.75. Fortunately, we received $200 from CP Connect to help pay for the last of manufacturing. Appendix G contains the final budget spreadsheet, detailing the all the grants we received and our expenses.

5.7 Safety Analysis

Safety is a major priority when designing a camming device because the camming device is used as a protection device. With the inherent risk of rock climbing, any structural failure can result in a possibility of a life-threatening injury. We have conducted a Failure Modes and Effects Analysis (FMEA), for our camming device, and it can be seen in Appendix H: Failure Modes and Effects Analysis. Through this analysis, we found that a lot of failures have a high risk including the following: lobe breaking, lobe buckling, axle breaking, carriage breaking, and stem breaking. Any of these failures would result in the climber falling and potentially a life-threatening injury. To address these concerns, we followed industry leaders in rating our camming device to a 14 kN load, to decrease the occurrence of these failure modes. In addition to failure analysis, we will be conducting tests to ensure that the device can hold the required load. The only way to detect the possibilities of these failures is by inspection, which is done when the device is manufactured. In addition, the user of the device should inspect the device completely for any visual flaws prior to each use to reduce the risk of unexpected failure. However, the device cannot be completely safe because failure of the rock that the cam is placed in can occur.

Proper care of the device is important to ensure it works properly. The cam should be cleaned when dirty to prevent the seizing of the camming device, as well as uncover any flaws that were hidden by dirt or grime. The device should be properly stored in a cool dry space away from direct sunlight. If the trigger cords become frayed or break, they can be repaired, with a replacement kit of trigger cords. If any other part of the cam has a flaw, repair is not an option for that cam. In Appendix I: Operations Manual, we have outlined the correct handling of the device to maximize the lifespan of the cam.

6 Manufacturing

The following manufacturing plan provides a step by step process of how our final design was created and assembled. All materials outlined in this section are detailed in the indented bill of materials seen in Appendix J: Indented Bill of Material. This section is broken into subsections based on the component. A final assembly subsection is included last.

6.1 Carriage Soft Jaws

Soft jaws are a fixture used to secure the carriage in the vise while the part is being CNC machined. These fixtures were cut using a CNC mill. The equipment required to make the soft jaws is a CNC mill loaded with a 1/2-inch end mill and the proper CNC programs. A test indicator and a file were also needed. The soft jaws were first loaded into a vise fixed to the machining table of the CNC mill. They were then adjusted, using the test indicator for guidance, so that they were parallel to the machine table. The CNC program was then run, which cuts the holding geometry into the soft jaws. Finally, a hand file was used to remove any burrs left on the soft jaws.

6.2 Carriage

The carriage was machined by Noel Rodes at Rogue Engineering. The shape of the carriage resembles a three-dimensional H, shown in Figure 25, with two holes running the length of the two vertical lines and two holes side by side in the middle of the bridge perpendicular to the previous holes.

Figure 25. The carriage component for the final cam design.

The vertical holes house the axles while the perpendicular holes are used to attach the stem. (Picture) A CNC mill loaded with a 9/32-inch drill, a 5/16-inch reamer, a 1/2-inch chamfer tool, a 3/16-inch drill, and a 1/2-inch flat end mill was used along with the proper CNC programs. The carriage was secured to the mill table with a vise and the carriage soft jaws. It was then cut in four operations. The first operation contoured the external H-shape of the carriage and chamfers the top edges. The two stem holes were also drilled. The part was flipped, and the second operation faced the part to the appropriate thickness. The bottom was chamfered. The part was turned on its side and the axle holes were drilled halfway. The edges and holes were chamfered. The part was flipped again, and the final operation finished the axle holes. The reamer was used to ensure the holes were within specification. The remaining edges and holes were chamfered. A deburring tool was used to break all sharp edges.

6.3 Stem

Since braided steel cable was used, the stem only needed to be cut to length. To do this, a tape measure and marker was used to make a mark at 34 inches. The cable was then cut using cable or bolt cutters. Marks were made at 1, 2, 2.5, 3.5, 14.5, 20.5, 31.5, 32.5, and 33 inches with a

marker. These will be used during assembly. After swaging and the addition of the thumb loop sling, the final stem subsystem is shown in
Figure 26.

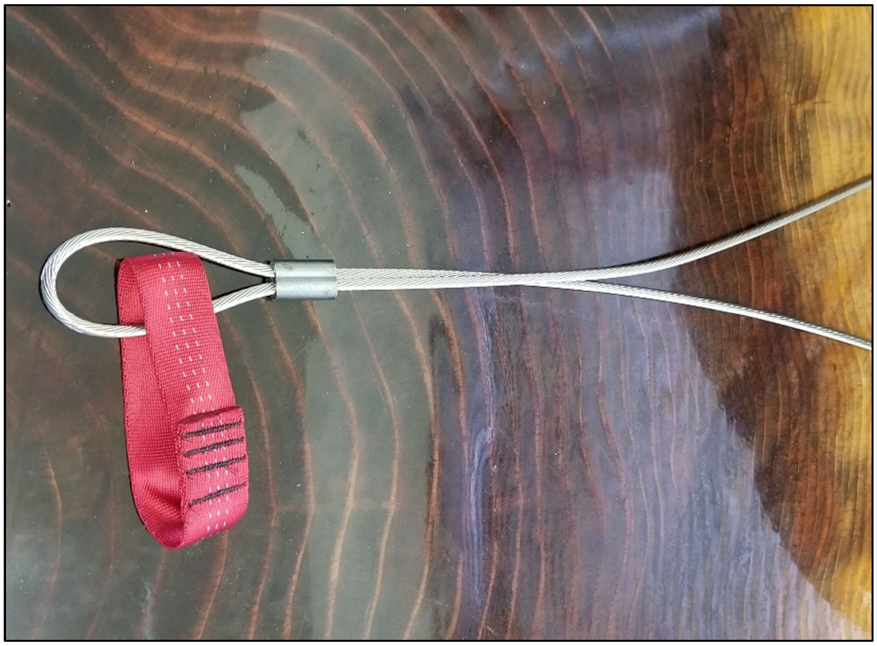


Figure 26. The stem made of the stainless steel aircraft cable, and the sling attached to the thumb loop.

6.4 Axles

A manual lathe loaded with a stop, a tail stock, a CNMG-432 insert tool, a 1/2-inch center drill, a live center, and a grooving tool, were needed for this process. The part was loaded into the jaws until there was about an inch of stick out and the machine jaws were tightened. The part underwent four operations. The first faced one end and drilled a center hole using the tail stock. The part was flipped, and the operation was repeated. The part was reloaded using the stop, tail stock, and live center. Half the length was turned to the proper diameter in three passes. Finally, a 1/32-inch grooving tool available in the shop was used to cut the groove. The part was flipped, and the operation was repeated. A final axle is shown in
Figure 27. A file was used to break all sharp edges.

Figure 27. One of the two finished axles.

6.5 Lobe Soft Jaws

Custom soft jaws were required to hold the unique shape of the lobes into the vise while they were being machined. To make the soft jaws for the lobes, a CNC mill loaded with a 1/2-inch end mill and the proper CNC program was used. The soft jaws were first loaded into a vise on the table of the CNC mill. They were then adjusted, using a test indicator for guidance, so that they were parallel to the machine table. The CNC program was run, cutting the holding geometry into the soft jaws. Finally, a file was used to remove any burrs left on the soft jaws.

6.6 Lobes

A CNC mill loaded with a 1/2-inch chamfer tool, a 3-inch facing tool, a 1/8-inch drill, a 3/16-inch drill, a 1/4-inch flat end mill, and a 1-inch flat end mill were needed along with the proper CNC program and a set of parallels. Each lobe was cut in two operations. For the first operation, the lobe was loaded into the vise with a pair of 1 7/8-in. parallels. The part was contoured and then the holes and pockets were cut. The part was flipped and loaded into the vise with the soft jaws. The second operation faced the rest of the stock from the opposite side of the part and chamfered all edges. All sharp edges were broken with a file. One of the four finished lobes is shown in Figure 28.

Figure 28. One of the finished lobes. We obtained this shape through extensive FEA.

6.7 Springs

Each spring was wound by hand due to their unique shape. Two springs are needed for each cam. A pair of needle nose pliers, a pair of lineman pliers, and a 3/8" round bar was needed to make the springs. Using a tape measure and marker, a mark was placed at .5, 1.0, 4.0, 7.0, 10.0, 10.5, and 11.0 inches. The wire was cut at 11 inches using the lineman pliers. A 90-degree bend was place at .5 and 10.5 inches using both pairs of pliers. These bends must be 180-degree from each other. Using the lineman pliers to grab onto the .5-inch bend, and with the round rod held in place between the pocket of the lineman pliers, the wire was wrapped around the rod in a tight clockwise pattern. The 1- and 4-inch mark should be lined up after two full rotations. This process was repeated on the other end of the wire. The second wire is made in the same manner, except the wire was wound in a tight counterclockwise pattern. The final torsional springs are shown in Figure 29.

Figure 29. The finished torsional springs.

6.8 Axle Linkage

The axle linkages, one of which is shown in Figure 30, were machined by Rogue Engineering. A 1-inch strip of material was cut. The material was clamped to a piece of plywood on one side and a strip of aluminum on the other. The holes were drilled, and nuts and bolts were used to hold the three pieces together. The part was then loaded into a CNC machine and the profile was machined. All sharp edges were broken with a file.

Figure 30. Finished axle linkage.

6.9 Triggers

An STL file was created using SolidWorks and submitted to the Innovation Sandbox, a free service offered to Cal Poly students on campus, to be 3D printed. This process took between three days and one week. Sandpaper was used to round any sharp edges or flatten any rough surfaces. Some holes were re-drilled using a drill press. A finished trigger is shown in Figure 31.

Figure 31. Finished trigger handle.

6.10 Trigger Cord

The 2.7mm accessory cord was cut during the assembly process and will be described in Section 6.13. A double fisherman's knot and glue were used to secure the string to the lobes.

6.11 Nylon Sling

A nylon sling is used to connect the climber's rope to the cam. 1-inch tubular webbing was sewn into a loop by Myles Wittman.

6.12 Assembly:

First, the stem was bent to form a U in the middle of the wire. The nylon sling was slid over one end of the wire so that it rested in the bottom of the U. Both ends of the wire were inserted into a swage which was then slid to the base of the loop and lined up with the marks at 14.5 and 20.5 inches. It was then crimped and forms the thumb loop. The sling attached to the thumb loop at the end of the stem is shown in Figure 32.

Figure 32. Sling attached to the thumb loop.

The head assembly was assembled next. Another swage was placed and crimped at the 3.5- and 31.5-inch marks. The two ends of the stem were inserted into the holes on the same side of the bridge of the carriage. Then, two more swages were placed and crimped above the carriage, shown in Figure 33.

Figure 33. Crimped swage above the carriage, which secures it to the stem.

A gap was left between the two swages to analyze any movement during testing. Excess wire was cut using bolt cutters. The axles were then put into the carriage and the first lobe was placed onto the axles. The first spring was placed over the axles and then attached to the first lobe. The second lobe was placed onto the axles and attached to the other end of the spring. The operation was repeated on the other side. The axle links were slid onto the axles and a snap ring is placed onto the end of each axle. The lobes secured in this way are shown in Figure 34.

Figure 34. Lobes secured to the axles and carriage subassembly using snap rings.

Finally, the trigger assembly was attached to the cam. The tiller clamp was placed onto the stem using one screw. Tape was wrapped around the stem starting and the base of the carriage and ending at the tiller clamp. Four layers were used to provide stability to the flexible stem. Four more layers of tape were used at the base of the thumb loop to provide comfort when actuating the cam. The triggers were then attached to the tiller clamp using a 1.5-inch bolt with a nut secured to the end using thread lock. The first trigger wire was passed through the first lobe, tied, and glued to the lobe, fed through the trigger, and glued and tied to the second lobe. The process was repeated on the other side. The fully assembled cam is shown in Figure 35.

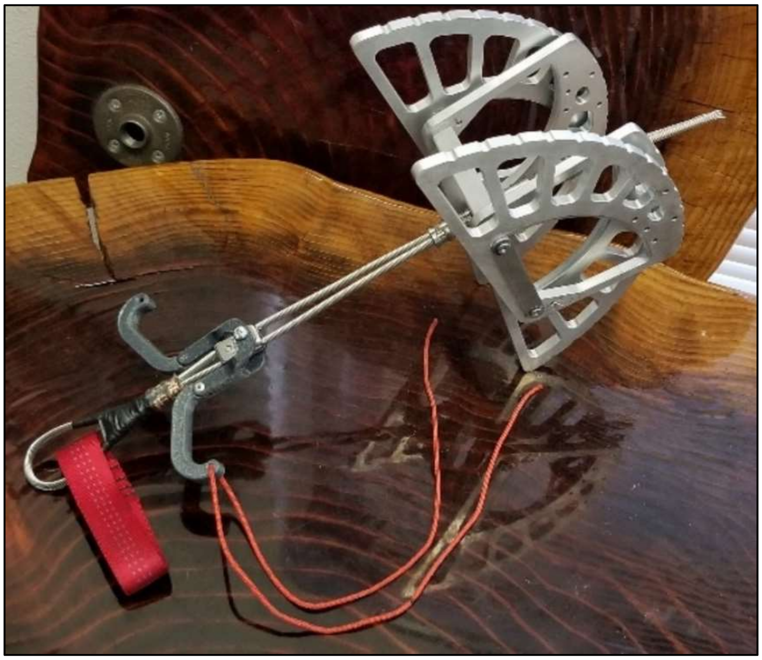


Figure 35. Fully assembled camming device.

All individual component drawings as well as the assembly can be found in Appendix K: Drawing Package.

6.13 Challenges and Recommendations

It was difficult to find manufacturers and the cost of prototyping can be very expensive. When you outsource that cost is greatly increased. Therefore, it is recommended that as much machining be done in house as possible.

Swaging around the carriage can also be difficult. In order to prevent any potential failures, the last two swages should be crimped before the one at the bottom of the carriage. This ensures that the load bearing swages are properly set.

7 Design Verification

Prior to the COVID-19 outbreak and campus closure, we were planning to test our camming device design to determine it met the specifications listed in Table 5: tensile strength, cost, weight, range, bending deformation, and stem buckling. A complete summary of our former design verification plan can be found in Appendix L: Design Verification Plan. However, since Cal Poly campus is closed and we do not have access to a machine shop or tensile tester, we were unable to complete all the tests to determine whether our camming meets theses specifications. Therefore, the Design Verification section is broken up into two subsections. The first subsection, Completed Tests and Results, documents the testing, and results we were able to complete prior to and during the COVID-19 situation. The second subsection, Incomplete

Tests, outlines the tests we were unable to complete due to COVID-19. Each of the test procedures can be found in Appendix M: Test Procedures.

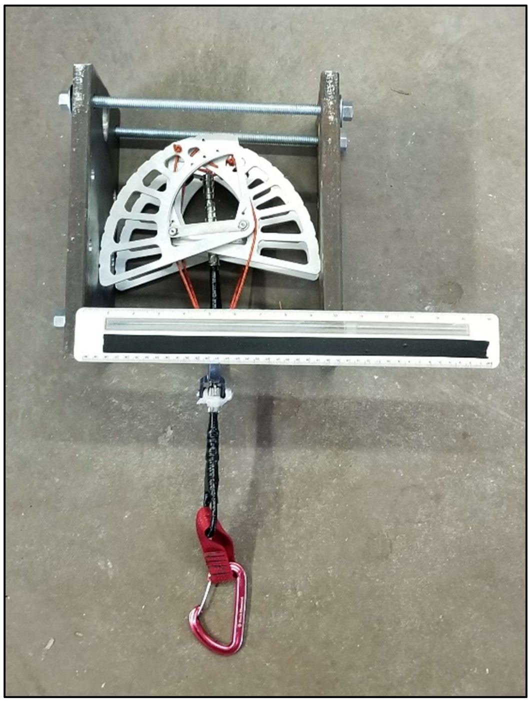
7.1 Completed Tests and Results

Since we were able to construct a single verification prototype, we were able to complete all the non-destructive specification tests. Firstly, we have the maximum cost-to-manufacture specification of $130. This price was chosen to keep the retail price of the cam comparable to other cams on the market. Prior to COVID-19, since we were manufacturing the camming devices ourselves, the cost of the cam was dictated primarily by the cost of materials. Since we planned on manufacturing multiple cams and iterating on our design, we purchased the material in bulk, reducing the cost of each cam to $80.43, well below our $130 goal. A full cost analysis can be found in Section 5.6: Cost Analysis by Component. However, since we did not have access to the Cal Poly machine shops to manufacture the cams ourselves, we were forced to look to third-party manufacturers to complete our cam's manufacturing. Fortunately, we found and enlisted the services of Rogue Engineering. It cost $349.75 to machine the remaining carriage and axles. Thus, the overall cost of the verification prototype was $803.14, or $80.43 per cam. Since we intended on completing the manufacturing ourselves, we are still considering the price per cam to be $88.58. COVID-19 created an unorthodox situation, so the increased cost of our first prototype is not representative of the cost of a cam during normal circumstances.

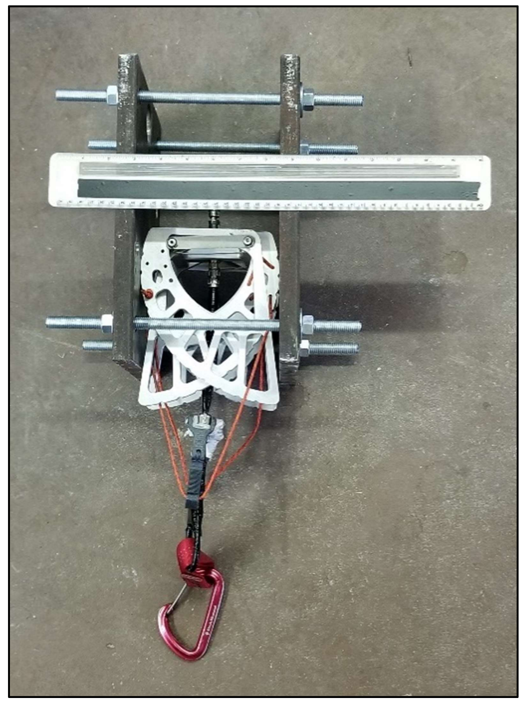
We then measured the weight of the cam using a small hand-scale. The maximum allowable weight of the entire cam was specified as 900 grams, but the lighter the cam, the better. As pictured in Figure 36, we measured the cam to weigh approximately 1135 grams, or about 2.5 pounds. If we were able to iterate and produce multiple prototypes, we are sure we would able to reduce the weight below 900 grams by further adjusting the lobe and carriage geometry.

Figure 36. Weighing the cam. The weight is 1135 g.

The next specification test was to determine the camming range. We designed the cam to have a usable range of 6 to 9 inches. To test the range, we placed the cam in the same test fixture as the planned tensile tests. A description and picture of the test fixture can be found in the Section 5.7 Incomplete Tests. By adjusting the distance between the test fixture's steel plates, we placed the cam at its maximum and minimum activation, and measured the distance between the contact points using a ruler, as depicted in Figure 37. We measured the cam's range to be between 6 to 9 inches wide, fulfilling our design specification.



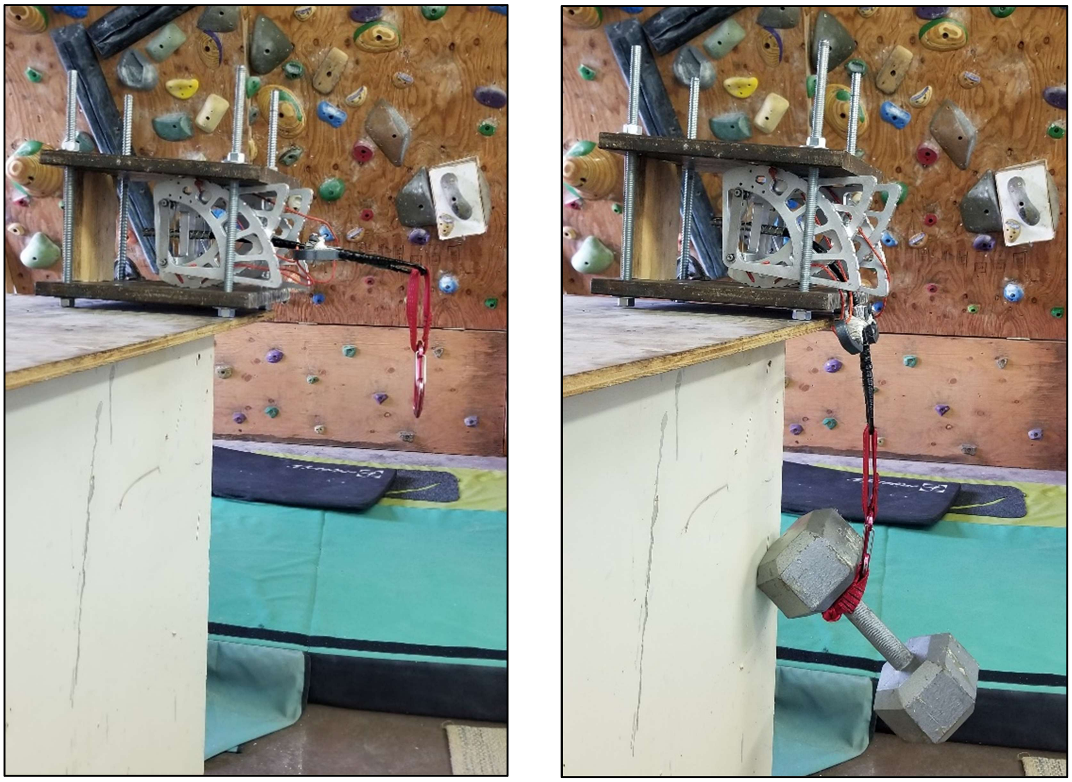
(a)



(b)

Figure 37. Using a ruler to measure the distance between the lobes' contact points when it is (a) unactuated and (b) 100% actuated.

Next, we tested that there is no be no permanent deformation of the stem when placed around a 90-degree corner. To test this specification, we again placed the cam in our test fixture jig and bending the stem around the 90-degree edge of the steel plate. This will simulate the stem bending around the edge of a crack. To pass the test, the stem must have no permanent deformation when released from the bend. As seen in Figure 38, after the bend test the cam's stem was able to bend around the without permanent deformation.



(a) (b)

Figure 38. Using a weight to simulate a bend test of the stem. (a) The cam in the test jig without a weight attached. (b) The cam's stem was able to bend around a 90 degree corner without sustaining permanent deformation.

Our last specification is that there is no buckling of the stem during the actuation and placing of the cam by the climber. This design verification test consists of inspecting the stem for buckling while it is being activated, placed, pushed, and retrieved from a crack. The cam passes the inspection if there is no buckling of the stem during any of these actions and fails if it buckles in any of these scenarios. As shown in Figure 39, the stem did not buckle when the cam is fully actuated.


Figure 39. Testing that the stem does not buckle during the actuation of the cam.

7.2 Incomplete Tests

Unfortunately, the one test we were unable to complete was also the most integral for optimization design: the cam's tensile test. Our design goal was that the camming devices could support a static 14 kilonewton load without yielding. We chose a 14 kN load because other camming devices on the market have similar strength ratings. This specification will be tested by completing three separate pull tests. These pull tests, which are outlined in the EN 12276-2016 and UIAA 125 standards for frictional anchors, are conducted at 75% and 25% of the cams total range. The third test is conducted in "umbrella mode" where the cam is placed in an inactivate camming position, shown in Figure 40, and the four lobes are rested upon the edges of the fixture. All tests are conducted until failure.

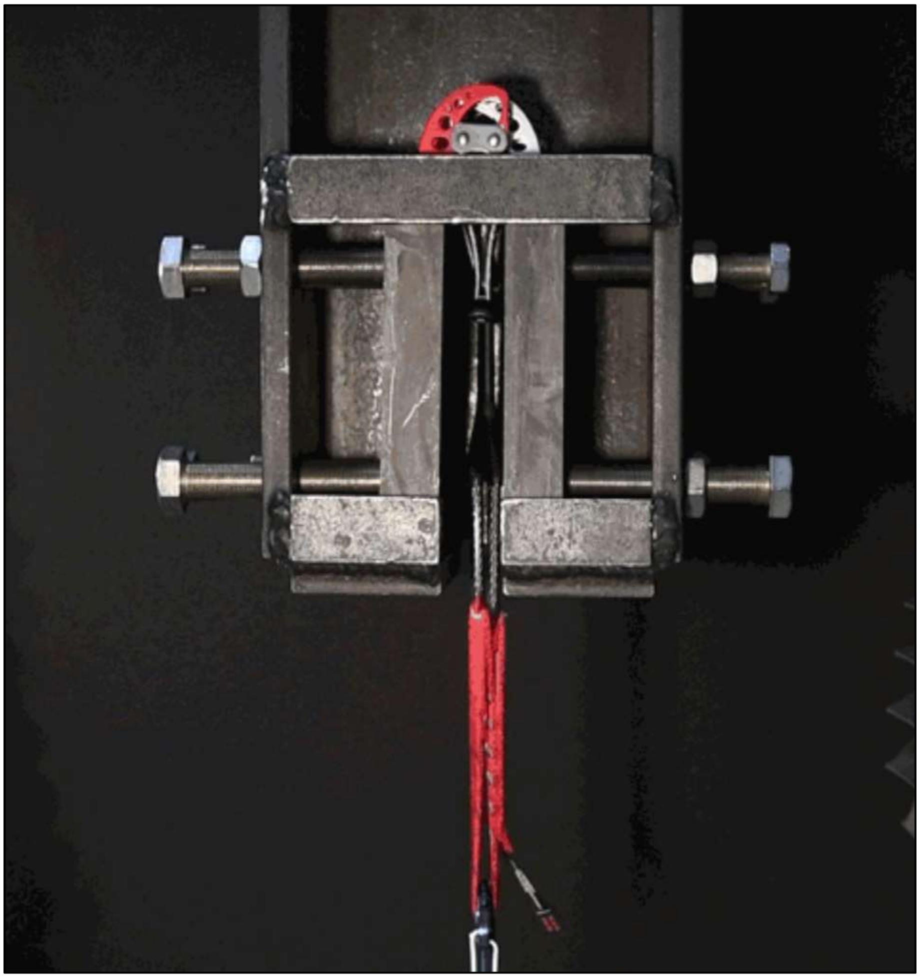
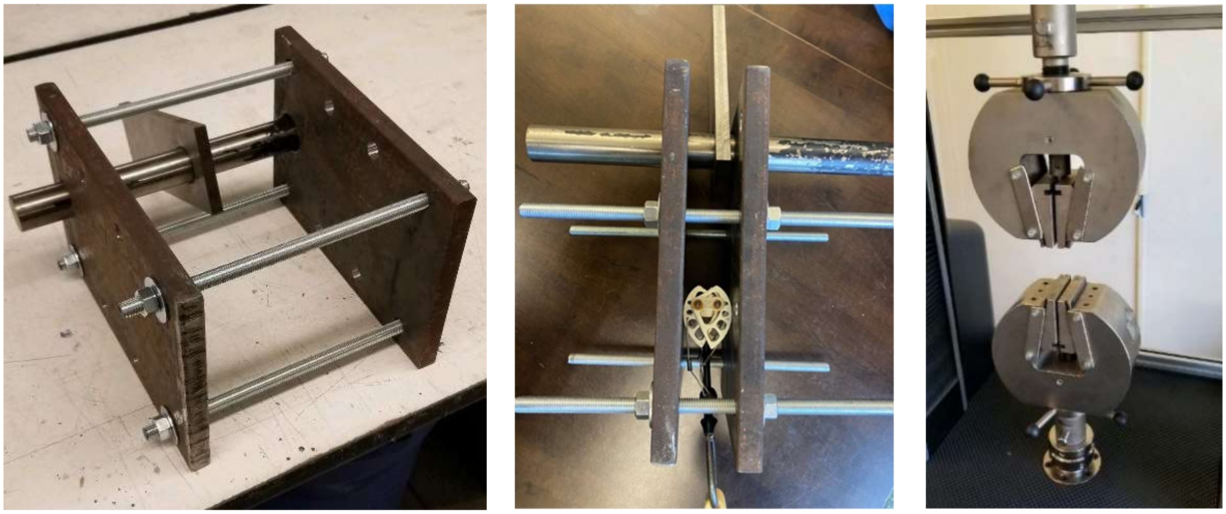


Figure 40. Black Diamond Pull-testing a Cam in Umbrella Mode [28]

These tests were to take place in the Composites Laboratory on Cal Poly campus using the Ametek mechanical tensile tester. With the tensile tester, we would data documenting the stress-strain data of the cam under load, allowing us to accurately determine when the cam begins to fail. Using donated materials from the Cal Poly Machine Shops, we designed and constructed a testing jig, as seen in Figure 18, to hold the camming device within the tensile tester. We used spare materials from the Cal Poly Machine Shops For the 75% and 25% range tensile tests, the test fixture would hang from the top jaws of the tensile tester, and the camming device would be fixed in place using the two parallel steel plates, as shown in Figure 18. Just in case the plates are not rough enough to hold the cam, we purchased tape-on sandpaper to increase the plates' roughness. For the "umbrella mode" test, the test fixture is rotated 90 degrees within the tensile tester, and the bottom set of bolts would support the open cam under load.



(a) (b) (c)

Figure 41. Tensile testing equipment. (a) Tensile Test Fixture, (b) Sample Cam within Test Fixture, (c) Ametek Tensile Tester Jaws

Our plan was to first test one camming device from an external manufacturer to verify that our test fixture works, and the cam does not slip. Also, since the cam has a specified rated failure load from the manufacturer, we can verify that the tensile tester and our test procedure yields accurate data. In addition, we were going to tensile test different configurations of webbing that attaches to the cam. Following these initial calibration tests, we would then begin testing our own cams. If the cam successfully supported the 14 kN load without any component yielding, then we would go back to the drawing board and use further FEA and testing to eliminate unnecessary material from the design. In doing this we would be working towards make the cam as light as possible while still maintaining the required 14 kN tensile strength. If our cam failed under load, we would use both the tensile test data as well as visual inspection to diagnose where the design failed and be able to identify how to alleviate the problem, summarized in our Failure Mode Analysis found in Appendix H. We would then repeat this process until our final design meets all our design specifications. The detailed tensile test procedure can be found in Appendix M: Testing Procedures.

8 Project Management

The Project Management section outlines the plan that we made to complete our project and meet the key deliverables we aimed to fulfill. It explains the design process taken from conceptualization to the final design, and how we evaluated the effectiveness of the final cam. To see a full breakdown of tasks and please refer to Appendix N: Gantt Chart.

8.1 Overall Design Process

Early on, we dedicated time to brainstorm ideas for the final design. We feel that we dedicated sufficient time to this task, however it would have been to our benefit to use multiple methods

of converging on a trigger design. We were unable to determine a final design for this component before the outbreak of COVID-19, however at the time we dismissed this as an unimportant decision. Looking backwards, coming to a design decision on all components before beginning manufacturing would have answered a lot of the questions that we have now. If we could change one thing, it would be to have had all final design decisions made before manufacturing. Mixing the design development of the triggers with the manufacturing steps would not have been detrimental had it not been for the COVID outbreak. In fact, because of this, we would have changed several things in our process. We also would have applied for additional funding to cover the costs of outsourcing some of the manufacturing processes, however this was much more out of our control. On a similar note, we cannot stress enough the importance of planning ahead. A well-thought out Gantt chart and making our plan as detailed as possible would have been time-saving in the wake of the global health emergency.
The assignment of specific roles on the team proved to be an effective way of each of us knowing generally what we are responsible for was useful. The Team Gantt software enabled this practice, and it was useful that we were reminded of upcoming deadlines that we were individually responsible for.

8.2 Unique Processes Used

These are the following unique processes that we used for design, prototyping, and building.

Finite Element Methods for Design:

We used the software Abaqus to conduct Finite Element Analysis on the carriage and lobe components. The purpose of this was to shave as much weight off the cam as possible, without compromising strength and durability.

Tensile Testing the Structural Cams:

As a part of the testing procedures, we planned to utilize the Ametek pull-tester with a custom jig to pull the cams until breaking. Unfortunately, due to the campus closure, we did not end up using this method.

Trigger Design:

Throughout the duration of this project, we continued to produce rapid prototypes of new trigger designs. We used 3D printing to rapidly produce the triggers, making it very easy to quickly determine whether the design fit our ergonomic goals.

9 Conclusion

The goals of this project were to design, build, and test a strong and lightweight camming device for off-width climbing that features a flexible stem. Additionally, we wanted to improve upon the ergonomics of the limited options for a large camming device currently on the market. These goals were mostly achieved during throughout the entire design process. During the first two quarters of the project, our team designed and built a novel camming device.

One large goal of ours was to build test and iterate on our design to improve the device. However, we were unable to test the device to verify that it met all our specifications. The largest hurdle that faced this project was the closure of the Cal Poly Campus due to the COVID-19 outbreak. Due to this closure, our plans to manufacture and test the cams ourselves on the Cal Poly Campus were no longer possible. Instead we quickly adapted and located external manufactures to continue to build the device for us. However, due to the unpredictable nature of the pandemic, we lacked sufficient funding to outsource the production of ten camming devices that we could test. Instead we got a single cam build be a manufacture as an initial prototype.

9.1 Next Steps:

Although we are building and testing the design direction stated in this report, we would like to iterate the final design several times based on the results of this and all subsequent testing. We also recommend iterating the lobe design and the geometry of the carriage based on further FEA to reduce the weight of the overall device. The trigger sizing would continue to be modified once we have more structural prototypes to bring to the local climbing gym and obtain feedback from climbers. Moving forward, we would test multiple families of devices. The first test that will be conducted would determine the best manufacturing method for the stem to carriage connection. After this test, we would test the optimized carriage dimensions. The final few prototypes would be built for aesthetics. For these more finalized devices, we would use plastic injection molding to produce a sleeve for the wire cable that will contribute to the stiffness of the cable. This would also be the final ergonomic decision to implement, and for this we would require more user feedback.

One aspect of the device that still needs to be designed is the sleeve that encapsulate the wires in the stem. This sleeve increases the stiffness of the cam allowing the cam to be stable while in use. If more time were available, we would injection mold a plastic sleeve with different thicknesses in different areas that need stiffness. This variable stiffness would need to be tested to ensure that the stem of the cam does not buckle during use, and it is not too stiff as to prevent flexibility in the stem.

In addition, to injection molding the stem sleeve we would injection mold the triggers as well, if this device were to be manufactured at a larger scale. This would increase the overall feel of the device, as well as decrease production cost and time in the long run.

The connection of the stem and the carriage would also be modified if more time were available. Although the swage supports the necessary loads, we would look to find a more elegant solution to increase the aesthetics of the device and reduce the weight. In addition, the new solution would need to simplify the assembly of the device.

Another modification to the cam that would be added if there was more time would be to anodize the lobes. This would increase the durability and the corrosion resistance of the lobes.

Finally, a one-handed locking mechanism would be a necessary feature for this cam in the future. Although this was a goal of ours, with time constraints we were not able to implement a locking mechanism for the cam.

9.2 Reflection

Over the duration of this project, the tasks we completed well were the following: locating sufficient funding to cover our initial projections, reaching out to industry experts for help and resources, locating a testing location, brainstorming ideas, and lastly our time-management improved sufficiently when we started having more regular "check-in" meetings.

Similarly, there are many things that we could have done better throughout the project. First, we could have made design decisions earlier on. This problem was accompanied by too much time planning, and not enough testing new ideas quickly with simple prototypes. This would have allowed us to find new solutions to our problems more quickly and allowed us to progress with new designs. With respect to analysis we could have completed the FEA on the axle and carriage more promptly. The largest issue with this was that we were not experts using FEA and were learning the finite element method while trying to complete analysis for our device. Because of this completing the analysis took much longer than anticipated because we ran into problems that we did not know how to fix quickly. This set back the final design of the cam and restricted the amount of testing that we were able to complete. Overall allocating our time and resources properly was our biggest internal issue that we faced during the project. This was a direct effect of this being our first major long-term project, and we were learning and refining our design process throughout.

Ultimately, during this project we learned how invaluable it is to build early prototypes, as having a physical object to manipulate and test significantly cuts the amount of time speculating an idea's feasibility. Prototypes also provide the team confidence in their design direction and analysis. We also learned not to be afraid of reaching out to others in industry for advice and assistance. On we multiple occasions, we were astounded by how willing others were to help us achieve our goal of building our cam. Another factor that really helped us as a team is that we strived for open feedback and respectful criticism. We wanted to make the best camming device possible, so we were willing to change our behavior to make sure the team was working cohesively.

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Appendix A: Quality Function Development Table

Correlations	
Positive	+
Negative	−
No Correlation	

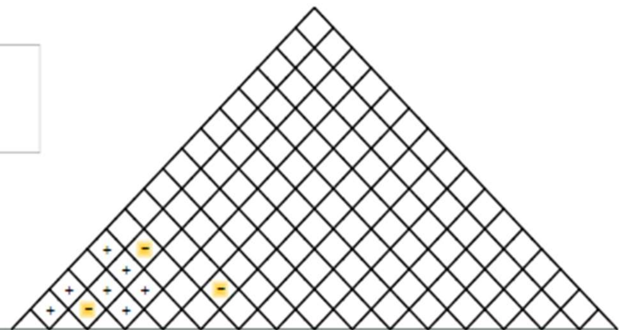
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: _Spring Loaded Camming Device_

Revision Date: ___10/15/2019___



Row #	Weight Chart	Relative Weight	Rock Climber	Manufacturing	Retail/company	Company	Maximum Relationship	WHAT: Customer Requirements (Needs/Wants) / HOW: Engineering Specifications (tests)	Tensile Strength	Cost	Weight	Usable range	Angle of stem deformation over	Machining Tolerances	Buckle under trigger load	8	9	10	11	12	13	14	15	16	Valley Giant # 9	Merlin Cam #8	Black Diamond #6	Trango Big Bros	Kong Gispy	Row #
								Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16						
								Direction of Improvement	▲	▼	▼	▲	▲	▲	▼															
1		8%	8	1	6	6	9	Lightweight*	○	○	●	▽			○										2	5	4	4	4	1
2		8%	8	1	6	6	9	Large Usable Range		▽		●													3	4	4	5	4	2
3		11%	8	5	6	6	9	Flexible Stem*	▽	▽	▽		●		●										2	1	4	5	5	3
4		8%	8	5	5	5	3	Durable*	○	▽			▽		▽										4	3	4	4	4	4
5		8%	7	1	7	7	3	Quality (Feeling)			▽		▽	○	○										2	3	4	4	3	5
6		7%	7	1	5	5	9	Affordable*		●															3	3	4	3	4	6
7		10%	1	9	2	6	9	Manufacturability		○		▽		●											4	3	3	5	4	7
8		8%	4	1	8	8	3	Marketable	▽	○	▽	▽	▽												3	3	5	4	3	8
9		9%	9	5	5	7		Biteable																	4	4	4	1	2	9
10		7%	6	3	4	5		Locking Mechanism																	3	3	4	5	3	10
11		8%	6	5	5	6	1	Ergonomic							▽										3	2	4	4	3	11
12		8%	8	2	6	6	3	Holding power	○			▽													4	4	4	3	3	12
13		0%																												13
14		0%																												14
15		0%																												15
16		0%																												16

WHO: Customers; NOW: Curr. Products

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	HOW MUCH: Target Values	>141N	<$200	<900g	6-9 in	>90°	0.002 in	Y/N									
	Max Relationship	3	9	9	9	9	9	9									
	Technical Importance Rating	91.69	162.1	95.09	102.4	120.1	113.7	159.4				0	0	0	0	0	0
	Relative Weight	11%	19%	11%	12%	14%	13%	19%				0%	0%	0%	0%	0%	0%
Curr. Products	Valley Giant # 9	5	2	2	3	1	3	5									
	Merlin Cam #8	2	2	4	3	1	3	5									
	Black Diamond #6	4	4	5	1	4	3	4									
	Trango Big Bros	3	3	5	4	5	3	5									
	Kong Gispy	4	3	4	2	5	3	5									
	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Appendix B: Idea Bank

The following document is a list of all the ideas we accumulated during our research and ideation sessions. The ideas are categorized by component/function and are ordered from most realistic and feasible to most imaginative

Lobe Design
Logarithmic Spiral
Super Cam
Totem Cam
Wavy edge
Extra block
Sandpaper edge
Soft Metal
Bicycle Spokes
Carbon Fiber
Teeth
Suction cup
Carrousel
Balloon
Wings
Umbrella
Gecko Hands

Miscellaneous
Bungee cord
Parachute
Net
Propeller
Pad
Static electricity
Big Bro
Springboard
Kong
UFO Webbing
Car Jack
Wedges

Stem Design
Pure U Stem
Pressed U Stem
Single Strand, Looped
Single Strand No Loop
Totem Double Pressed U
X4
Z4
Ribbed Stem

Trigger Mechanism
Straight Bar
U-bar
Butterfly Trigger
I-Shaped Trigger
Pulley Trigger
Individual Lobe Control
Internal Trigger

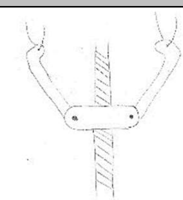
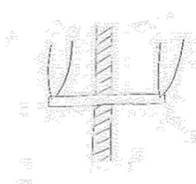
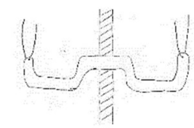
Locking Mechanism
Collar Lock
Spring Loaded Pin
Twist Hook
Clips (Like Black Diamond)
Rotating U-Pin
Pen Lock
Skirt Notch
Slot Lock
Magnet
Hook
Trigger slide
Tongs
Twisting ring lock

Appendix C: Pugh Matrices

Once we filtered through our ideation notes and finished creating concept prototypes, we spent time ranking the ideas we found most feasible using Pugh Matrices. In a Pugh matrix, we set one of the concepts as a datum, and judge whether the other solutions perform better, worse, or equivalent to the datum design in set of criteria. We created Pugh matrices for the Trigger Mechanism, Stem Design and Locking Mechanism. We did not make a Pugh matrix for the Lobe design as we plan on using a logarithmic spiral. Other, more exotic designs are either patented or impractical. Any design deviation from the logarithmic spiral shape will be dictated by geometric and finite element analysis.

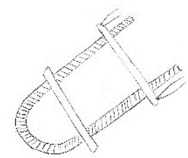
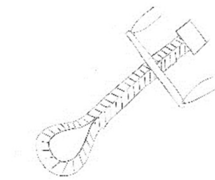
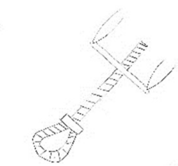
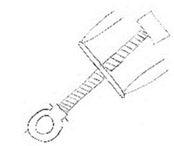
Trigger Design

S: Datum Performance
+: Better than Datum Performance
-: Worse than Datum Performance

		Concepts		
		 **Butterfly Trigger**	 **Straight Bar**	 **U-Bar**
Criteria	**Size** Small (+)/Large (-)	+	S	S
	Ergonomics High (+)/Low (-)	S	S	+
	Ease of Manufacturing Easy (+)/Difficult (-)	-	S	S
	Travel Less (+)/More (-)	+	S	S
Sums	**Σ (+)**	2	0	1
	Σ (-)	1	0	0
	Σ (S)	1	4	3
	Total Score	1	0	1

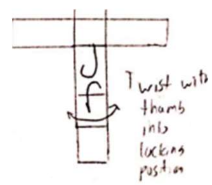
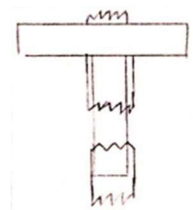
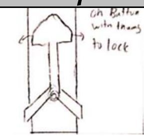
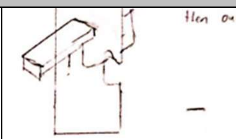
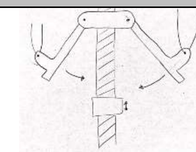
Stem Design

S: Datum Performance
+: Better than Datum Performance
-: Worse than Datum Performance

		Concepts			
					
		Pure U	**Pressed U**	**Single Strand Looped**	**Single Strand No Loop**
Criteria	**Size** Small (+)/Large (-)	**-**	**S**	**S**	**S**
	Tensile Strength High (+)/Low (-)	**+**	**+**	**S**	**S**
	Flexibility Flexible (+)/Inflexible (-)	**-**	**-**	**S**	**S**
	Ease of Manufacturing Easy (+)/Difficult (-)	**S**	**S**	**S**	**-**
	Resistance to Buckling High (+)/Low (-)	**+**	**+**	**S**	**S**
Sums	**Σ (+)**	2	2	0	0
	Σ (-)	2	1	0	1
	Σ (S)	1	2	5	4
	Total Score	0	1	0	-1

Locking Mechanism

S: Datum Performance
+: Better than Datum Performance
- : Worse than Datum Performance

		Concepts				
		 **Twist Lock**	 **Pen Lock**	 **Thumb Press Lock (Tong)**	 **Lateral Finger Bar (Slot)**	 **Collar** **(With Butterfly Trigger)**
Criteria	**Ease of Manufacturing** Easy (+)/Difficult (-)	+	**S**	+	+	+
	One Handed Locks Easy (+)/Difficult (-)	-	**S**	-	**S**	-
	One Handed Unlocks Easy (+)/Difficult (-)	**S**	**S**	**S**	**S**	**S**
	Accidental Unlocks Difficult (+)/Easy (-)	-	**S**	-	**S**	**S**
	Size Large (+)/Small (-)	+	**S**	-	+	+
	Potential for Snagging High (+)/Low (-)	-	**S**	-	-	+
Sums	**Σ (+)**	2	0	1	2	3
	Σ (-)	2	0	4	1	1
	Σ (S)	2	0	1	3	2
	Total Score	0	0	-3	1	1

Appendix D: Design Hazard Checklist

The design hazard checklist helps us ensure that we have a plan to address any safety concerns our design may possess. After identifying potentially hazardous aspects of our design, we provided a brief description of our corrective-action plans for each concern.

Y N

× ☐ 1. Will the system include hazardous revolving, running, rolling, or mixing actions?

☐ × 2. Will the system include hazardous reciprocating, shearing, punching, pressing, squeezing, drawing, or cutting actions?

☐ × 3. Will any part of the design undergo high accelerations/decelerations?

☐ × 4. Will the system have any large (>5 kg) moving masses or large (>250 N) forces?

☐ × 5. Could the system produce a projectile?

☐ × 6. Could the system fall (due to gravity), creating injury?

☐ × 7. Will a user be exposed to overhanging weights as part of the design?

× ☐ 8. Will the system have any burrs, sharp edges, shear points, or pinch points?

☐ × 9. Will any part of the electrical systems not be grounded?

☐ × 10. Will there be any large batteries (over 30 V)?

☐ × 11. Will there be any exposed electrical connections in the system (over 40 V)?

× ☐ 12. Will there be any stored energy in the system such as flywheels, hanging weights or pressurized fluids/gases?

☐ × 13. Will there be any explosive or flammable liquids, gases, or small particle fuel as part of the system?

× ☐ 14. Will the user be required to exert any abnormal effort or experience any abnormal physical posture during the use of the design?

☐ × 15. Will there be any materials known to be hazardous to humans involved in either the design or its manufacturing?

☐ × 16. Could the system generate high levels (>90 dBA) of noise?

☐ × 17. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, or cold/high temperatures, during normal use?

× ☐ 18. Is it possible for the system to be used in an unsafe manner?

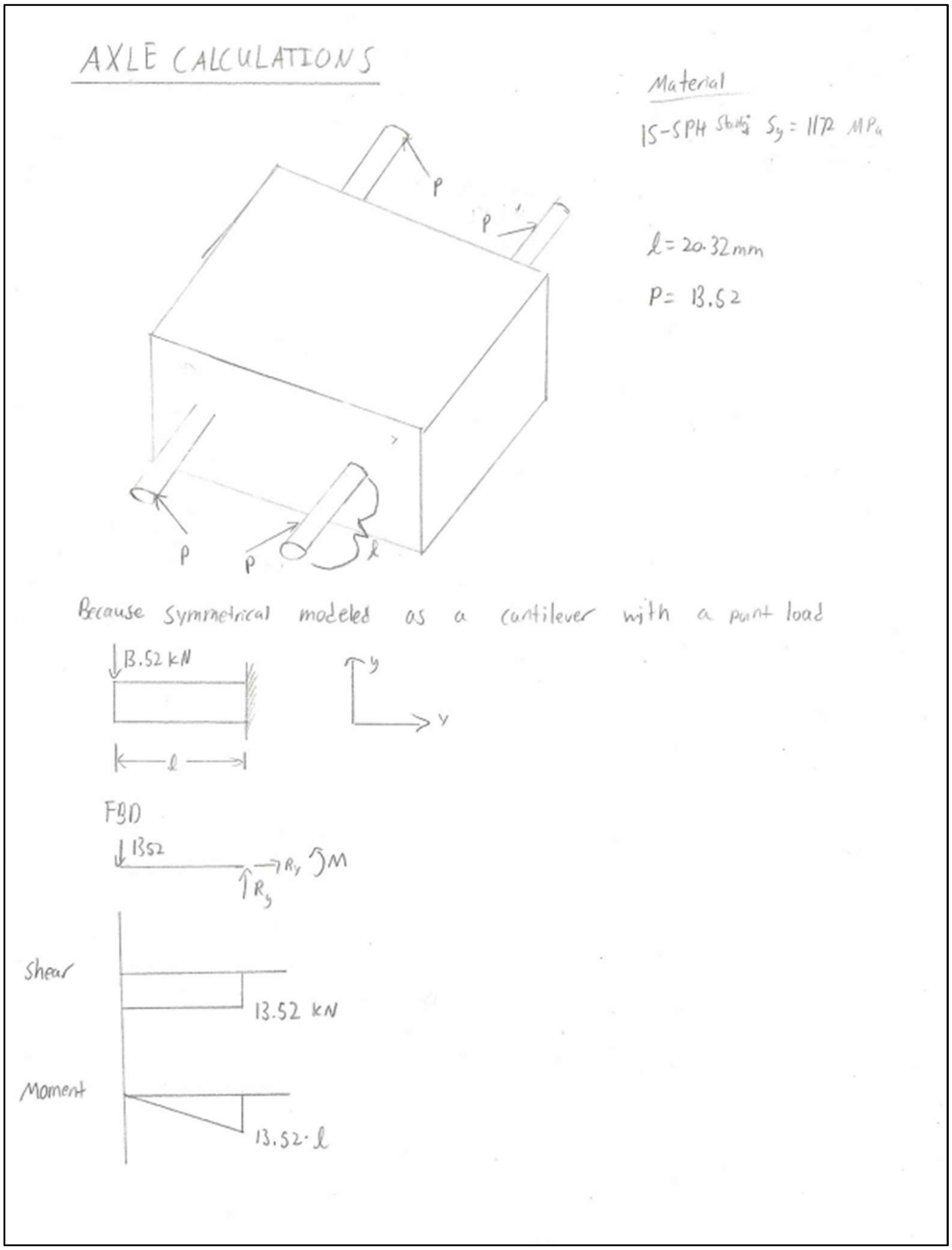
☐ × 19. For powered systems, is there an emergency stop button?

☐ × 20. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
Will the system have any pinch points?	It is possible that the user could pinch their fingers between the rotating cam lobes. However, when in use, if the device is being used correctly, their fingers should far away from the lobes. Unfortunately, the lobes are integral to design of the cam, so we cannot avoid the pinch point. We will design the lobes to have large edge radiuses to avoid unwanted lacerations.	April	2/28
Will there be any stored energy in the system such as flywheels, hanging weights or pressurized fluids/gases?	The device will be spring-loaded. When loading the trigger, a spring acts as resistance. We will ensure that the spring is not too stiff and easily loaded using finger strength.	January	1/30
Is it possible for the system to be used in an unsafe manner?	If improperly placed, the cam can fail to hold the force of a falling person. We plan to include an instruction manual detailing how to properly place the cam.	April	4/20

Appendix E: Hand Calculations

The following hand calculations were used to size the cam's axles and lobe thickness.



Bending

$$\sigma = \frac{My}{I}$$

$$\sigma = \frac{Pl \cdot \frac{d}{2}}{\frac{1}{4}\pi\left(\frac{d}{2}\right)^4}$$

$$\sigma = \frac{Pl}{\frac{1}{4}\pi\left(\frac{d}{2}\right)^3}$$

$$F_S = \frac{S_y}{\sigma}$$

$$\sigma = \frac{S_y}{F_S}$$

$$\frac{S_y}{F_S} = \frac{Pl}{\frac{1}{4}\pi\left(\frac{d}{2}\right)^3}$$

$$\frac{F_S\, P \cdot l}{\frac{1}{4}\pi S_y} = \left(\frac{d}{2}\right)^3$$

$$\left(\frac{F_S\, P \cdot l}{\frac{1}{4}\pi S_y}\right)^{1/3} \cdot 2 = d$$

$$\left(\frac{1 \cdot 13.52\,kN \cdot 20.32\,mm \cdot \frac{1000N}{1\,kN}}{\frac{1}{4}\pi\ 1172\ MPa}\right)^{1/3} \cdot 2 = d$$

$d = 13.4\ mm$

MUCH LARGER Than comparable cams need a better model.

Shear

$$\tau = \frac{4V}{3A}$$

$$\tau = \frac{4V}{3\pi \frac{d}{2}^2}$$

$$F_S = \frac{\tau_y}{\tau}$$

$$\tau = \frac{\tau_y}{F_S}$$

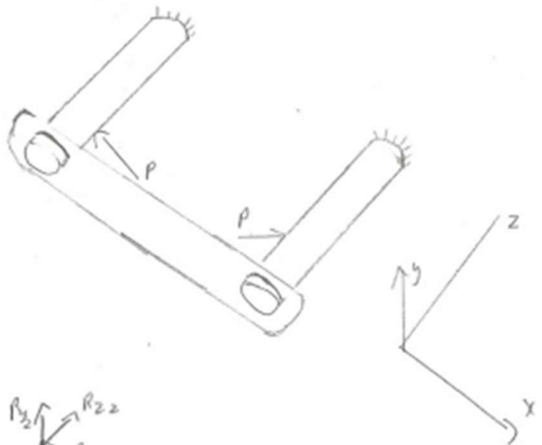
$$\frac{\tau_y}{F_S} = \frac{4V}{3\pi\left(\frac{d}{2}\right)^2}$$

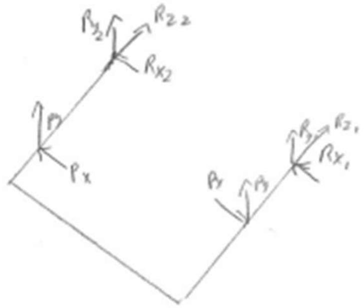
$$d = 2 \cdot \left(\frac{4V\ F_S}{3\pi\ \tau_y}\right)^{1/2}$$

$$d = 2 \cdot \left(\frac{4 \cdot 13.52\,kN \cdot \frac{1000N}{1kN}}{3\pi\ 1172\ MPa}\right)^{1/2}$$

$d = 4.66\ mm$

New Model with Structural end caps





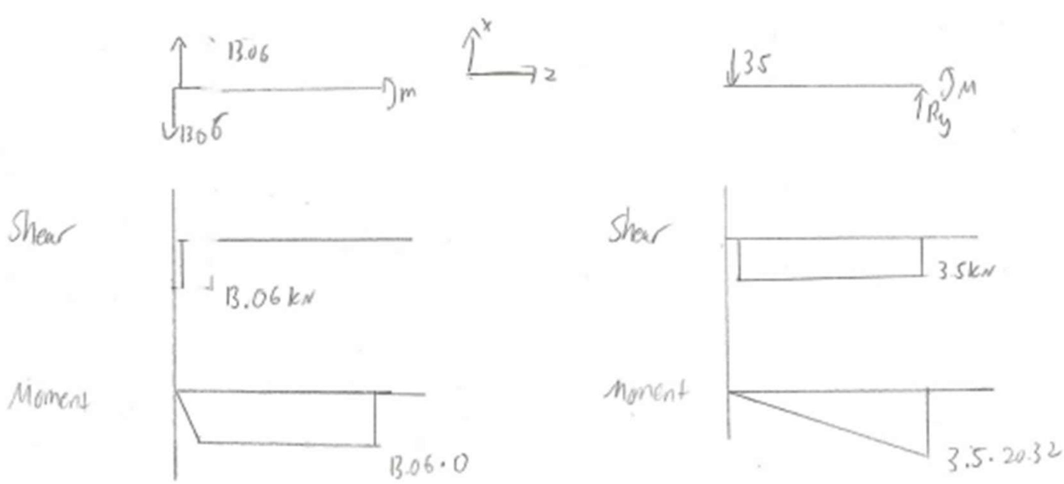
$\Sigma F_x = 0$

$-R_{x_1} - R_{x_2} - P_x + P_z = 0$

$-R_{y_1} = R_{y_2} = 0$

X-z plane with end cap cut

y-z plane



Bending

$$\sigma = \frac{M_{max}\, y}{I}$$

$$d = \left(\frac{F_s P \ell}{\frac{1}{4}\pi S_y}\right)^{1/3} \cdot 2 = d$$

$$d = \left(\frac{1 \cdot 3.5\,kN \cdot 20.32\,mm \cdot 1000\,\frac{1000\,N}{kN}}{\frac{1}{4}\pi\ 1172\ MPa}\right)^{1/3} \cdot 2$$

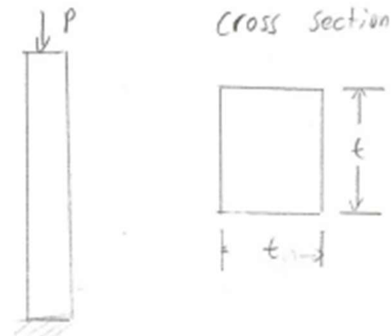
d = 8.511 mm

Shear

Max Shear Same as previous model

d = 4.66 mm

Buckling analysis



Fixed Free end conditions

Euler column buckling

$$P_{cr} = \frac{C \pi^2 E I}{\ell^2}$$

$$P_{cr} = \frac{C \pi^2 E \frac{1}{12} b(h)^3}{\ell^2}$$

<u>IN Plane</u>

$$P_{cr} = \frac{C \pi^2 E\, t(t)^3 \frac{1}{12}}{\ell^2}$$

$$\frac{12 P_{cr} \ell^2}{C \pi^2 E} = t^4$$

$$t = \left(\frac{12 P_{cr} \ell^2}{C \pi^2 E} \right)^{1/4}$$

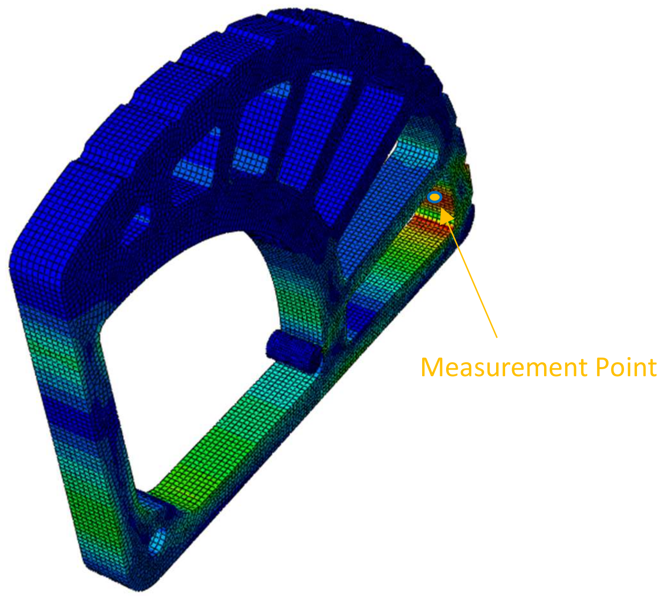
$$t = \frac{12 \cdot 13.52\,kN \cdot \left(7.104\,in \cdot \frac{1\,mm}{0.0394\,in}\right)^2}{.25 \cdot \pi^2 \cdot 68.9\,GPa}$$

$t = 13.28\,mm$

$t = 0.52\,in$

Appendix F: Lobe FEA Convergence Study

Measurement Point



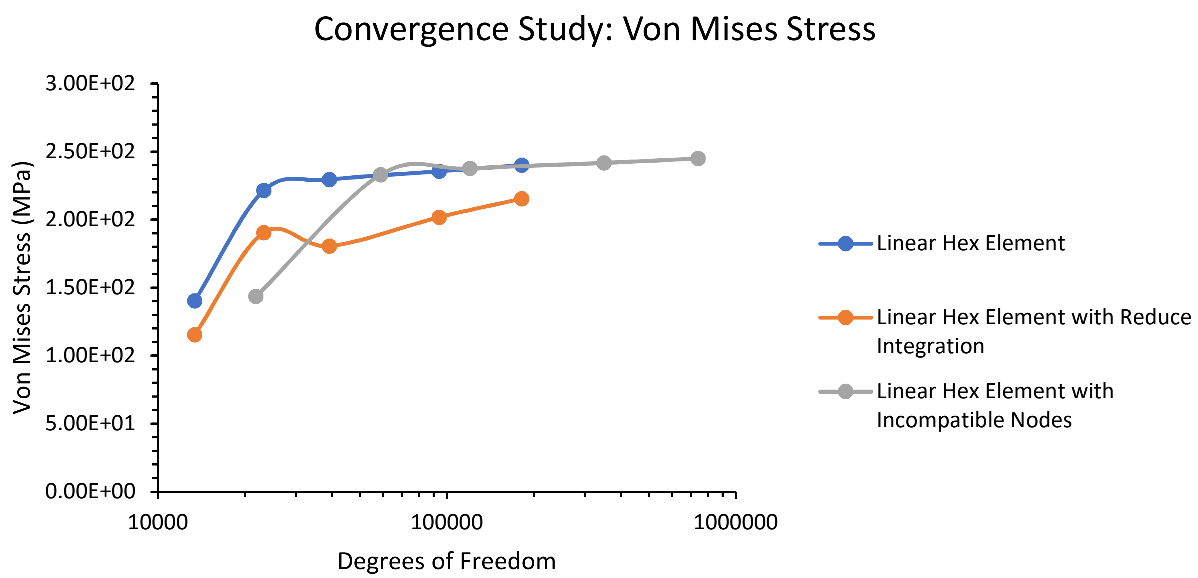
Von Mises Stress Convergence Tables and Plot

Table 1a: Von Mises Convergence for Linear Hex Element		
Global Mesh Size (mm)	Degrees of Freedom	Von Mises Stress (MPa)
10	13401	1.40E+02
5	23229	2.21E+02
3	39234	2.29E+02
2	94041	2.36E+02
1.5	181707	2.40E+02

Table 1b: Von Mises Convergence for Linear Hex Element with Reduced Integration		
Global Mesh Size (mm)	Degrees of Freedom	Von Mises Stress (MPa)
10	13401	1.15E+02
5	23229	1.90E+02
3	39234	1.81E+02
2	93969	2.02E+02

1.5	181707	2.15E+02

Table 1c: Von Mises Convergence for Linear Hex Element with Incompatible Nodes		
Global Mesh Size (mm)	Degrees of Freedom	Displacement (mm)
10	21825	1.43E+02
5	58953	2.33E+02
3	119990	2.38E+02
2	349588	2.42E+02
1.5	739914	2.45E+02



Principle Stress Convergence Tables and Plot

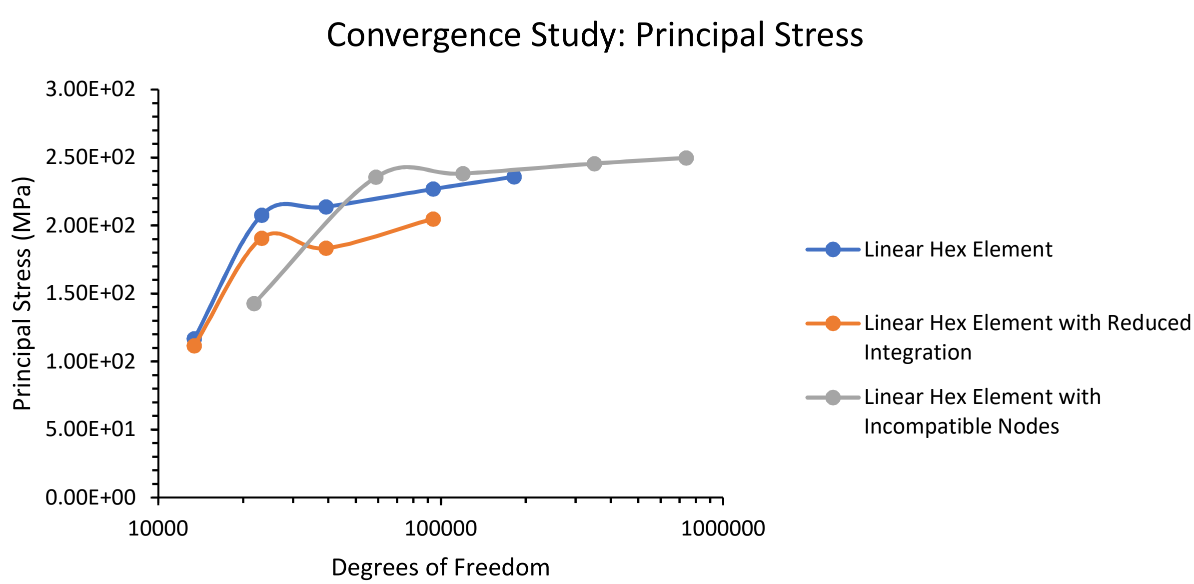
Table 2a: Principle Stress Convergence for Linear Hex Element		
Global Mesh Size (mm)	Degrees of Freedom	Principal Stress (MPa)
10	13401	1.17E+02
5	23229	2.08E+02
3	39234	2.14E+02
2	94041	2.27E+02
1.5	181707	2.36E+02

Table 2b: Principle Stress Convergence for Linear Hex Elements with Reduced Integration		
Global Mesh Size (mm)	Degrees of Freedom	Principal Stress (MPa)

10	13401	1.12E+02
5	23229	1.91E+02
3	39234	1.83E+02
2	93969	2.05E+02
1.5	181707	2.19E+02

Table 2c: Principle Stress Convergence for Linear Hex Element with Incompatible Nodes

Global Mesh Size (mm)	Degrees of Freedom	Principal Stress (MPa)
10	21825	1.43E+02
5	58953	2.36E+02
3	119990	2.38E+02
2	349588	2.46E+02
1.5	739914	2.50E+02



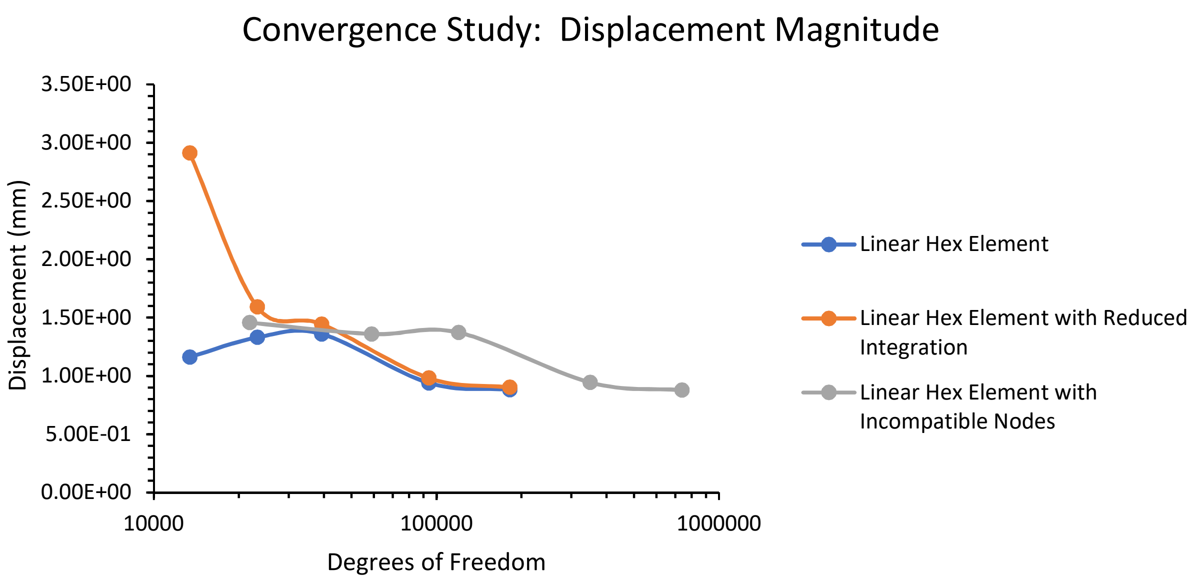
Displacement Convergence Tables and Plot

Table 3a: Displacement Convergence for Linear Hex Element with Incompatible Nodes

Global Mesh Size (mm)	Degrees of Freedom	Displacement (mm)
10	13401	1.16E+00
5	23229	1.33E+00
3	39234	1.36E+00
2	94041	9.40E-01
1.5	181707	8.81E-01

Table 3b: Displacement Convergence for Linear Hex Element with Incompatible Nodes		
Global Mesh Size (mm)	Degrees of Freedom	Displacement (mm)
10	13401	2.91E+00
5	23229	1.59E+00
3	39234	1.44E+00
2	93969	9.81E-01
1.5	181707	9.02E-01

Table 3c: Displacement Convergence for Linear Hex Element with Incompatible Nodes		
Global Mesh Size (mm)	Degrees of Freedom	Displacement (mm)
10	21825	1.46E+00
5	58953	1.36E+00
3	119990	1.37E+00
2	349588	9.44E-01
1.5	739914	8.78E-01



Appendix G: Complete Cost Tables

The complete cost table details the price and source for each component of the cam.

Table 1F: Component Cost Table

Subsystem	Part Number	Component	Materials to Purchase	Size/ Quantity needed per Cam	Source	Source Contact Information	Shipment Time	Source Size/Quantity	Purchase Quantity	Cost	Cost Per Cam
Carriage	105	Carriage	1″ x 5″ Bar Stock 6061 Al	3.5″ x 2.5″	Coast Aluminum	Phone: 555-495-6061 Website: coastaluminum.com	2-Days	12 ft.	1	$175.67	$17.57
Head Assembly	211	Axles	17-4PH SS, 5/16 Round Stock	10 in	Online Metals	Website: onlinemetals.com	2 Days	5 ft.	2	$74.05	$7.41
	221	Lobes	.625″ x 5″ Bar Stock 6061 Al	8 in	Coast Aluminum	Phone: 555-495-6061 Website: coastaluminum.com	2-Days	12 ft.	3	$325.51	$32.55
	231	Axle Linkage	304 SS, 14 Gauge Sheet	3″ x 0.5″	Metals Depot	Website: metalsdepot.com	5-Business Days	1′ x 1′	1	$43.07	$4.31
	241	Axle Springs	0.05″ D Piano Wire	1.5 ft	Home Depot	Phone: (805)596-0857 Store Hours: 6 AM – 8PM	5 Days	9 ft.	2	$8.14	$0.81
	251	Snap Rings	Pre-built	4	McMaster Carr	Website: mcamaster.com	4 Days	100	1	$16.72	$1.67
Stem Assembly	311	Stem Cable	3/16″, 1x19 T304 Cable	2 ft.	Lexco Cable	Website: lexcocable.com	1-week	Can be specified	15 ft	$41.38	$4.14
	321	Swage	Pre-built	4	McMaster Carr	Website: mcmaster.com	4 Days	Pack of 10	4	$52.85	$5.28
	331	Electrical Tape	Pre-built	~ 5 ft.	Home Depot	Phone: (805)596-0857 Store Hours: 6 AM – 8PM	None	66 ft.	1	$4.75	$0.48
Trigger Assembly	411	Trigger A	None: 3-D Printed Part (ASA Plastic)	2	Innovation Sandbox	Email: sandboxprinting@gmail.com Website: theinnovationsandbox.com	Maximum: 2 weeks Typical: 1 week	Can be specified	2	$0.00	$0.00
	421	Trigger B	None: 3-D Printed Part (ASA Plastic)	2	Innovation Sandbox	Email: sandboxprinting@gmail.com Website: theinnovationsandbox.com	Maximum: 2 weeks Typical: 1 week	Can be specified	2	$0.00	$0.00
	431	Trigger Cord	2.75 mm Accessory Cord	2 ft.	Amazon	N/A	2 Days	50 ft.	1	$24.67	$2.47
	441+451	Tiller Wire Clamp + Flathead Screw	Pre-built	1	Amazon	N/A	5 Days	2	5	$34.96	$3.50

Subsystem	Part Number	Component	Materials to Purchase	Size/ Quantity needed per Cam	Source	Source Contact Information	Shipment Time	Source Size/Quantity	Purchase Quantity	Cost	Cost Per Cam
	461+471	Through Screw + Nut	Pre-built	1 of Each	Home Depot	Phone: (805)596-0857 Store Hours: 6 AM – 8PM	None	5 of Each	2	$2.36	$0.24
									Totals	$804.13	$80.43

Table 2F: Transaction Record Table

Date	Description	Source	Recipient	Amount
1/23/2020	Tiller Clamps	Jared Christner	Amazon	$7.51
1/24/2020	Stem Cable for Structural Prototype	Kaitlin DeHerrera	Lexco Cables	$40.38
2/7/2020	MESFAC Funding	MESFAC	Team	$835.40 available for reimbursement
2/11/2020	Kevlar Line for Trigger Wire (Unused)	Jared Christner	Amazon	$10.76
2/14/2020	Metal Stock for Lobes and Carriage	John Hickey	West Coast Aluminum	$562.44
2/21/2020	Steel Round Stock for Axles	Jared Christner	Online Metals	$74.05
3/3/2020	Sheet Metal for Axle Linkage	Jared Christner	Metals Depot	$43.07
3/4/2020	Snap Rings	Jared Christner	McMaster-Carr	$16.72
3/5/2020	Stem Materials	Kaitlin DeHerrera	Lexco Cables	$55.63
4/1/2020	Reimbursement for Stem Materials	MESFAC	Kaitlin DeHerrera	$41.28
4/30/2020	Reimbursement for Sheet Metal, Round Stock, and Snap Rings	MESFAC	Jared Christner	$133.84
5/13/2020	Machining Carriage and Axles	John Hickey	Rogue Engineering	$349.75
N/A	Reimbursement for Metal Stock	MESFAC	John Hickey	$562.44
N/A	Funding for Outsourced Manufacturing	CPConnect	John Hickey	$200.00

Appendix H: Failure Modes and Effects Analysis

The following table list the ways our cam could fail, the failure's severity, and its relative priority.

System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	Priority	Recommended Action(s)
Lobe/ secure into crack	Lobes Break	Falling	10	1) Lobe too weak 2) lobe too thin 3) axle holes shear 4) Lobes too soft	1) weigh users 2) impact factor 3) stress analysis 4) fatigue strength	2	Inspection	4	80	Resize lobe
	Lobes don't expand	Falling	10	1) spring too weak 2) lobes too heavy 3) too much resistance	1) smooth all edges/deburring 2) impact factor 3) stress analysis 4) fatigue strength	2	Inspection	3	60	Resize springs or lobes
	Lobe Buckles	Falling	10	1) Lobe too thin	1) weigh users 2) impact factor 3) stress analysis 4) Buckling analysis	2	Inspection	4	80	Resize lobe
Axles/lobe rotation	Axles Break	Falling	10	1) axle shears 2) axle too small 3) axle too big	1) weigh users 2) impact factor 3) stress analysis 4) axle shear analysis	2	Inspection	4	80	Resize axles
carriage/ supports lobes and step	carriage breaks	Falling	10	1) carriage too weak 2) axle holes shear 3) stem connection too weak	1) weigh users 2) impact factor 3) stress analysis 4) hole shear analysis	2	Inspection	4	80	Resize carraige
	too heavy	Dissatisfied customer	3	1) carriage to large 2) axle too small	1) stress analysis	2	Inspection	3	18	No action Necessary
Stem/Support Person	Stem Interface Breaks	Falling	10	1) Stem too weak 2) carriage connection too weak	1) weigh users 2) impact factor 3) stress analysis	2	Inspection	3	60	Resize stem cap
Stem/ Comfortable use	too rigid (Stem Breaks)	Falling	10	1) Stem too thick 2) stem too short 3) stem too stiff	1) Buckling analysis	2	Inspection	3	60	Resize stem
	too flexible	Not easy to place	4	1) Stem too thin 2) stem too long 3) too much resistance to contraction	1) Buckling analysis	2	In-field testing	3	24	No Action Necessary
	Uncomfortable	User is uncomfortable	3	1) Stem too short 2) stem too long 3) shape of trigger not ergonomic	1) Prototyping 2) stakeholder feedback	5	Survey	3	45	No Action Necessary
Trigger/ Contract lobes	trigger wire breaks	Cannot move one or more lobes with the trigger	5	1) Trigger wire too thin 2) Trigger wire too weak 3) Too much lobe resistance	1) stress analysis	5	Inspection	3	75	reseize trigger wire
	triggers break	Cannot actuate the lobes. User may have to leave the device on the wall if it gets stuck.	5	1) Trigger too weak 2) trigger connection too weak	1) stress analysis	4	In-field testing	2	40	No Action Necessary
Trigger/ provides comfort	Too much resistance	hard to use	4	1) Springs too strong 2) stem too stiff 3) Lobes too soft	1) stakeholder feedback	5	Inspection	3	60	No Action Necessary
	trigges bars uncomfortable	uncomfortable to use	4	1) Trigger bar sharp 2) Trigger bar to far away 3) Slippery trigger bar 4) Lobes too soft	1) stakeholder feedback	5	Survey	3	60	No Action Necessary
	trigger wires interfere with fingers	difficult to fully contract	4	1) trigger wires too close to fingers 2) stem too short 3) stem too stiff 4) Lobes too soft	1) stakeholder feedback	4	Survey	2	32	No Action Necessary
Lock/Lock lobes in contracted position	Can't lock with one hand	difficult to lock	3	1) requires two hands 2) 3) stem too stiff 4) Lobes too soft	1) stakeholder feedback	4	Survey	4	48	No Action Necessary
	Unlocks Accidently	Unexpected expansion	2	1) collar rotating 2) tabs breaking 3) collar breaking 4)	1) stakeholder feedback	5	In-field testing	4	40	No Action Necessary

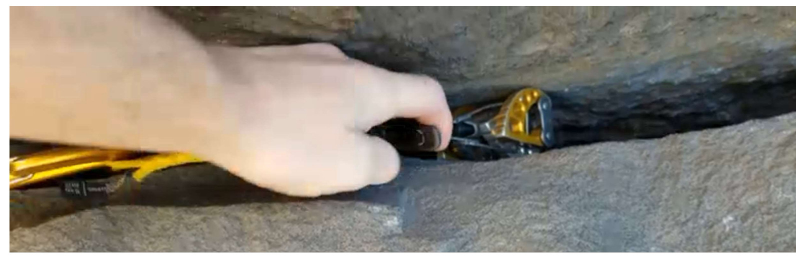
Appendix I: Operations Manual

WARNING [EN]

Climbing is inherently dangerous. You must understand and accept the risks involved before participating. You are responsible for your own actions and decisions. You must read and understand all instructions and warnings before use of this product. Be familiar with this device's capabilities and limitations before use. It is recommended that every climber seek training on proper use of this device. Failure to follow warnings could result in serious injury or death!

HOW TO USE YOUR CAM

Using this and other equipment correctly along with redundant systems will reduce some of the risk associated with climbing. Proper supervision is highly suggested if you lack experience.



Example of Proper Cam Placement

HOW TO CARE FOR AND MAINTAIN YOUR CAM

Keep the cam free of dirt and debris, and do not use the camming device for anything other than its intended use.

LIFESPAN, INSPECTION, AND RETIREMENT

Inspect the teeth of the cam for any flat spots these could be a sign the cam is not safe to use.
Look for any cracks or bends or sharp spots in the lobes of the cam. Check the spacing between the lobes and ensure that they do not slide along the axle.

Some worn material in a sling.

Worn down teeth on cam's lobes.

LIFESPAN, INSPECTION, AND RETIREMENT cont.

Inspect for any bends on the axle or missing material, which could cause stress concentrations.

Check the trigger wires for any fraying cuts or breaks. Inspect the slings for any fraying, cuts, or discoloration of the slings.

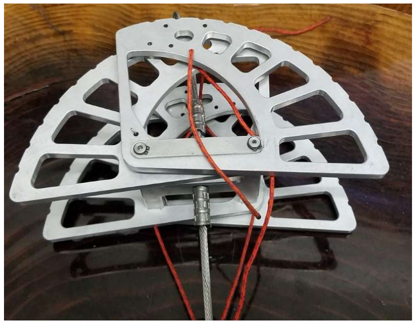
Photos:
Figures 3, 4, 5, 6. (2013). photograph. Retrieved from https://www.thebmc.co.uk/have-you-cahecked-your-camming-devices-recently

Fraying wire cable in stem.

An example of worn wire cable.

HOW TO PROPERLY STORE YOUR CAM

Keep your cam in a dry location and avoid placing it under any heavy objects, as this could damage the trigger strings.



The red/orange cord is the trigger cord, which should not be crushed under heavy objects as it can fray or be damaged.

Appendix J: Indented Bill of Materials

The indented bill of materials lists each component, its material, its cost per cam, and source.

Spring Loaded Camming Device

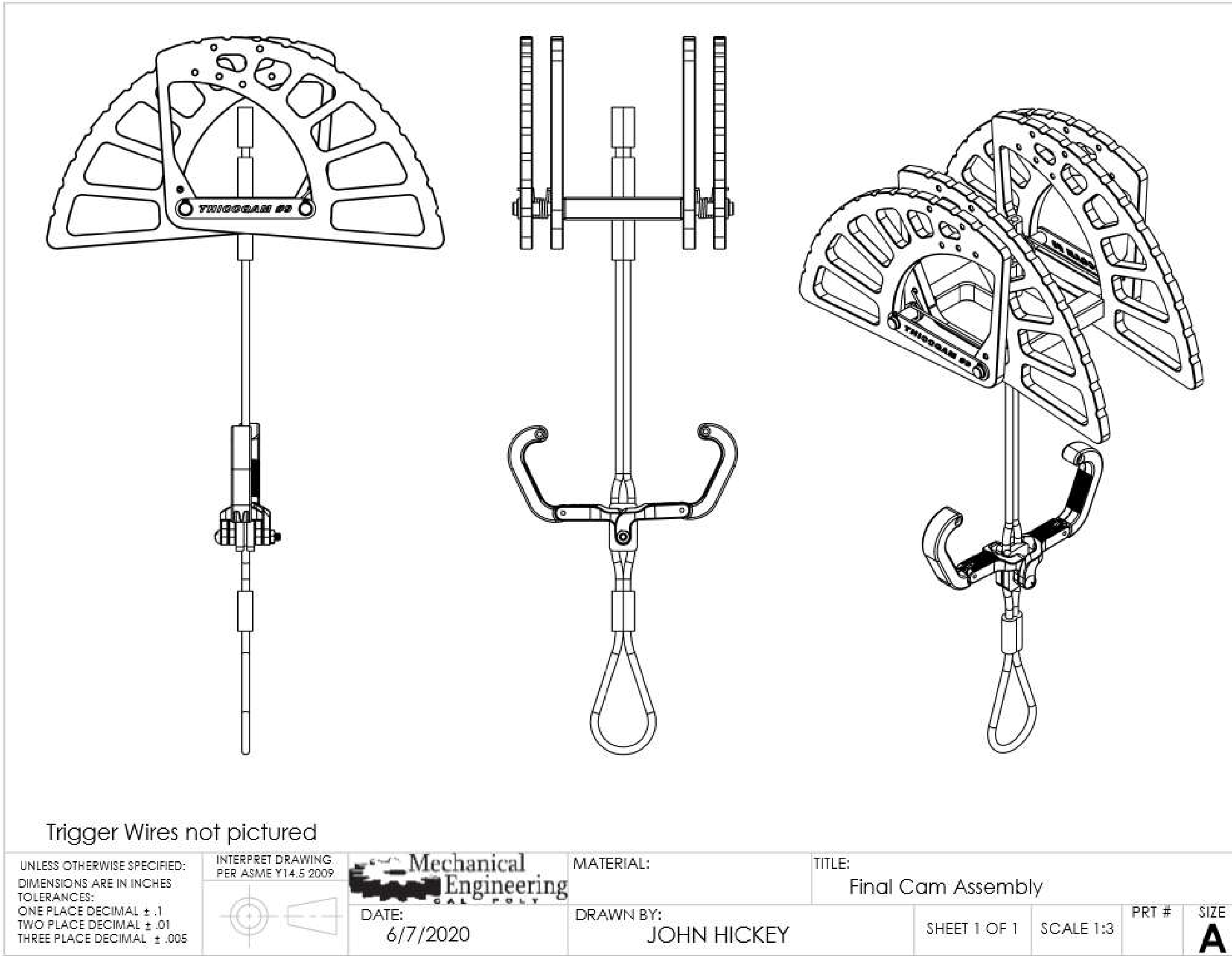
Indented Bill of Material (iBOM)

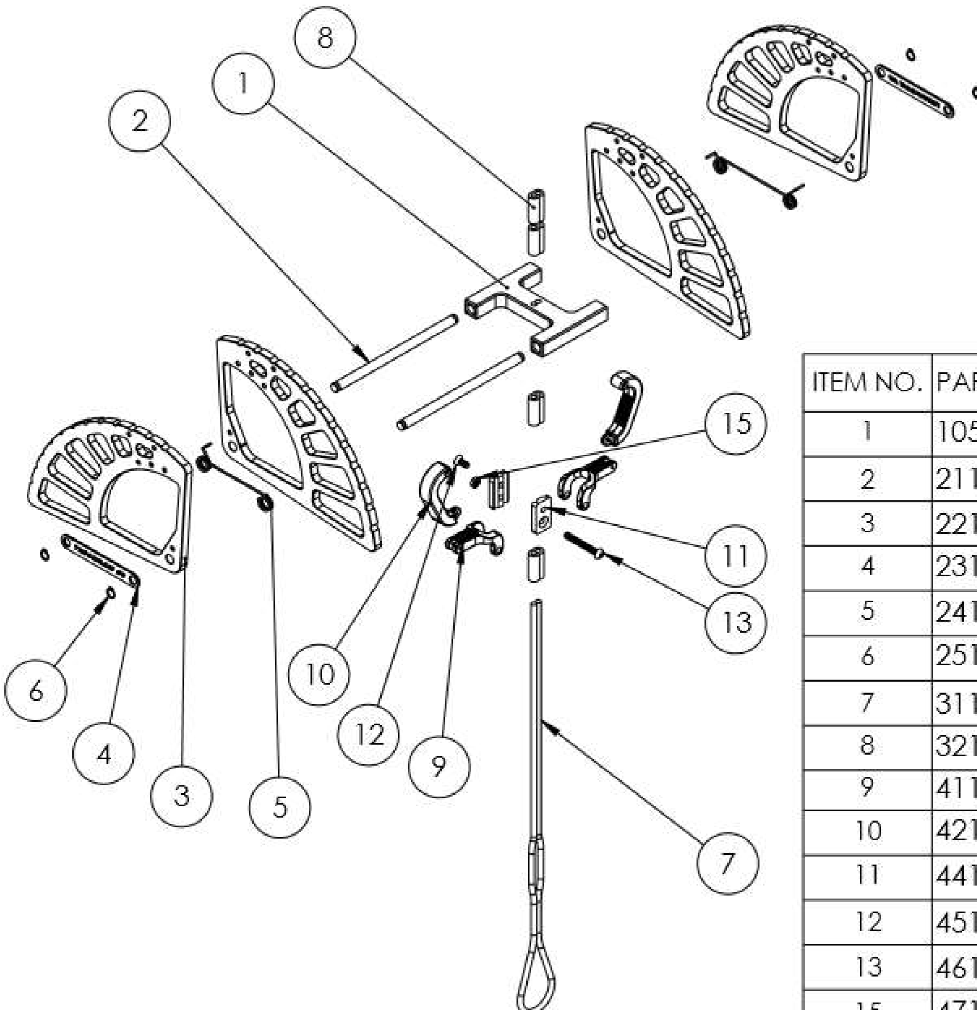
Assembly Level	Part Number	Description Lvl0	Lvl1	Lvl2	Lvl3	Lvl4	Matl	Qty	Cost	Ttl Cost	Source	More Info
105	Carriage						Al 6064 T6	1	$17.57	$17.57	Coast Aluminum	Item 15B61
200	—	Head Assembly										
	211		—	Axles			15-5PH Steel	2	$3.71	$7.41	Online Metals	
	221		—	Lobes			Al 6061-T6	4	$8.14	$32.55	Coast Aluminum	Item 585B61
	231		—	Axle Linkage			304 SS, 14 Gauge Sheet	2	$2.16	$4.31	Metals Depot	
	241		—	Axle Spring			0.05 Piano Wire	2	$0.41	$0.81	Home Depot	
	251		—	Snap Rings			1060 Spring Steel	4	$1.67	$1.67	McMaster-Carr	
300	—	Stem Assembly										
	311		—	Stem Cable			1x19 SSAC T304 cable	1	$4.14	$4.14	Lexco Cable	1x19 3/16" x 32"
	321		—	Swage			Zinc Plated Copper	4	$1.32	$5.28	McMaster-Carr	Item 3898T16
	331		—	Electical Tape			Electrical Tape	1	$0.48	$0.48	Home Depot	To wrap around the stem
400	—	Trigger Assembly										
	411		—	Trigger A			ASA Plastic	2	$0.00	$0.00	Innovation Sandbox	
	421		—	Trigger B			ASA Plastic	2	$0.00	$0.00	Innovation Sandbox	
	431		—	Trigger Cord			2.75 mm Accessory Cord	1	$2.47	$2.47	Amazon	
	441		—	Tiller Cable Clamp			Zinc	1	$3.50	$3.50	Sea dog line	
	451		—	#10-24 Flat Head Screw			Stainless Steel	1	$0.00	$0.00	Sea dog line	Comes with Tiller Clamp
	461		—	# 10-24 x 1.5 in. Screw			Stainless Steel	1	$0.24	$0.24	Home Depot	
	471		—	# 10-24 Nut			Stainless Steel	1	$0.00	$0.00	Home Depot	Comes with 1.5 in. Screw
	Total Parts							**30**		**$80.43**		

(Green) Parts we manufactured

Appendix K: Drawing Package

The drawing package contains all the detailed drawing of our manufactured components.





Trigger Cord not pictured

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	105	Carriage	1
2	211	Axles	2
3	221	Lobes	4
4	231	Axle Linkage	2
5	241	Axle Spring	2
6	251	Axle Snap Ring	4
7	311	Stem Cable	1
8	321	Swage	4
9	411	Trigger A	2
10	421	Trigger B	2
11	441	Tiller Cable Clamp	1
12	451	#10-24 Flathead Screw	1
13	461	#10-24 x 1.5 in. Screw	1
15	471	#10-24 Nut	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
ONE PLACE DECIMAL ± .1
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .005

INTERPRET DRAWING PER ASME Y14.5 2009

Mechanical Engineering CAL POLY

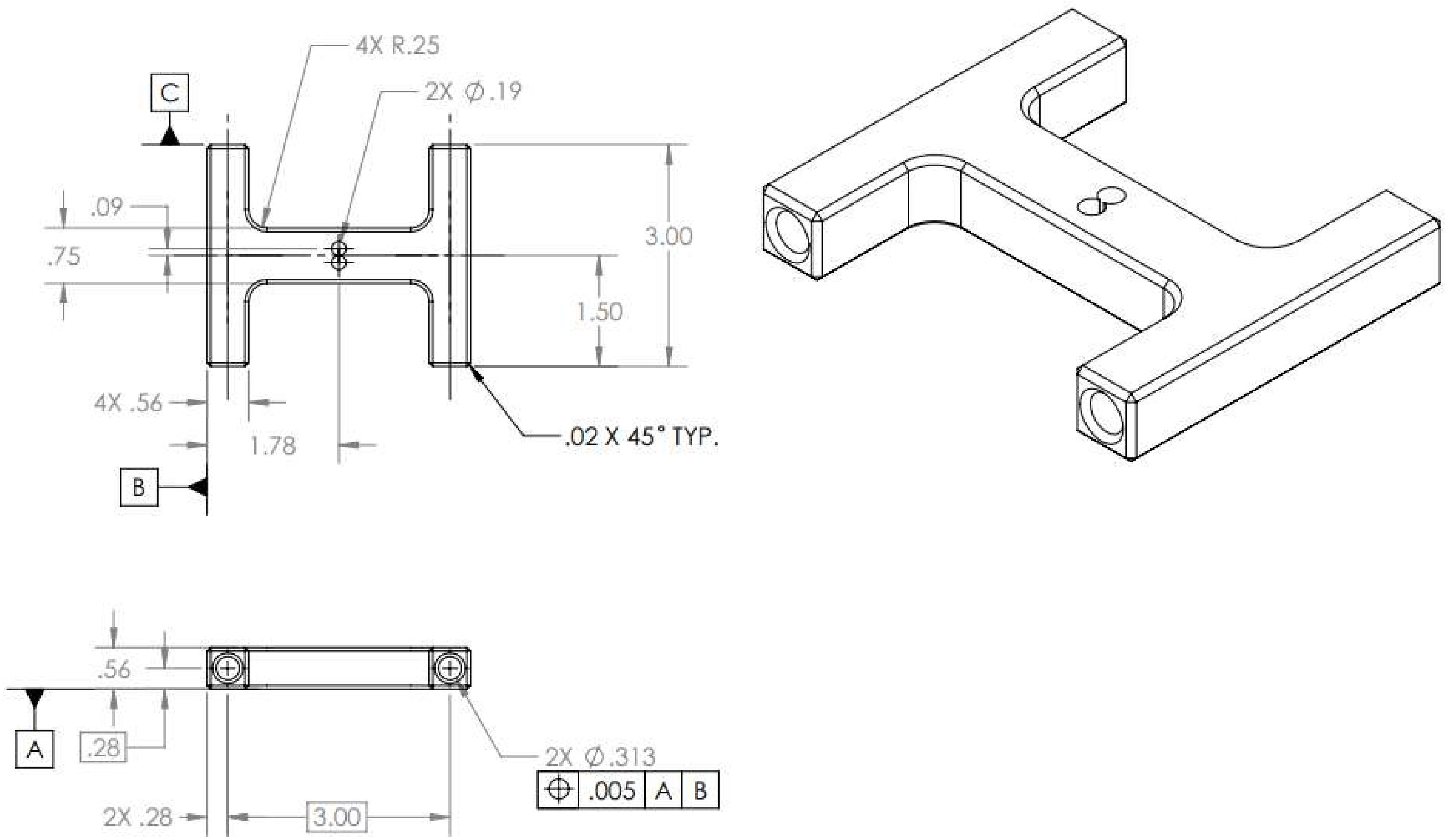
MATERIAL:

TITLE: Exploded Assembly Drawing

DATE: 6/8/2020

DRAWN BY: JOHN HICKEY

SHEET 1 OF 1 | SCALE: 1:5 | PRT # | SIZE A



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
ONE PLACE DECIMAL ± .1
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .005

INTERPRET DRAWING PER ASME Y14.5 2009

Mechanical Engineering

MATERIAL: 6061-T6 ALUMINUM

TITLE: CARRIAGE

DATE: 6/7/2020

DRAWN BY: John Hickey

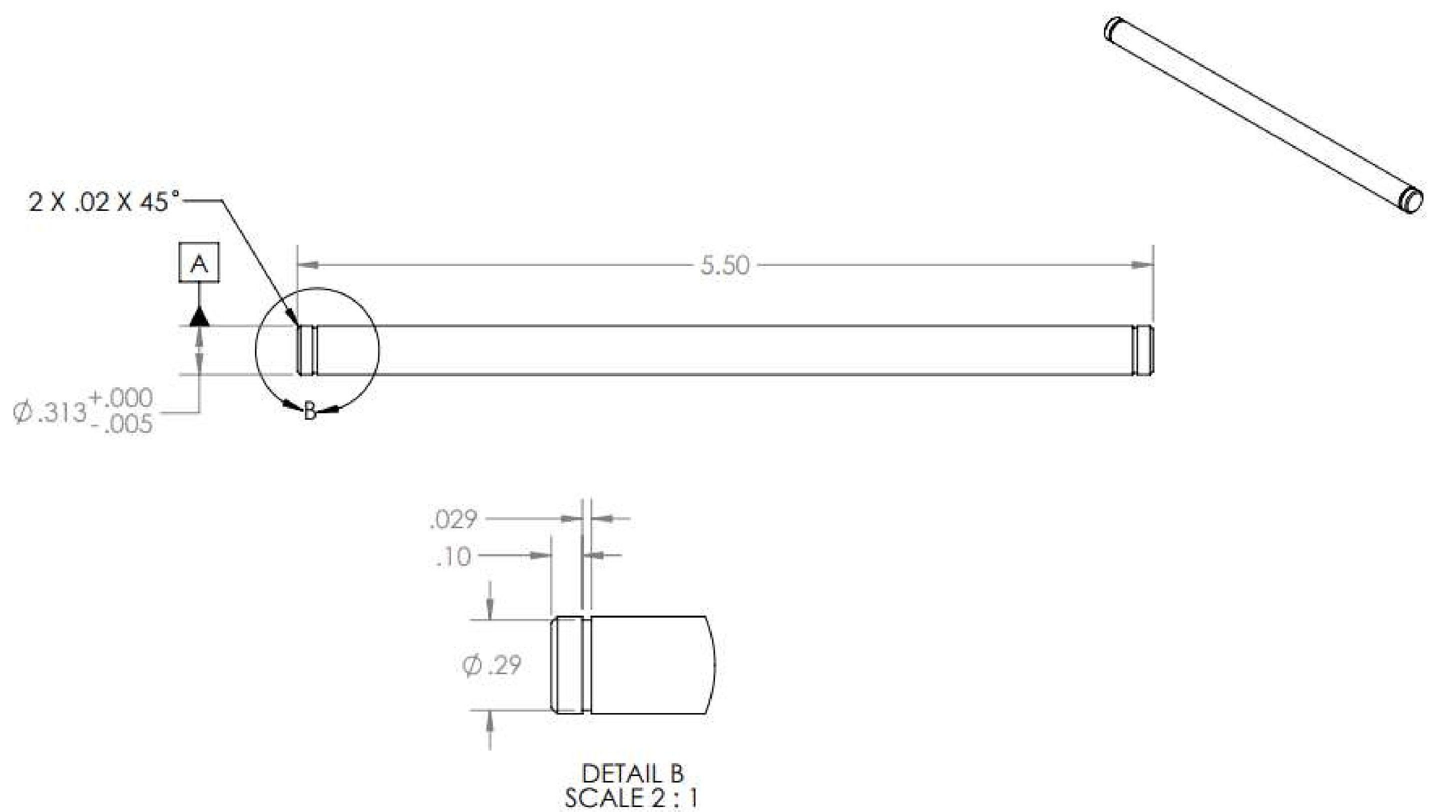
SHEET 1 OF 1

SCALE: 1:2

PRT # 105

SIZE A

Y



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
ANGLES ± 1°
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .005

INTERPRET DRAWING PER ASME Y14.5 2009

Mechanical Engineering

MATERIAL: 17-4 PH STAINLESS STEEL

TITLE: AXLE

DATE: 4/8/2020

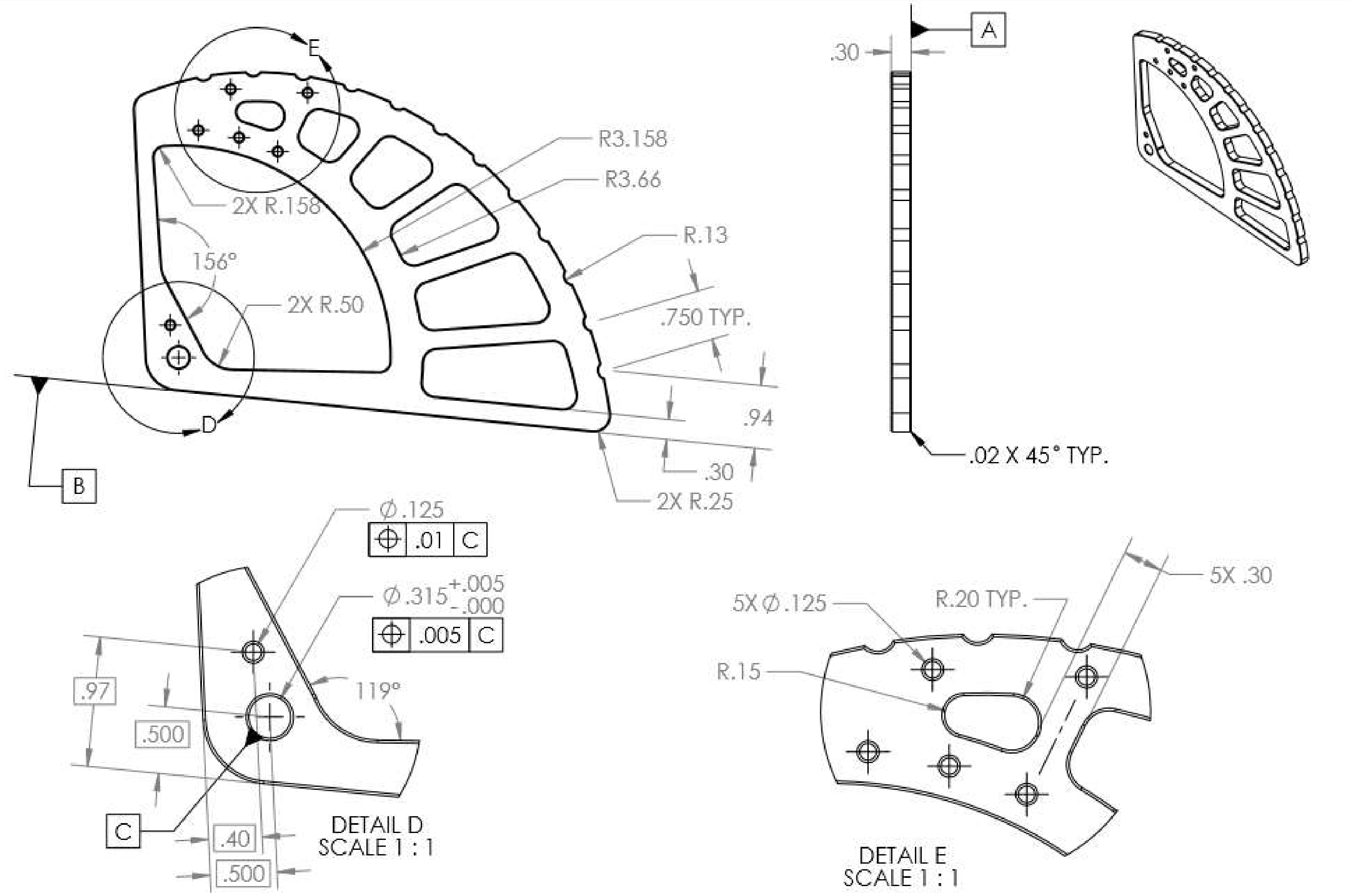
DRAWN BY: JOHN HICKEY

SHEET 1 OF 1

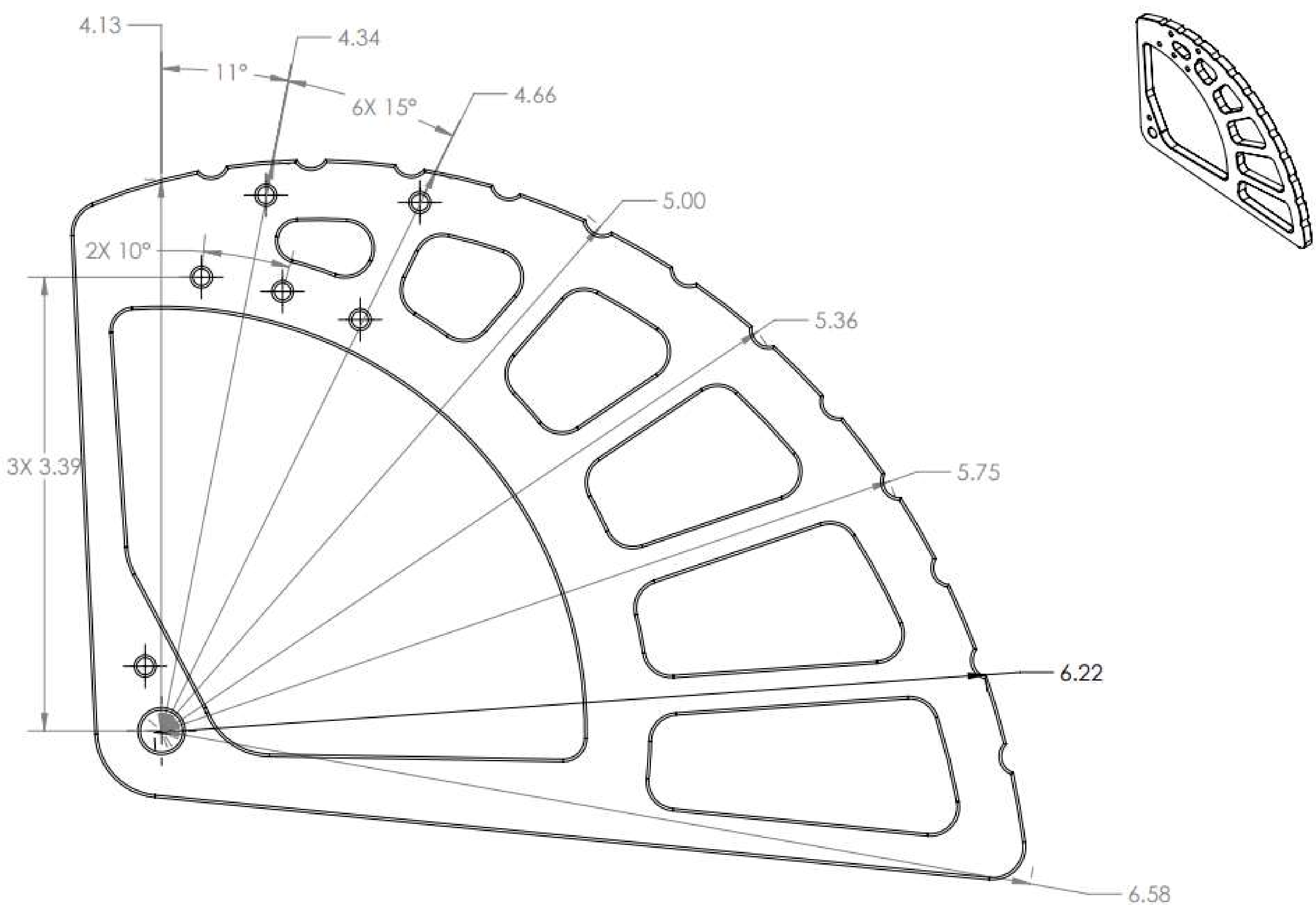
SCALE: 1:1

PRT # 211

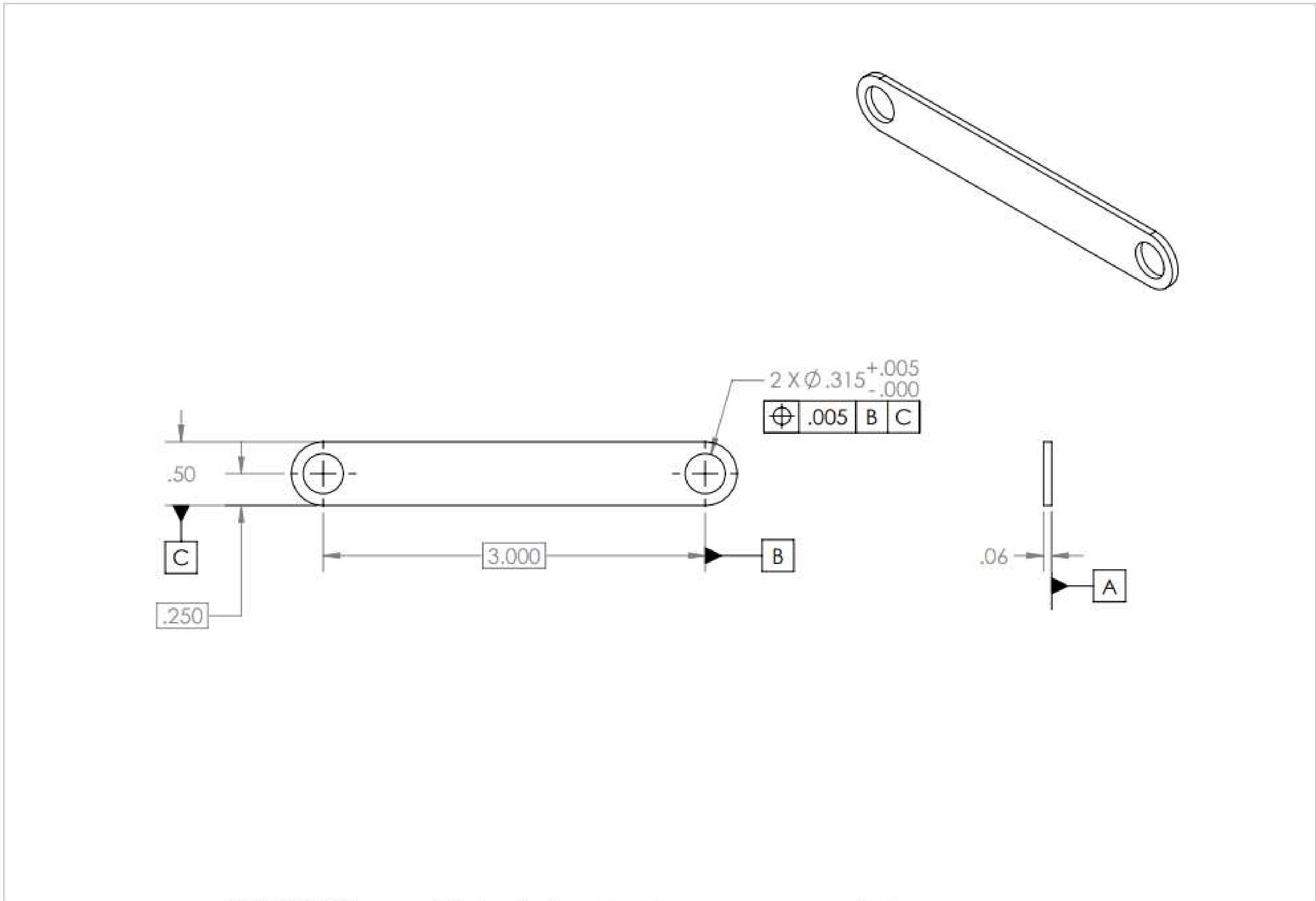
SIZE A



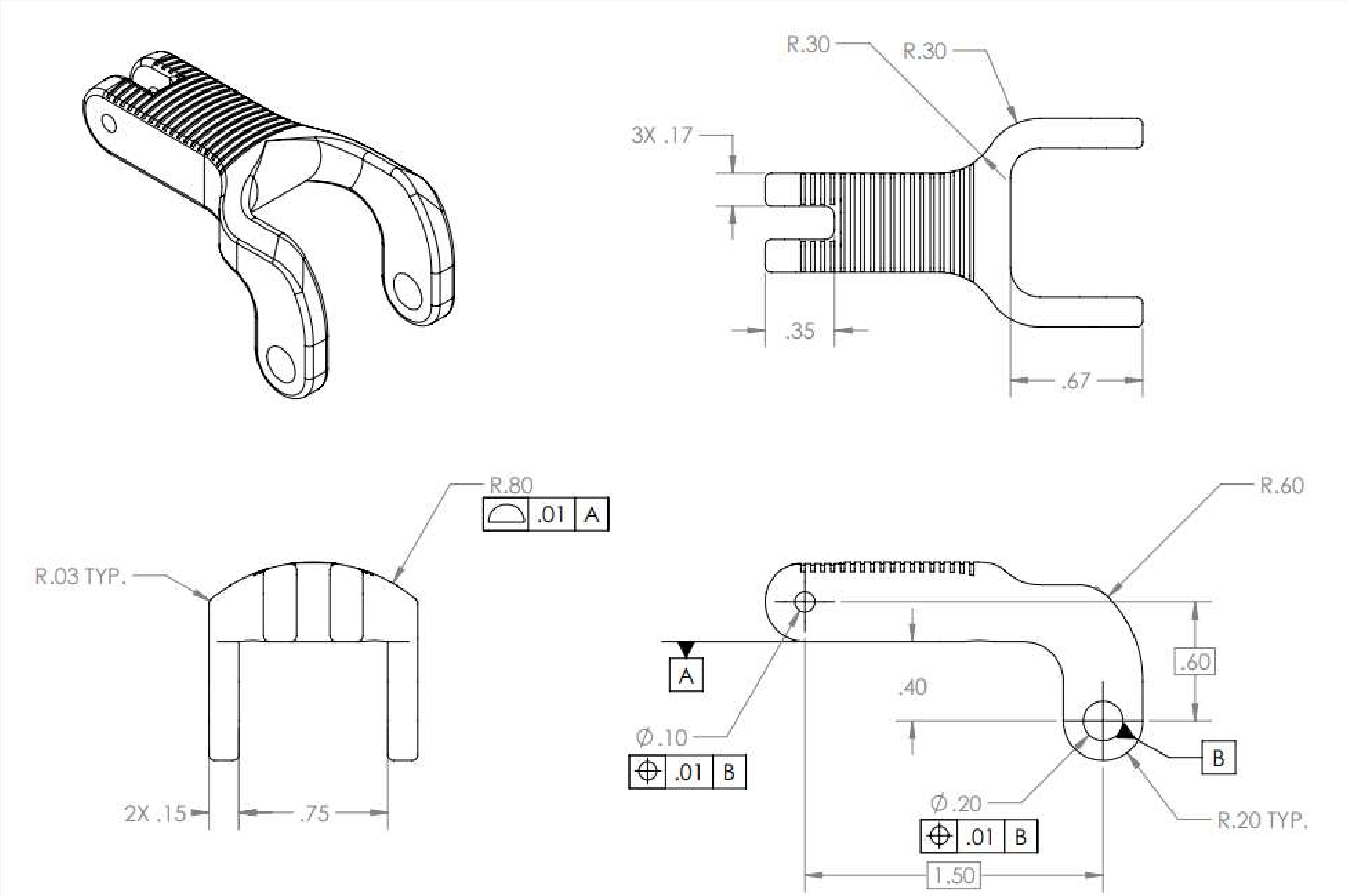
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: ONE PLACE DECIMAL ± .1 TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .005	INTERPRET DRAWING PER ASME Y14.5 2009	Mechanical Engineering CAL POLY	MATERIAL: 6061-T6 ALUMINUM	TITLE: LOBE			
		DATE: 6/7/2020	DRAWN BY: John Hickey	SHEET 1 OF 2	SCALE: 1:2	PRT # 221	SIZE A



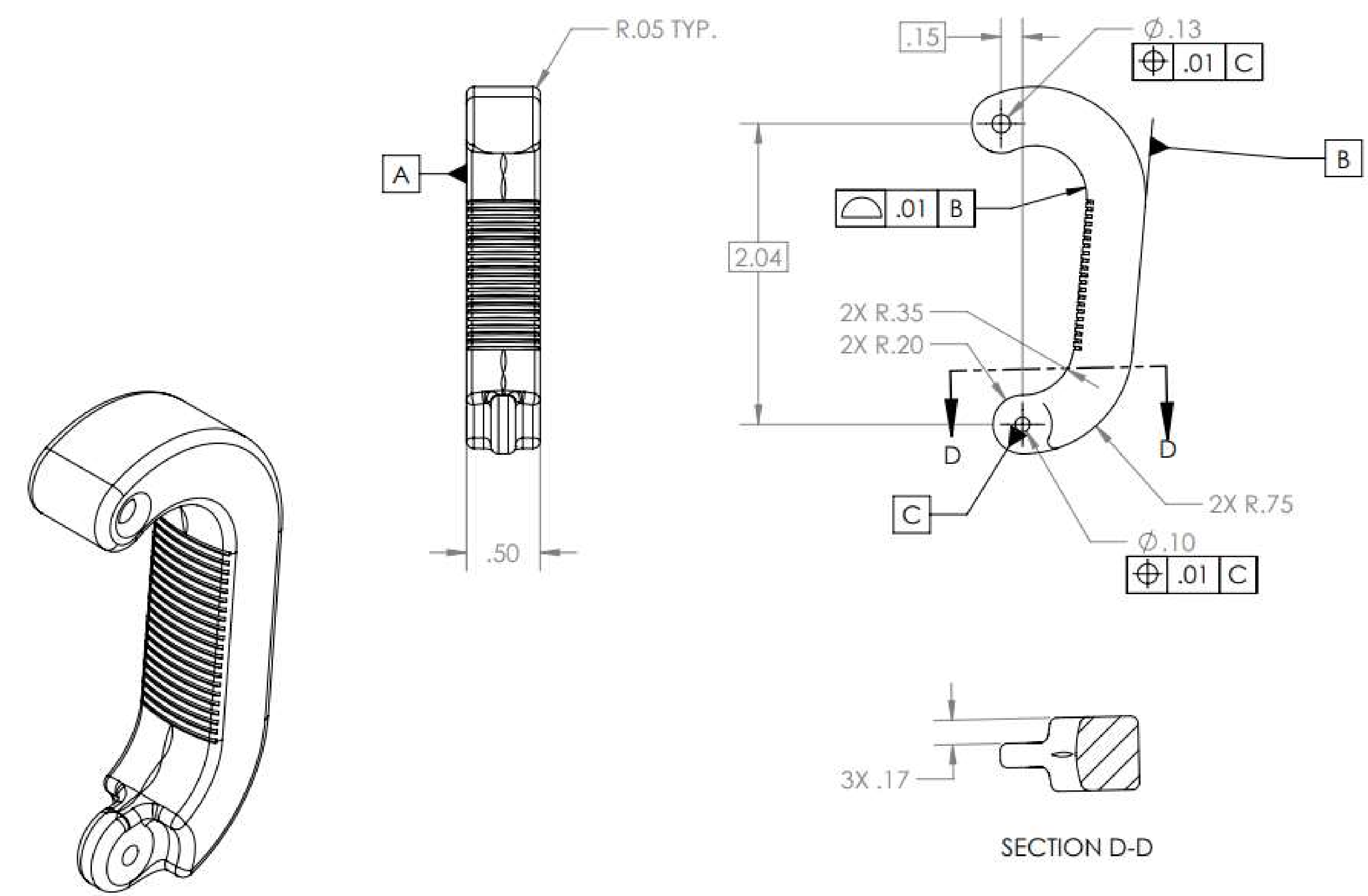
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: ONE PLACE DECIMAL ± .1 TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .005	INTERPRET DRAWING PER ASME Y14.5 2009	Mechanical Engineering	MATERIAL: 6061-T6 ALUMINUM	TITLE: LOBE			
		DATE: 6/7/2020	DRAWN BY: John Hickey	SHEET 2 OF 2	SCALE: 1:1	PRT # 221	SIZE A



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: ONE PLACE DECIMAL ± .1 TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .005	INTERPRET DRAWING PER ASME Y14.5 2009	Mechanical Engineering DATE: 4/7/2020	MATERIAL: 17-4 PH STAINLESS STEEL DRAWN BY: JOHN HICKEY	TITLE: AXLE LINK SHEET 1 OF 1	SCALE: 1:1	PRT # 231	SIZE A



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: ONE PLACE DECIMAL ± .1 TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .005	INTERPRET DRAWING PER ASME Y14.5 2009	Mechanical Engineering CAL POLY DATE: 6/7/2020	MATERIAL: PLA PLASTIC DRAWN BY: John Hickey	TITLE: TRIGGER PART A SHEET 1 OF 1 · SCALE: 3:2 · PRT # 411 · SIZE A



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: ONE PLACE DECIMAL ± .1 TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .005	INTERPRET DRAWING PER ASME Y14.5 2009	Mechanical Engineering	MATERIAL: PLA PLASTIC	TITLE: TRIGGER PART B
		DATE: 6/7/2020	DRAWN BY: John Hickey	SHEET 1 OF 1 · SCALE: 1:1 · PRT # 421 · SIZE A

Part 251: Snap Rings

McMASTER-CARR.

External Retaining Ring
for 5/16" OD, Black-Phosphate 1060-1090 Spring Steel

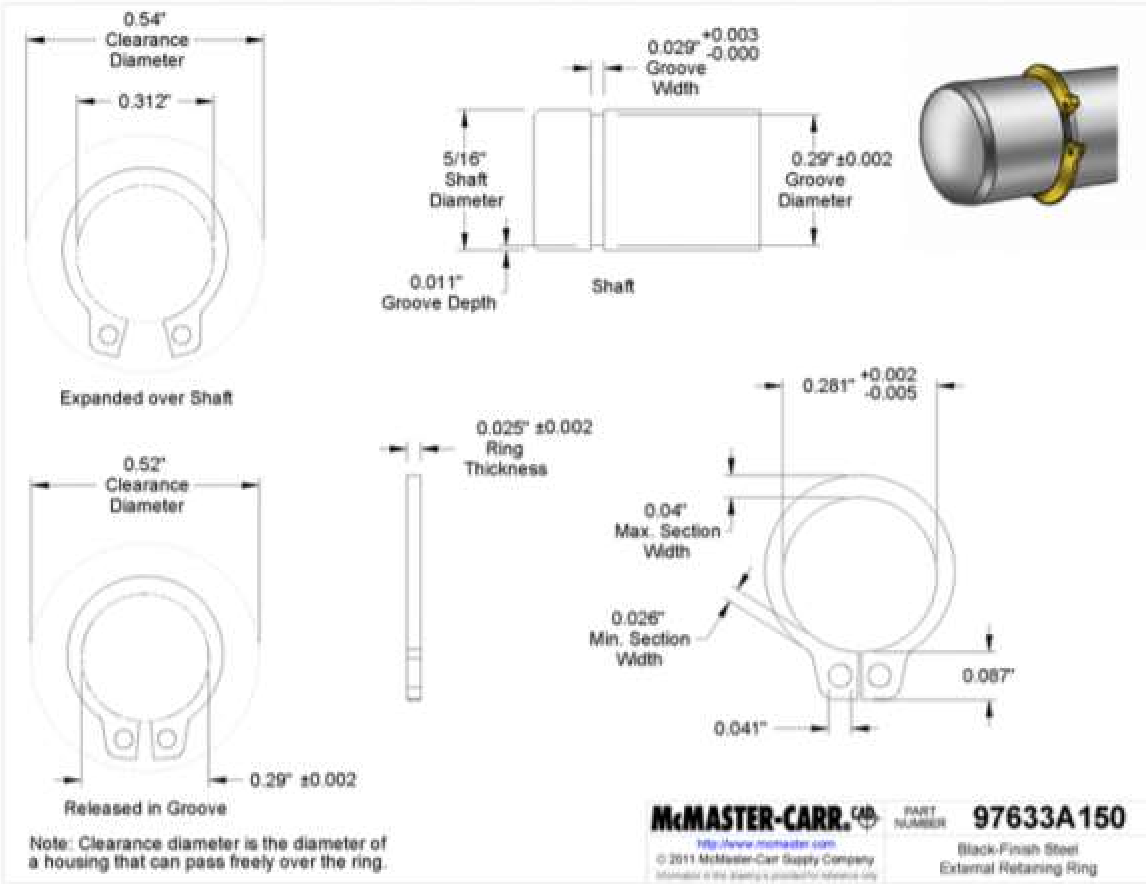
$9.20 per pack of 100
97633A150

Retaining Ring Type	External
Retaining Ring Style	Standard
System of Measurement	Inch
Material	1060-1090 Spring Steel
Finish	Black Phosphate
For OD	5/16"
For Groove	
Diameter	0.29"
Diameter Tolerance	-0.002" to 0.002"
Width	0.029"
Width Tolerance	0" to 0.003"
Ring	
ID	0.281"
ID Tolerance	-0.005" to 0.002"
Thickness	0.025"
Thickness Tolerance	-0.002" to 0.002"
Min. Hardness	Rockwell C40
Thrust Load Capacity	750 lbs.
Magnetic Properties	Magnetic
Specifications Met	ASME B18.27.1
REACH	REACH (EC 1907/2006) (07/16/2019, 201 SVHC) Compliant
RoHS	RoHS 3 (2015/863/EU) compliant

Open these rings, pass them over the end of a shaft, and release to spring into the groove. Ring ID is measured with the ring uninstalled. Use retaining ring pliers (sold separately) to install and remove rings.

1060-1090 spring steel rings are an economical choice with good strength. A black-phosphate finish is mildly corrosion resistant in dry environments.

Thrust load capacity, also known as PR, is based on using a shaft that is harder than the ring.



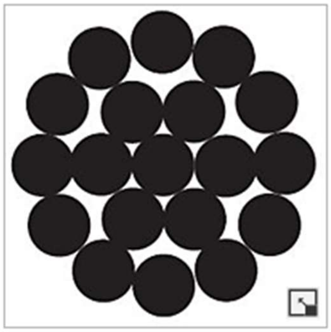
The information in this 3-D model is provided for reference only.

Part 311: Stem Cable

Item # 316119SS, 1 X 19 SS Aircraft Cable Type 302/304

Request Information

Printable Page Download PDF Email This Page



Warning: Wire rope & aircraft cable should never be used at breaking strength. 10:1 safety factor minimum is recommended for critical/overhead application. Do not use for overhead lifting without consulting a wire rope rigging professional. End fittings may not hold to 100% of strength efficiency so a safety factor such as 5:1 should be divided into the assembly actual strength. A pull test is recommended for quality assurance.

Request Quote –

Qty. 1 QUOTE

RFQ

DOWNLOADS –

Aircraft Cable FAQs

Specifications	
Dia (in)	3/16
MBS (lbs) ?	4,700
WT/100' (lb)	7.7
WT (lb/1000 ft)	77
Construction	1x19
Material	Stainless Steel

Part 321: Swage

McMASTER-CARR.

Wire Rope Compression Sleeve-for Lifting

for Steel Rope, Copper, for 3/16" Rope Diameter

$12.29 per pack of 10
3897T7

Fitting Type	Compression Sleeve
Application	For Lifting
Material	Copper
For Wire Rope Material	Steel
For Wire Rope	
Diameter	3/16"
Construction	6 × 19 IWRC 7 × 7 Strand Core 7 × 19 IWRC 7 × 19 Strand Core
Attachment Type	Loop
Sleeve Length	15/16"
Required Installation Tool	Compression Tool
Required Number of Compressions	4
Capacity	100% of the Rope's Capacity
Specifications Met	ASME B30.9, MS-51844
RoHS	RoHS 3 (2015/863/EU) Compliant
REACH	REACH (EC 1907/2006) (07/16/2019, 201 SVHC) Compliant
Related Product	Compression Tools

Install with a compression tool to create a strong, permanent loop. Compression sleeves are also known as ferrules, crimps, swaging, and splicing sleeves. They're compatible with Nicopress compression tools.

Warning: Fittings must match rope diameter and be installed correctly to obtain maximum holding power. Test all assemblies for required strength before use. Do not use with coated rope unless the coating is removed.

Part 331: Electrical Tape

Model # 6132-BA-10 Store SKU #565679 Store SO SKU #1003142024

San Luis Obispo

✔ 19 in stock | Aisle: 04 Bay: SC3 | Text to Me

Share Save to Favorites Print

3M >

Scotch Super 33+ 3/4 in. x 66 ft. x 0.007 in. Vinyl Electrical Tape, Black

★★★★★ (45) Write a Review Questions & Answers (1)

- Superior adhesion for indoor/outdoor use
- Withstands rough temperatures and weather conditions
- Resists abrasion, moisture and flames

$4.42

Save up to $100[1] on your qualifying purchase.
Apply for a Home Depot Consumer Card

How to Get It

Store Pickup	Ship to Home	Scheduled Delivery
Available	Get it by **Fri, Jun 12**	As soon as **Tomorrow**
FREE	**Free with $45 Order**	**$79.00**

19 in stock at **San Luis Obispo.**
Check Nearby Stores

⚠ Due to order volume, this item may not be available for pickup until tomorrow

Product Overview

Scotch Super 33+ Vinyl Electrical Tape offers the highest quality available. Long lasting with superior adhesion and handling, this tape is suitable for a wide range of temperatures and conditions. It offers flexibility and easy handling, while also protecting against abrasion and moisture.

- Insulates and protects against abrasion and moisture
- Flame resistant for added safety
- UL Listed and CSA certified
- Suitable for both indoor and outdoor use
- Lead-free vinyl material is suitable for a wide range of applications
- Click Here to See which Electrical Tools you should Use for your Project

Part 431: Trigger Cord

Roll over image to zoom in

Sterling Ropes 2.75mm Accessory Cord

by Sterling

Price: $22.95 ✓prime

Get $70 off instantly: Pay $0.00 ~~$22.95~~ upon approval for the Amazon Prime Rewards Visa Card. No annual fee.

Color: **Orange**

Size:

Select

- Diameter: 2.75 mm
- Length: 50 ft
- Strength: 1.2 kN
- Recommended Use: everything
- Manufacturer Warranty: lifetime

Report incorrect product information.

PillPack by Amazon Pharmacy
Your medication, delivered Learn more >

Product description

?These smaller cords can be used in a wide range of applications from tie-down straps to braided bracelets and any other non-life-safety applications. Accessory cords are not for use as lead climbing ropes.

Part 441 and 451: Tiller Cable Clamp and #10-24 Flat Head Screw

Roll over image to zoom in

Sea Dog 918521 TILLER CABLE CLAMPS, 1/8-3/16I CHROME PLATED ZINC CABLE CLAMP

by Sea Dog Line

Price: $8.30 & **FREE Shipping**

Not eligible for Amazon Prime.

- A 3/16"
- Case 10 pr Card
- C 11/16"
- B 1-3/16"

New (7) from $8.30 + FREE Shipping

Report incorrect product information.

Product description

Chrome-plated zinc cable clamp. Fits 3/16" cable diameter. Pack of 2. Sea-Dog Line is a 3rd generation family company with a history of satisfied customers stretching back to the company's start in 1933. The company is the recipient of multiple industry awards for quality and efficiency.

Product details

Item Weight: 1.6 ounces
Shipping Weight: 4 ounces (View shipping rates and policies)
ASIN: B001PRTTOK
Item model number: 918521

Appendix L: Design Verification Plan

The following table list the tests we wish to conduct to ensure that our verification prototype meets our specifications.

Senior Project DVP&R													
Date: 6/8/2020		Team: Weekend Whippers	Sponsor: Myles Whitman		Description of System: Spring Loaded Camming Decive					DVP&R Engineer:			
TEST PLAN										TEST REPORT			
Item No	Specification #	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES		TIMING		TEST RESULTS			NOTES
						Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	1	75% activated pull test	14 KN	Ryan	FP	1	Sys						
2	1	25% activated pull test	14 KN	Ryan	FP	1	Sys						
3	1	0% activated pull test	14 KN	Ryan	FP	1	Sys						
4	2	Cost analysis	$130 max	Jared	FP	1	Sys	5/19/2020	5/19/2020		1	0	With the need for outsourcing the manufacturing the cost of the cam increased. In ideal conditions, the cam would cost less than $130
5	3	Max weight	900 g	Kaitlin	FP	1	Sys	5/19/2020	5/19/2020	1135	0	1	
6	4	Range	6-9 in	John	FP	1	Sys	5/25/2020	5/25/2020	5.5-9.5	1	0	
7	5	Bending around 90 degree corner	No permenant deformation	John	FP	1	Sub	5/19/2020	5/19/2020	No Defomation	1	0	
8	6	Stem Buckling while used	No Buckling	Jared	FP	1	Sys	5/19/2020	5/19/2020	No Buckling	1	0	

Appendix M: Test Procedures

Test Procedure 1: Cam Device Tensile Test

Description

The following test determines the tensile strength of the cam design and to verify that the cam can take a static 14 kN load without any part yielding.

Required Materials

- Three identical, completely assembled camming devices
- Tensile Tester
- Carabiner
- Carabiner Mount for Tensile Tester (In final, picture would be provided)
- Cam Jig fitted for tensile tester (In final, picture would be provided)
- Protractor
- Safety Glasses

Procedure

1. Tighten bottom jaws of tensile tester onto carabiner mount, fixing the mount in place.
2. Tighten top jaws of tensile tester onto Cam Jig, fixing it in place.
3. Attach carabiner to webbing loop on camming device.
4. Set the walls of the of cam testing jig 6.75 inches apart (25% of the cam's usable range)
5. Place the cam between the two walls of the cam jig, releasing the triggers and fixing the cam in the jig.
6. Raise the top fixture of the tensile tester to reduce slack in cam. Zero the data.
7. Set the extension rate of the tensile tester to 2* inches/min and begin test.
   *: (Extension rate is unverified and may change.)
8. Record test results.
9. Repeat Steps 3 through 8 but set the walls of the Cam Jig to 8.25 inches apart (75% of the range)
10. Repeat Step 3 through 8 but instead of setting the cam between the walls of the jig, set two cross bars in the wall slots of the cam jig, turn the fixture 90 degrees, and set the open cam on top of the cross bars.

Results

Did the cam yield?
Yes / No
If yes, at what load did the cam yield?
Inspect the cam and write any observations

Test Procedure #2: Camming Range

Testing Location
John's garage

Equipment Needed

- One finished camming device
- Adjustable test fixture
- Ruler

Procedure

1. Adjust the width of the jig to the desired crack size.
    a. The usable range is defined to be within 25% and 75% of the maximum width.
    b. We will test two points: 6 inches and 9 inches.
2. Place the camming device in the jig.
3. Take note of whether the cam fits in the range.
4. Rate on a pass/fail basis.
5. Remove the cam from the crack and repeat the test after adjusting the size of the jig.

Results

Crack Width [inches]	Pass	Fail
6		
9		

Test #3: Stem Bending Deformation

Description of Test:
Determine if bending stem over a 90-degree corner will cause permanent deformation.

Acceptance Criteria:
No permanent deformation in the stem of the camming device.

Required Materials:
Camming Device
90-degree corner

Testing Procedure:
1) Bend Stem around 90-degree corner in stiff direction
2) Inspect camming device for permanent deformation
3) Bend stem around 90-degree corner in flexible direction
4) Inspect camming device for permanent deformation

Results

	Pass	Fail
Stiff Direction		
Flexible Direction		

Test #4: Stem Buckling

Description of Test:

There will be four tests to see if the stem buckles while being used. The buckling will be checked while the cam is being:

1. Actuated
2. Placed
3. Pushed
4. Retrieved

Acceptance Criteria:

Any amount of buckling does not interfere with the action being performed.

Required Materials:

- Climbing anchor set up
- Climbing rope
- Technical climbing knowledge
- Belay partner with technical climbing knowledge
- Two harnesses
- Belay device
- Climbing shoes
- Test prototype

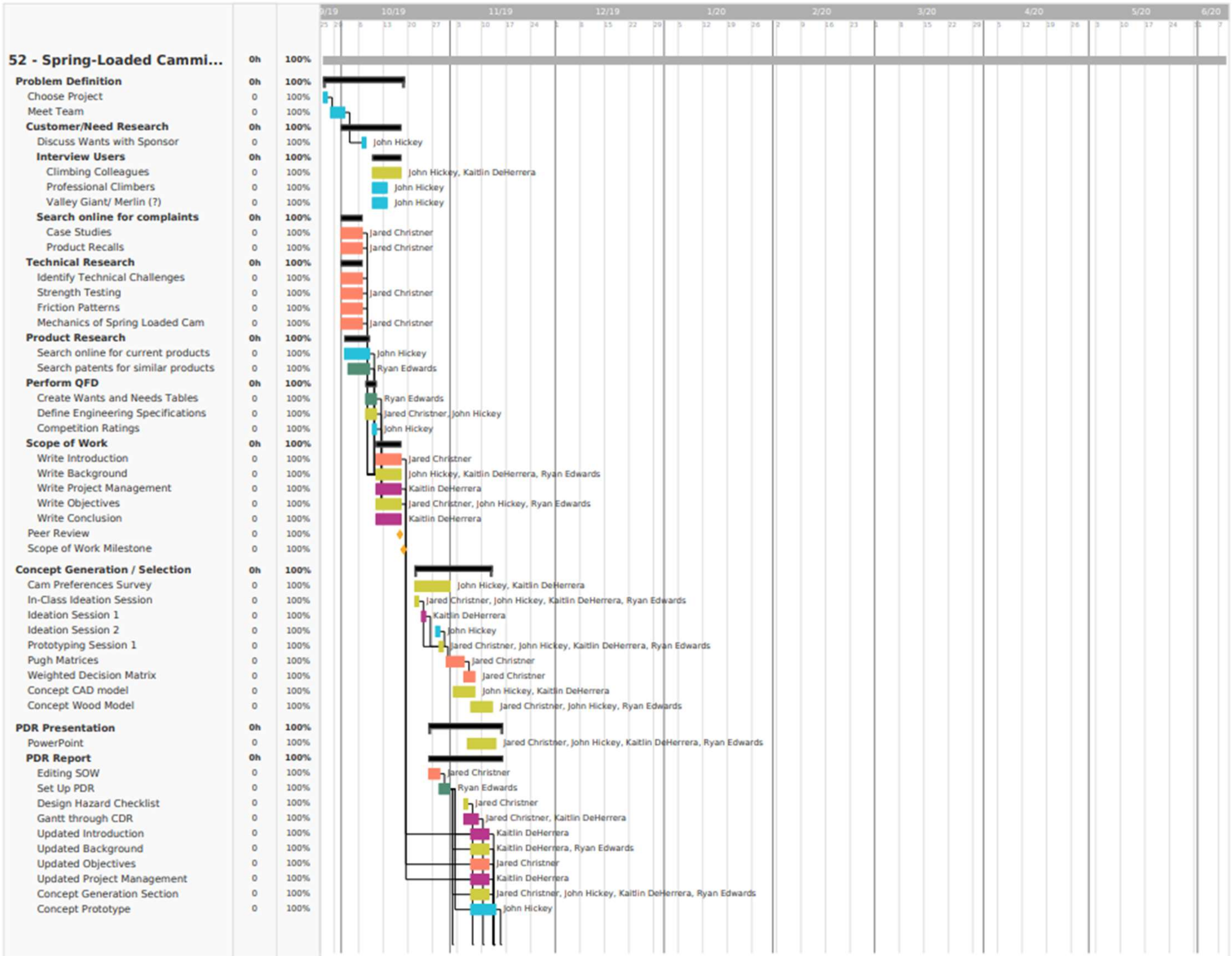
Testing Protocol:

1. Set up a top rope on Vance's Vertical Vent on Bishop's Peak.
2. Tie into rope and have belay partner put rope into belay device.
3. Go through proper belay commands and perform proper safety checks.
4. Begin climbing.
5. Check prototype placement every five feet until prototype properly fits into the crack.
6. Stop climbing when cam properly fits.
7. Check stem buckling while cam is being actuated.
8. Check stem buckling while cam is being placed.
9. Check stem buckling while cam is being pushed in six-inch increments.
10. Continue climbing and bumping cam until it no longer properly fits into the crack.
11. Check stem buckling while cam is being retrieved.

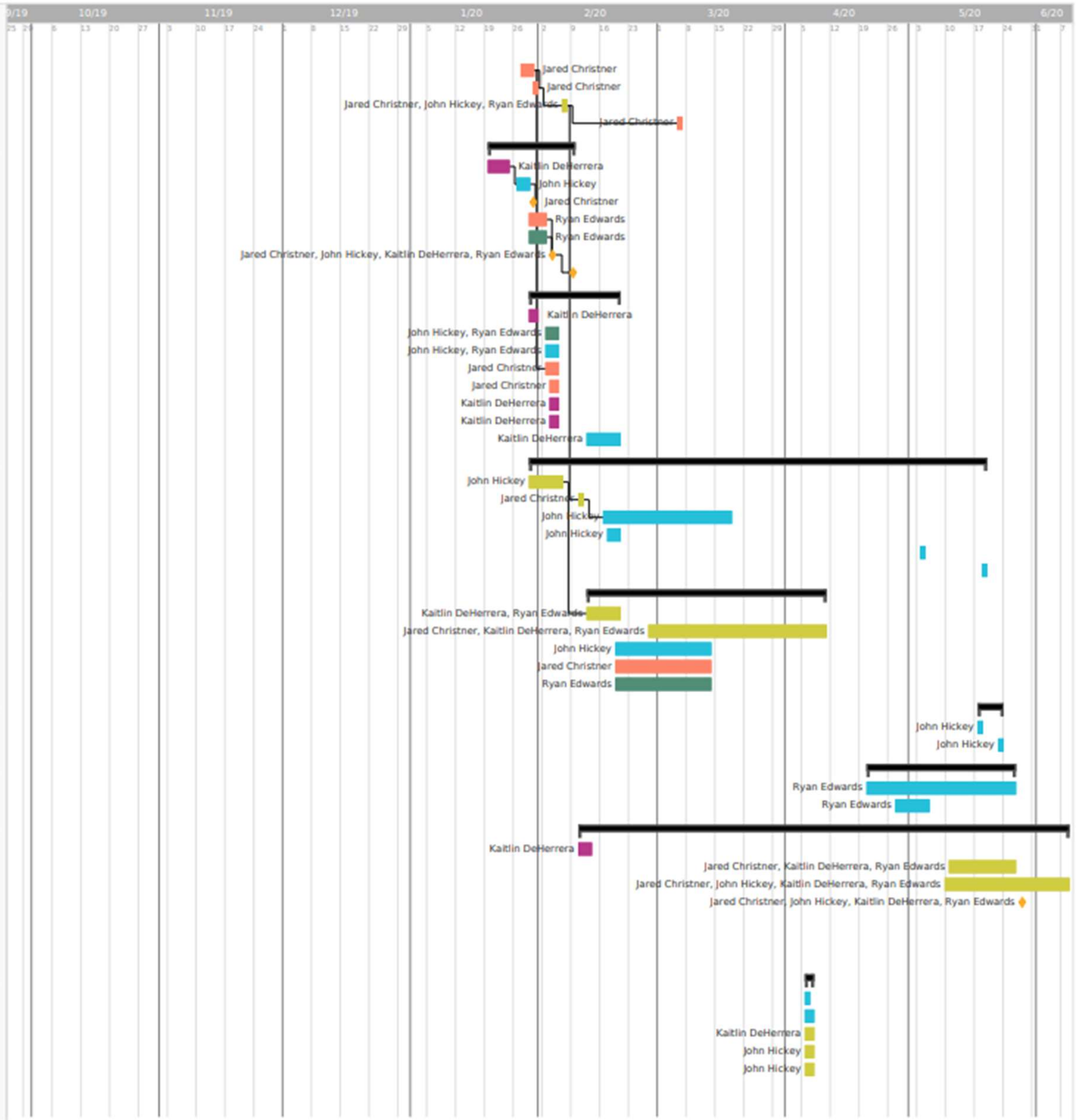
Results:

Actuated (Pass/Fail)	Placed (Pass/Fail)	Pushed (Pass/Fail)	Retrieved (Pass/Fail)

Appendix N: Gantt Chart and Gantt List



Indented BOM	0	100%
Proposal Statement	0	100%
Attend MESFAC Meeting	0	100%
MESFAC Reimbursement Due	0	100%
CDR Report	**0h**	**100%**
Update sections from PDR	0	100%
Manufacturing Plan	0	100%
CAD/Manuf Plan Review	0	100%
Chapter on Final Design	0	100%
Design Verification Plan	0	100%
CDR Peer Review	0	100%
CDR to Myles	0	100%
CDR Presentation	**0h**	**100%**
Introduction	0	100%
Design Description	0	100%
Design Justification	0	100%
Manufacturing/Cost	0	100%
Testing	0	100%
Potential Issues	0	100%
Next Steps	0	100%
Edit CDR Report	0	100%
Verification Prototypes	**0h**	**100%**
Ergo Prototype Manufacturing	0	100%
Order Materials	0	100%
Manufacture 1st Iteration Protoype ...	0	100%
Create Testing Jig	0	100%
Send Material for Final Parts	0	100%
Final Assembly	0	100%
Analysis	**0h**	**100%**
Ergo Prototype Analysis	0	100%
1st Iteration Analysis	0	100%
FEA Lobes Optimization	0	100%
FEA Axles Optimization	0	100%
FEA Carriage Optimaization	0	100%
Testing	**0h**	**100%**
Stem Bend Test	0	100%
Field Testing	0	100%
Documentation	**0h**	**100%**
Operating Manual	0	100%
Universal Design of products	0	100%
Senior Project Assignments	**0h**	**100%**
Risk Assessment	0	100%
Videos/Website	0	100%
FDR Report	0	100%
Expo	0	100%
General Video	0	100%
Technical Video	0	100%
Expo Webpage	0	100%
New Plan	**0h**	**100%**
Moving Forward Meetings	0	100%
Planning Document	0	100%
Advice from Erick	0	100%
Talk to Tom Barsch	0	100%
Talk to Moses	0	100%



52 - Spring-Loaded Camming Device

▾ **Problem Definition** (100%)	September 26, 2019	October 18, 2019
100% Choose Project	September 26, 2019	September 26, 2019
100% Meet Team	September 28, 2019	October 1, 2019
▾ **Customer/Need Research** (100%)	October 1, 2019	October 17, 2019
100% Discuss Wants with Sponsor	October 7, 2019	October 7, 2019
▾ **Interview Users** (100%)	October 10, 2019	October 17, 2019
100% Climbing Colleagues	October 10, 2019	October 17, 2019
100% Professional Climbers	October 10, 2019	October 13, 2019
100% Valley Giant/Merlin (?)	October 10, 2019	October 13, 2019
▾ **Search online for complaints** (100%)	October 1, 2019	October 6, 2019
100% Case Studies	October 1, 2019	October 6, 2019
100% Product Recalls	October 1, 2019	October 6, 2019
▾ **Technical Research** (100%)	October 1, 2019	October 6, 2019
100% Identify Technical Challenges	October 1, 2019	October 6, 2019
100% Strength Testing	October 1, 2019	October 6, 2019
100% Friction Patterns	October 1, 2019	October 6, 2019
100% Mechanics of Spring Loaded Cam	October 1, 2019	October 6, 2019
▾ **Product Research** (100%)	October 2, 2019	October 8, 2019
100% Search online for current products	October 2, 2019	October 8, 2019
100% Search patents for similar products	October 3, 2019	October 8, 2019
▾ **Perform QFD** (100%)	October 8, 2019	October 10, 2019
100% Create Wants and Needs Tables	October 8, 2019	October 10, 2019
100% Define Engineering Specifications	October 8, 2019	October 10, 2019
100% Competition Ratings	October 10, 2019	October 10, 2019
▾ **Scope of Work** (100%)	October 11, 2019	October 17, 2019
100% Write Introduction	October 11, 2019	October 17, 2019
100% Write Background	October 11, 2019	October 17, 2019
100% Write Project Management	October 11, 2019	October 17, 2019
100% Write Objectives	October 11, 2019	October 17, 2019

100%	Write Conclusion	October 11, 2019	October 17, 2019
	Peer Review	October 17, 2019	October 17, 2019
	Scope of Work Milestone	October 18, 2019	October 18, 2019
	Task Milestone Subgroup		

▾ **Concept Generation / Selection** (100%)		October 22, 2019	November 12, 2019
100%	Cam Preferences Survey	October 22, 2019	October 31, 2019
100%	In-Class Ideation Session	October 22, 2019	October 22, 2019
100%	Ideation Session 1	October 24, 2019	October 24, 2019
100%	Ideation Session 2	October 28, 2019	October 28, 2019
100%	Prototyping Session 1	October 29, 2019	October 29, 2019
100%	Pugh Matrices	October 31, 2019	November 4, 2019
100%	Weighted Decision Matrix	November 5, 2019	November 7, 2019
100%	Concept CAD model	November 2, 2019	November 7, 2019
100%	Concept Wood Model	November 7, 2019	November 12, 2019
	Task Milestone Subgroup		

▾ **PDR Presentation** (100%)		October 26, 2019	November 15, 2019
100%	PowerPoint	November 6, 2019	November 13, 2019
▾ **PDR Report** (100%)		October 26, 2019	November 15, 2019
100%	Editing SOW	October 26, 2019	October 28, 2019
100%	Set Up PDR	October 29, 2019	October 31, 2019
100%	Design Hazard Checklist	November 5, 2019	November 5, 2019
100%	Gantt through CDR	November 5, 2019	November 8, 2019
100%	Updated Introduction	November 7, 2019	November 11, 2019
100%	Updated Background	November 7, 2019	November 11, 2019
100%	Updated Objectives	November 7, 2019	November 11, 2019
100%	Updated Project Management	November 7, 2019	November 11, 2019
100%	Concept Generation Section	November 7, 2019	November 11, 2019
100%	Concept Prototype	November 7, 2019	November 13, 2019
100%	Formatting	November 7, 2019	November 14, 2019

Peer review PDR Report	November 12, 2019	November 12, 2019
Final PDR Turn in	November 15, 2019	November 15, 2019
Task Milestone Subgroup		

Detailed Design (PDR to CDR) (100%)	November 19, 2019	February 20, 2020
100% FMEA	November 19, 2019	November 21, 2019
Safety/FMEA to Sponsor	November 22, 2019	November 22, 2019
Contacts/Orders (100%)	December 3, 2019	January 28, 2020
100% Contact Dr. Mello About Tensile Testing	December 3, 2019	December 5, 2019
100% Contact Professor Elghandour About Tensile Testing	January 7, 2020	January 9, 2020
100% Contact Leo Taranta-Slack about 3-D Printing Materials and Sizing	December 3, 2019	December 5, 2019
100% Contact Professor Trian About Material Sourcing	December 3, 2019	December 5, 2019
100% Contact Professor Trian about Injection Molding Cab	January 7, 2020	January 9, 2020
100% Contact Lexco About Cable Sizing	December 16, 2019	January 5, 2020
100% Contact Eric Davidson about Stem Carriage Interface	December 16, 2019	January 5, 2020
100% Contact Professor Davol About Lobe Buckling	January 9, 2020	January 9, 2020
100% Order Cable Samples from Lexco	January 21, 2020	January 23, 2020
100% Contact Trian for Aluminum Stock	January 16, 2020	January 23, 2020
100% Receive a quote from Coast Aluminum	January 28, 2020	January 28, 2020
100% Order Tiller Cable Clamp	January 23, 2020	January 23, 2020
Research/Ideation (100%)	January 14, 2020	January 23, 2020
100% Z4 Patent Hunt		
100% Trigger wire decision matrix	January 14, 2020	January 15, 2020
100% Locking Mechanism Decision Matrix	January 22, 2020	January 23, 2020
Prototyping/Testing (100%)	December 31, 2019	January 29, 2020
100% Trigger Ergonomics Prototyping	December 31, 2019	January 7, 2020
100% Composites Safety Training	January 29, 2020	January 29, 2020
CAD Models (100%)	January 7, 2020	February 20, 2020
100% Trigger Models 2.0	January 14, 2020	January 16, 2020
100% Trigger Drawing	January 21, 2020	January 23, 2020
100% Basic Carriage Model 2.0	January 17, 2020	January 19, 2020

100%	Carriage Drawing	January 21, 2020	January 23, 2020
100%	Basic Stem Model 2.0	January 14, 2020	January 16, 2020
100%	Basic Locking Model 2.0	January 25, 2020	January 26, 2020
100%	Lobe Model 2.0	January 14, 2020	January 16, 2020
100%	Lobe Drawing	January 21, 2020	January 24, 2020
100%	Assembly Drawing	February 1, 2020	February 2, 2020
	Analysis (100%)	January 7, 2020	February 20, 2020
100%	Carriage Axle Sizing Calculation	January 9, 2020	January 16, 2020
100%	Lobe Profile Excel Calculation	January 7, 2020	January 9, 2020
100%	Lobe Buckling Calculation	January 10, 2020	January 13, 2020
100%	Spring Sizing	February 17, 2020	February 20, 2020
	Interim Design Review (100%)	January 16, 2020	January 16, 2020
	Interim Design Review	January 16, 2020	January 16, 2020
	Task Milestone Subgroup		

	Structural Prototype/Manufacturing (100%)	November 28, 2019	February 6, 2020
100%	Draft Manuf. Plan	November 28, 2019	December 5, 2019
100%	Final Manufacturing Plan	January 21, 2020	January 23, 2020
100%	Bill of Materials	January 28, 2020	January 30, 2020
100%	Living Document of Purchased Parts	January 28, 2020	January 30, 2020
100%	Write G-code for Lobes	January 30, 2020	February 2, 2020
100%	Turn Stem Cap	February 4, 2020	February 4, 2020
100%	Carriage CNC	February 5, 2020	February 5, 2020
100%	3D Printing Triggers	January 28, 2020	February 3, 2020
100%	Cut the Cables to Length	February 4, 2020	February 4, 2020
100%	Create Springs	February 6, 2020	February 6, 2020
	Aquire Tiller Clamp	January 30, 2020	January 30, 2020
100%	3-D Print Lobes	January 29, 2020	February 6, 2020
	Task Milestone Subgroup		

	MESFAC Proposal (100%)	January 28, 2020	March 6, 2020

100%	Indented BOM	January 28, 2020	January 30, 2020	
100%	Proposal Statement	January 31, 2020	January 31, 2020	
100%	Attend MESFAC Meeting	February 7, 2020	February 7, 2020	
100%	MESFAC Reimbursement Due	March 6, 2020	March 6, 2020	
	Task Milestone Subgroup			

▾ CDR Report (100%)		January 20, 2020	February 9, 2020	
100%	Update sections from PDR	January 20, 2020	January 24, 2020	
100%	Manufacturing Plan	January 27, 2020	January 29, 2020	
◇	CAD/Manuf Plan Review	January 30, 2020	January 30, 2020	
100%	Chapter on Final Design	January 30, 2020	February 2, 2020	
100%	Design Verification Plan	January 30, 2020	February 2, 2020	
◇	CDR Peer Review	February 4, 2020	February 4, 2020	
◇	CDR to Myles	February 9, 2020	February 9, 2020	
	Task Milestone Subgroup			

▾ CDR Presentation (100%)		January 30, 2020	February 20, 2020	
100%	Introduction	January 30, 2020	January 31, 2020	
100%	Design Description	February 3, 2020	February 5, 2020	
100%	Design Justification	February 3, 2020	February 5, 2020	
100%	Manufacturing/Cost	February 3, 2020	February 5, 2020	
100%	Testing	February 4, 2020	February 5, 2020	
100%	Potential Issues	February 4, 2020	February 5, 2020	
100%	Next Steps	February 4, 2020	February 5, 2020	
100%	Edit CDR Report	February 13, 2020	February 20, 2020	K
	Task Milestone Subgroup			

▾ Verification Prototypes (100%)		January 30, 2020	May 19, 2020	
100%	Ergo Prototype Manufacturing	January 30, 2020	February 6, 2020	J
100%	Order Materials 9/9	February 11, 2020	February 11, 2020	J

100%	Manufacture 1st Iteration Protoype (Crimped Cap)	3/4	February 17, 2020	March 18, 2020	J
100%	Create Testing Jig		February 18, 2020	February 20, 2020	J
100%	Send Material for Final Parts		May 4, 2020	May 4, 2020	
100%	Final Assembly		May 19, 2020	May 19, 2020	
	Task Milestone Subgroup				

Analysis (100%)		February 13, 2020	April 10, 2020	
100%	Ergo Prototype Analysis	February 13, 2020	February 20, 2020	K R
100%	1st Iteration Analysis	February 28, 2020	April 10, 2020	J K R
100%	FEA Lobes Optimization	February 20, 2020	March 13, 2020	J
100%	FEA Axles Optimization	February 20, 2020	March 13, 2020	J
100%	FEA Carriage Optimaization	February 20, 2020	March 13, 2020	R
	Task Milestone Subgroup			

Testing (100%)		May 18, 2020	May 23, 2020
100%	Stem Bend Test	May 18, 2020	May 18, 2020
100%	Field Testing	May 23, 2020	May 23, 2020
	Task Milestone Subgroup		

Documentation (100%)		April 21, 2020	May 26, 2020
100%	Operating Manual	April 21, 2020	May 26, 2020
100%	Universal Design of products	April 28, 2020	May 5, 2020
	Task Milestone Subgroup		

Senior Project Assignments (100%)		February 11, 2020	June 8, 2020
100%	Risk Assessment	February 11, 2020	February 13, 2020
100%	Videos/Website	May 11, 2020	May 26, 2020
100%	FDR Report	May 10, 2020	Today
	Expo	May 28, 2020	May 28, 2020

100%	General Video		
100%	Technical Video		
100%	Expo Webpage		
	Task Milestone Subgroup		

▾ **New Plan** (100%)		April 6, 2020	April 7, 2020
100%	Moving Forward Meetings	April 6, 2020	April 6, 2020
100%	Planning Document	April 6, 2020	April 7, 2020
100%	Advice from Erick	April 6, 2020	April 7, 2020
100%	Talk to Tom Barsch	April 6, 2020	April 7, 2020
100%	Talk to Moses	April 6, 2020	April 7, 2020
	Task Milestone Subgroup		