4-DOF Video Jib System

Final Report

24-441 Product Design

12/12/2023

Team B: Elsa Schleicher, Isaiah Asah, Joshua Pen, Manuel Lancastre, Shawn Krishnan

Team Member Contributions: The team leader was Elsa Schleicher

Elsa Schleicher: Final CAD, Bill of Materials, Manufacturing and Assembly, Engineering Standards, Notes for Future Teams, Cost Analysis, Detailed Design Description (CAD), System Functional Analysis, Concept Generation and Evaluation, Report Revising
Isaiah Asah: Prototype Tests and Performance, FMEA, LCA, Report Revising
Joshua Pen: Engineering Analysis, Material Selection, Concept Generation and Evaluation, Opportunity and Design Problem, Project Planning and Timeline, Report Revising
Shawn Krishnan: Cost Analysis, Conclusion, Executive Summary
Manuel Lancastre: Cost Analysis, Concept Generation and Evaluation

1. Executive Summary

With the rising population of videography and the amateur filmmaker community, there is a rising demand for reliable and affordable equipment that provides versatility in motion capabilities. Existing products, including tripods, jibs, dollies, sliders, camera head mounts, and gimbals, offer specialized functionalities but come with limitations in terms of cost, quality, and specific motion capabilities. These products all lack the ability to provide a user with the ability to film an in-out motion shot, up-down motion shot, and left-right motion shot all on the same device. While some such expensive products exist in the professional film industry, products priced appropriately for amateur and hobbyist markets are not available to our stakeholders. Based on detailed customer research and benchmarking of existing products, this project aims to design a comprehensive, affordable system which combines the advantages of existing products into a single setup with professional-grade motion capabilities catering especially to amateur filmmakers. The proposed solution emphasizes motion-capability, modularity, affordability, stability, and ease of assembly to cater to the needs of amateur filmmakers. Using our knowledge gained throughout our undergraduate studies in mechanical engineering we progressed through the design cycle, first brainstorming ideas, then modeling, constructing, and testing our initial prototype, and second prototype. We finalized our design and created our true and complete CAD model after which we performed engineering analyses to confirm the strength capabilities of our design through FEA simulations and determine appropriate materials via Material Choice Optimization. From there we could choose affordable manufacturing processes to produce our jib and perform a full cost analysis. To achieve the motion capabilities presented in our design challenge, we have created a 4-DOF jib which consists of a fulcrum which attaches to a stable tripod, provides up-down and 360˚ left-right motion, and supports a four-bar linkage jib arm connected to a rail slider mechanism that provides in-out motion and supports a camera mount with a fourth camera-angling motion. This affordable product successfully supports a maximum 10 pounds of camera weight, has an under 30 minute assembly, can fit in a car and pan the height of a person, while also providing three complex motion shots with greater stability than one could by hand.

2. Opportunity and Design Problem

Customer Research

Videography was once exclusively filmed by professional teams or groups from big movie production companies. With the rise of social media platforms, the statistics of increased video uploading (e.g. 400 hours of video are uploaded to YouTube every minute worldwide) implies a continuous growth of the number of self-media such as amateur filmmakers [2][3]. There are numerous products available for filmmakers and photographers which allow for certain motion capabilities of a shot, however amateur filmmakers only have access to those products which have one or at most two directions of motion. There is a distinct lack of affordable options which provide users with the ability to take left-right, up-down, in-out shots with the same device.

To elaborate, professional tripods, jibs, dollies, sliders, camera head mounts and gimbals are six standard pieces of equipment that filmmakers and photographers use for stability and motion capabilities. Each of these products is designed only for a specific kind of motion. For instance, professional jibs emphasizes vertical and horizontal, or a combination of the two for capturing dynamic, sweeping shots [4]; dollies and sliders are especially beneficial to capturing horizontal or curved linear shots while being fixed to the ground [5]; camera head mounts help to aim the camera in an x, y, z direction and gimbals are handheld devices that aid fluid movements and prevent shaky video.

We conducted in-depth customer interviews with five potential stakeholders. Our interviews included: a veteran professional commercial filmmaker and photographer, three amateur photographers of various specialties and a student filmmaker. These detailed customer interviews indicate that amateurs and hobbyists have definite interest in increased capabilities of current products.Therefore, the primary target audience for our overall product includes amateur filmmakers, students in film programs, small-scale film production companies, and amateur photographers. Secondary stakeholders may include film equipment rental companies. See our references for a link to the transcript of our interviews [12][13].

Our interviews indicate that while professionals have access to a wide variety of products for purchase or through rental companies at prices reasonable to their respective jobs in the film industry, amateur hobbyists or film students do not have the budget to be able to use these products. Because the nature of film and photography products is to have modularity, wherein different devices/products are interchangeable to suit a variety of purposes, for amateur or upcoming stakeholders, the cost to purchase all types of equipment is prohibitive. The result being that non-professional stakeholders do not have easy access to the same motion capabilities as professionals do. The ability to have full range of motion is essential. As our professional filmmaker noted, to have a truly professional level of film, you need the right types of shots, not necessarily the best equipment. However, the equipment you do have should look professional for customers [12][13].

Additionally, while equipment of the six kinds mentioned above does exist in a cheaper format for non-professionals, it is notoriously shoddy. Several of our interviewees mentioned that they buy more equipment of a higher professional grade than they need simply because it is more pleasant to use. So, not only must a user buy multiple expensive existing products to get the full range of motion, the ones they are often able to afford are too inferior to be of much use[12][13].

Lastly, our photographer interviewees indicated a distinct wish for an improved ball joint camera head mount, since current ones are notorious for slipping when they should be locked into an angled position. The desire for this concept was corroborated by our film student, who noted that the ability for rotation of the camera in all directions was desirable. As it is, current ball joint heads are frustrating to use and could use improvement [12][13].

Thus, we see that while there are certainly many options out there for different ranges of motion, there is yet to be an affordable and reliable product that combines the positive features of the existing devices into one entity.

To create a better solution, our project aims to create an affordable product that combines the advantages of tripods, jibs, dollies, sliders, camera head mounts and gimbals into one system while maintaining professional-grade quality. We will focus on improving a jib design and a camera head mount design to use in combination with a standard tripod. This addresses the need for accessible filmmaking equipment with advanced capabilities.

There is a substantial market for such a solution, with around 134,700 amateur filmmakers in the United States [1] and numerous film equipment rental companies. This project has the potential to meet the needs of this niche market. Additionally, our interviewees have already noted their desire to spend more (upwards of their current spending of $500) if they could get a superior product. It is undeniable that people will pay for a solution, and they will be much happier to pay less than they currently are. Additionally, a more inclusive product means that the stakeholder would not have to pay for multiple $200-300 products to get the same features [12][13].

Our interviewees indicate that they care about stability, reliability, ease of use, and interchangeability. They often pay more to be able to achieve stability and reliability in their products. They desire products that are not too bulky and are not too heavy. However, their products also need to be able to be weighted down and used for a variety of different scenarios, even within the realm of a certain specified type of photography or filming. Thus, every aspect of the design must be able to be interchanged with another type of product and use standard sizes so this modularity is feasible [12][13].

With all this in mind, we will now consider a more in-depth benchmark of our closest competitors and how our proposal is both necessary and feasible.

Benchmarking

As mentioned above, existing professional tripods, jibs, dollies, sliders, camera head mounts and gimbals serve as benchmarks. These products offer various degrees of camera stabilization and motion but often come with limitations in terms of affordability, versatility, or range of motion. Current solutions are either too expensive, too shoddy and unreliable, lack certain motion capabilities, or are not easily portable. There is an unmet need for an affordable, all-in-one solution that provides X, Y, Z translational camera motion and rotational motion to aim the camera. (For a more in-depth description of what we refer to by motion, see Fig. 3.C.3 in the detailed Design Description section below.) Herein we provide a quick overview of the features, cost, and unmet needs using customer reviews for a favorably-reviewed jib, dolly, and gimbal, respectively, from online retailers for benchmarking the individual options. Additionally, we identify an expensive professional grade option that is the closest competitor to our proposed design.

Existing Product Research and Analysis of Weaknesses and Unmet Needs

1. Jib Proaim 12 ft Camera Crane Jib Arm for 3-axis Gimbals, Pan-Tilt & Fluid Head is advertised a top seller on Proaim [7].

This jib features stability, durability, affordability, and transportability. This device is built with high strength Aluminum, and is able to hold camera setups up to 17.6 lb (8 kg). A central fork with thrust roller bearings absorbs shock loads for smooth or stable jerk free jib movements. The product description states that for a payload under 17.6 lb (8 kg), this device might be the best crane within the affordable price range. The complete crane system fits in bags for easy storage and being carried with you to different locations. This device is available at $278.00 on Proaim. Because no review is posted on Proaim website, we looked into customer reviews rated at 4.6 on Amazon [10]. One review stated that it takes some time to assemble and disassemble the product. Also, there are no wheels on the Jib which prevents translational motion. This product provides both the up-down and left-right motion as well as a combination of the two for seeping shots. What it does not have is an in-and out camera motion.

2. SmallRig Universal Photography Tripod Dolly is rated 4.8 with 95 reviews [9].

This dolly features adjustability, lightweight, and compactness. The adjustable clamps and simple-to-use twist screws are flexible for tripod or Photography Light Stand up to a 33 lb payload, which fits most tripods. The dolly is mainly made using aluminum alloy as a lightweight but sturdy device. When it's in a folded structure it can form a compact transport package which is easy for outdoor photography. This device is available at $69.99 on Amazon. The customer reviews with lower rating pointed out weakness or limitation that this product is lightweight and thus not stable when moving on bumps, cracks, or debris in its path. This makes it suitable for most indoor shoots. Adding tracks or adding weights would make stable outdoor shoots possible. Also, the simple-to-use twist screws turn out to be not practical when mounting a tripod. A customer criticized that when screwing down a clamp, the other legs are about to slide off. This product will provide any planar movement on a flat surface, but will not provide any up and down motion.

3. The DJI RS 3 Pro, 3-Axis Camera Gimbal Stabilizer is rated 4.7 out of 5 with 381 reviews on Amazon [11].

This product features automation, extendability, and lightweight. The three axes of this device can be automatically locked and unlocked with the simple press of the power button for efficiency usage. Carbon Fiber Axis Arms provides leveling space for professional cameras with a payload up to 10 lb (4.5 kg). This also works with vehicle mounts, jibs, Steadicams, and so on. The carbon fiber is also a lightweight but sturdy material. This device is available at $869 on Amazon. Some review criticizes that the device does not work with a light set up like the Canon R5, and thus the number of payload is questionable. While some stated that the gimbal did not hold the horizon tilts right, and this might be another payload issue for this product. This device can provide any motion the user desires, with the drawback that the device is entirely supported by and dependent on the stability of the user’s arms.

4. Proaim 10’ Wave-2 Jib Tripod Kit with Pan/Tilt Head and Zoom Controller

The Proaim 10’ Wave-2 Jib Tripod Kit with Pan/Tilt Head and Zoom Controller is our highest performing competitor. It features a tripod, a tripod dolly, an adjustable crane arm, an electronic pan/tilt head, and a 2.5 mm LANC zoom controller. Each of these components come separate and can be attached to each other. The electronic pan/tilt head is controlled by a wired joystick controller that can be mounted to the crane arm along with the wired zoom controller. The zoom controller is compatible with Sony, Panasonic, and Canon cameras. The crane arm can be adjusted to lengths between 6’ and 10’. At 6’ in length, the device supports up to 55 lbs. At 10’ in length, the device supports up to 33 lbs.

A major weakness for this product is the price. The product is priced at $2,213 on the B&H Photo website [14]. The high cost makes this product unattractive to buyers that are looking to use the product in a non-professional capacity. An additional weakness is that this product’s only in and out motion comes from the wheeled dolly, which does not provide the smoothest shot for a device so large and heavy.

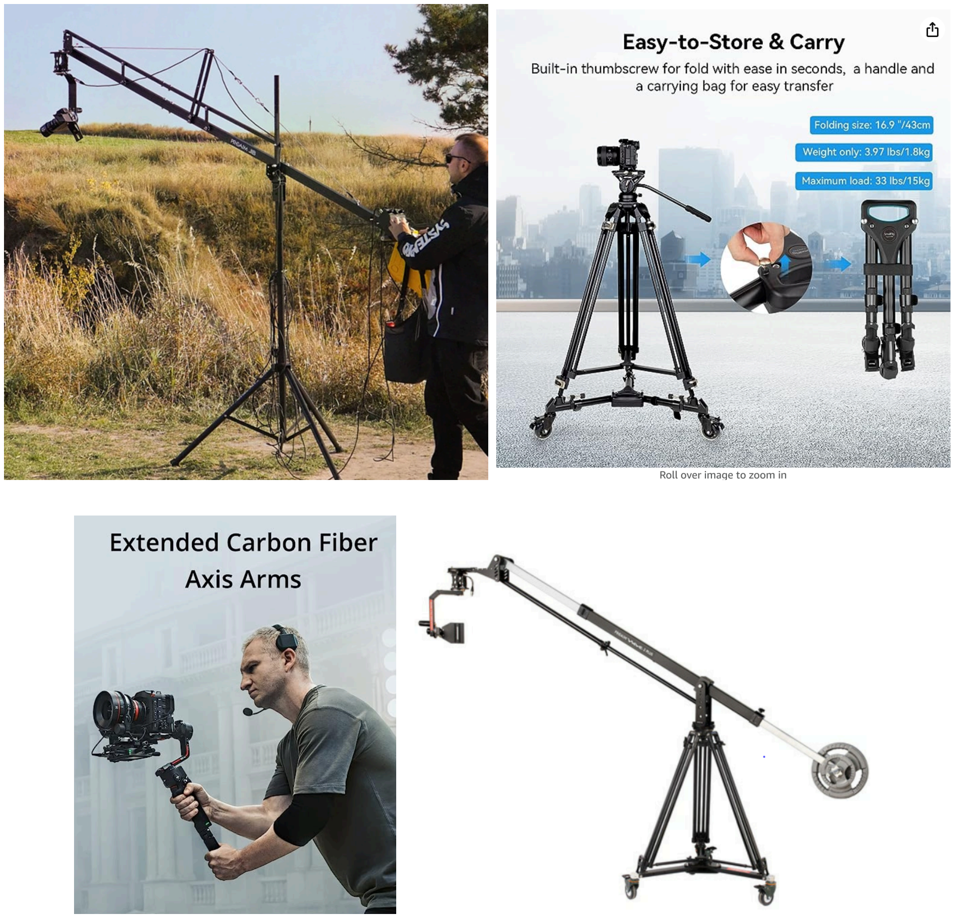


Figure 2.B.1. Accompanying photos for products *1* (top left), *2* (top right), *3* (bottom left), and *4* (top right).

Design Requirements

The proposed mechanical jib design provides in-out X translational motion, up-down Y translational motion, and a left-right X-Z planar motion (which could also be described as a rotation around Y per Fig. 3.C.3) and and a camera adjustment motion via an improved ball joint camera head mount at a reasonable price range. The motions make up what we call our four degrees of freedom (DOF). Having four degrees of freedom along with a reasonable price will satisfy the opening left by the greatest weaknesses of our competitors. The additional in-out X translational degree of freedom will give our product the versatility to capture various shots that competing products cannot capture and our reasonable price will make our product affordable for amateur filmmakers.

We will need to consider user-desired functional characteristics that will add value to our product such as, optimized weight, stability, portability, and ease of assembly. The following table expands upon these specific design requirements and provides verifiable metrics for which they can be evaluated in our prototypes and final design.

Table 2.C.1. Quantitative Metrics and Qualitative Metrics.

Quantifiable Metric	Customer Requirement
Hold at most 10 pounds of weight.	Jib must be able to support weight of a typical video camera used by amateur filmmakers
9 ft jib arm.	Allows Jib to fit into a car, but also can pan at least the height of a person
30 minute assembly/disassembly	Easy to use compared to professional jibs
$300-$700 price range	Cheaper than professional jibs and comparable to amateur jibs
Verifiable Metric	Customer Requirement
A standard connection for a typical weightlifting counterweight system	Allows users the freedom to use a variety of weights and means we do not need to provide weights with our product.
A standard tripod base with a spreader and center pole and lazy leg or a standard tripod connection.	Allows users the ability to adjust their tripod and ensures the users have an appropriately stable base for their shots.
An industry standard camera head mount and tripod mount.	Interchangeability in the type of camera mounts and tripods the user may already own.
A locking mechanism to fix every degree of freedom.	Can fix the camera in different positions mid shot. Allows the user to get any isolated direction of motion they desire for their shot.

3. Concept Generation and Evaluation

Concept Generation Methods and Outcomes

We began our concept generation method by starting with a very basic initial version of a functional decomposition diagram for our intended project as we understood it then. See Fig. 3.A.1 below which shows our proposed subsystems. For a more in-depth description of these subsystems and their function, see Section 3 Product Functionality and Section 4 Functional Decomposition Diagram. Then, we looked at each subsystem individually, considered its respective design requirements, and spent five minutes brainstorming as many potential ideas as possible. From this collection of both realistic and unrealistic ideas, we chose our top five personal concepts for each subsystem. This made up our first round of generated ideas. See Fig. 3.A.2 for an example of these ideas.

Then we pooled our ideas together and discussed the concepts as a group. From this collection, we generated further ideas which incorporated different aspects of each other's suggestions. We took the top two concepts for each subsystem to analyze in a pugh chart for a more in-depth analysis. This was our second round of generated ideas. See Fig. 3.A.3 for an example of these ideas. For more ideation images, see the Appendix.

Our customer research and benchmarking guided our solution concept generation focusing on some metrics, such as camera stability, camera weight support of, jib extendability, and cost-effectiveness. We can see such considerations in the pugh charts below in Tables 3.A.1, 3.A.2, and 3.A.3 below.

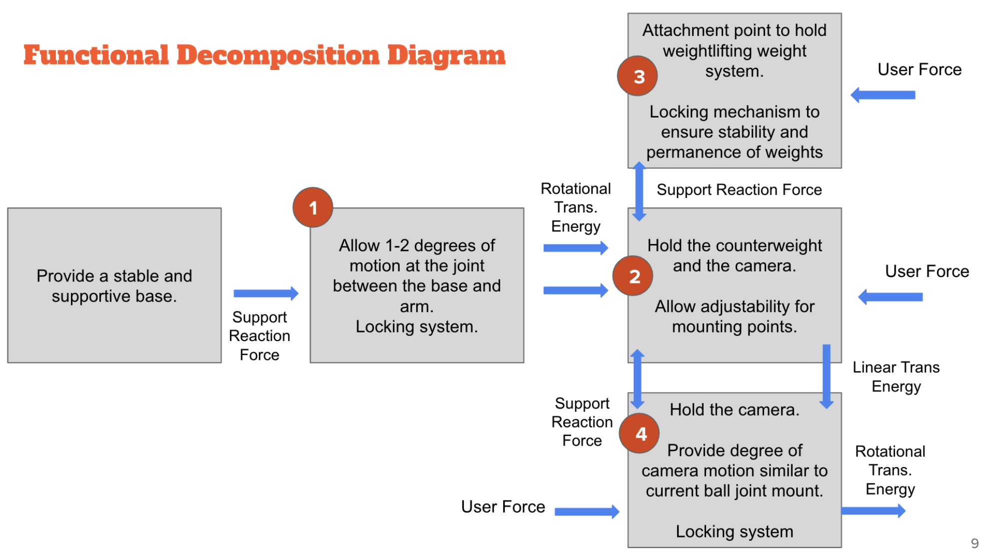


Figure 3.A.1. Simple Functional Decomp. Diagram

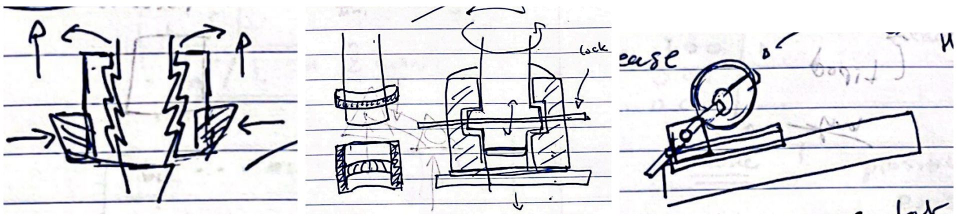


Figure 3.A.2. Example of rough first round idea generation. (For a locking barbell clamp, fulcrum mechanism, and sliding counterweight holder, respectively).

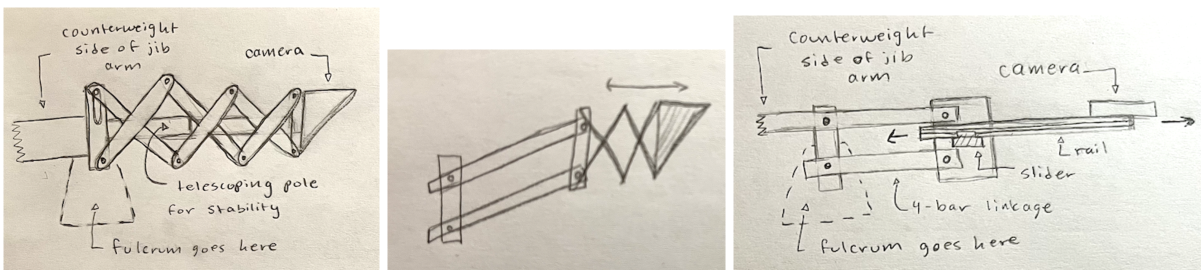


Figure 3.A.2. Example of second round idea generation. (For a scissor mechanism, scissor mechanism with 4-bar linkage fully shown, and rail-slider mechanism, respectively).

We ultimately crafted pugh charts for subsystems 1-3 on Fig. 3.A.1 above, since subsystem 4 required less ideation and is derivative of similar concepts used in subsystem 1.

For Pugh Chart 1, we compared mechanisms designed to provide the novel X motion of the camera on the jib arm to a standard jib arm design which has only Y motion and rotation about the Y axis. (See Fig 3.C.3 below for a description of what directions each motion refers to). Our first design is a scissor mechanism with a central support pole. Our second design is a rail and slider mechanism as shown in Table 3.A.1 and above in Fig. 3.A.2. We liked the scissor as a possible way to create a smooth motion that is not disjointed. It has another benefit over the slider-rail mechanism since it compresses to a smaller size, whereas the rail retains its same size, it just changes its position relative to the fulcrum.

For Pugh Chart 2 in Fig. 3.A.2, we compared mechanisms which would enable the fulcrum to rotate in the X-Z plane around the Y-axis and the fulcrum/arm to move up and down in the Y direction. Since our fulcrum will be mounted to a tripod, we compared our mechanisms to a standard set by a typical tripod with no motion capabilities, and a current tripod that incorporates the aforementioned motion abilities. Our first mechanism was a single-bearing fulcrum and the second was a dual-bearing fulcrum. For the X-Z planar rotation around the Y axis. Both mechanisms incorporate a pin joint to create the Y direction motion. The dual-bearing system has the benefits of extra stability for rotation, but is taller and has potential for extending the arm too high above the stable base of the tripod. Additionally it was designed to be a part of the tripod, and thus would remove the possibility of the videographer using their own tripod with our product.

For Pugh Chart 3 in Fig. 3.A.3, we compared mechanisms for the counterweight which would allow the weights to be easily added or removed. We compared these to a standard jib counterweight. Our first idea was to use simple barbell collars as clamps, since we intend to use weightlifting weights for our counterweight system. Our second design involves a slotted clamp which prevents rotation of the clamp, along with set screws to hold the clamp onto the weight-holding pole. The barbell is a simplistic design, but the slotted clamp is more difficult to attach and detach.

Concept Evaluation

Table 3.A.1. Pugh Chart 1 of the Jib Arm Subsystem, specifically the mechanism which will provide the in and out X motion DOF.

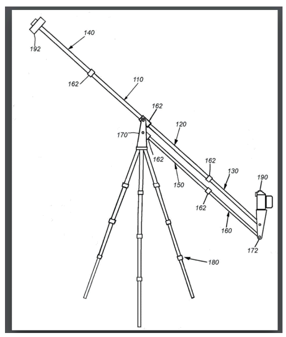
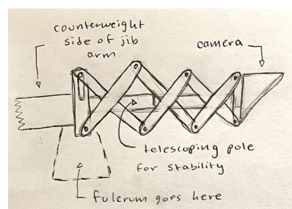
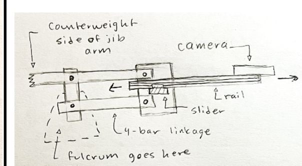
Description		2 bar 4 pin linkage (Datum)	Scissor Linkage	2 bar 4 pin linkage with slider
Sketch				
Criteria	Weight			
Cost of Material	2	0	- -	-
Repairability	1	0	-	-
Degrees of Freedom	2	0	++	++
Extendability	1	0	++	++
Range	2	0	++	++
Portability	2	0	++	0
Fluidity of Shot	2	0	++	0
Ease of Use	1	0	0	0
Stability of Shot	2	0	+	+
Interchange-ability	1	0	0	0
+		0	18	12
0		0	2	4
-		0	3	3
Net score		0	15	9

Table 3.A.2. Pugh Chart 2 of the Fulcrum Subsystem.

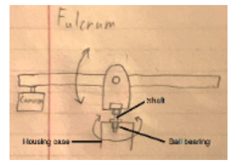
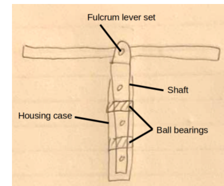
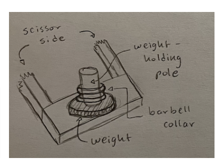
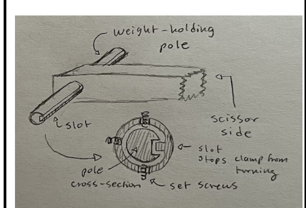
Description		No Fulcrum (Datum)	Best Fulcrum on Market	Single-Bearing Fulcrum Set	Dual-Bearing Fulcrum Set
Sketch					
Criteria	Weight				
Stability	2	0	++	+	+
Capacity (payload)	2	0	0	0	0
Cost	2	0	--	0	0
Intuitiveness	1	0	+	+	+
Interchange-ability	1	0	+	+	0
+		0	5	3	3
0		11	3	2	5
-		0	2	0	0
Net score		0	3	3	3

Table 3.A.3. Pugh Chart 3 of the Counterweight Subsystem.

Description		Standard Jib (Datum)	Barbell Collars	Lock and Key
Sketch			 	
Criteria	Weight			
Affordability	1	0	+	-
Counterweight Stability	2	0	0	0
Ease of Use	2	0	++	+
Durability	1	0	+	0
+		0	6	2
0		0	1	2
-		0	0	1
Net score		0	6	1

Assessment and justification of the top concept

We determined the criteria in the pugh charts to evaluate the design of each subsystem based on our design requirements gathered from research and the feedback obtained from interviews with potential customers. Among all subsystems, the Jib arm is the largest in our design, necessitating a greater amount of material compared to the others. Consequently, we assigned a weight of 2 to the cost of materials for this subsystem. We also believed that the criteria derived from the design requirements should carry more weight. Therefore, we assigned a weight of 2 to the degrees of freedom, range, portability, fluidity, and stability of shot. On the other hand, other criteria like extendibility, repairability, interchangeability, and ease of use, while necessary, were deemed more flexible; hence, we assigned them a weight of 1.

For the fulcrum, we assigned a weight of 2 to stability, capacity, and cost. As mentioned above, cost is a crucial factor listed in the design requirements. Stability is essential to the quality of the camera shot. Capacity quantifies what weight of the camera can be adequately supported by the fulcrum. The criteria weighted at 1 were considered less critical: for instance, interchangeability was a user requirement, but does not apply to the fulcrum. Intuitiveness represents the straightforwardness or easiness of operation of the Fulcrum to the end user. This is important, but there are only so many ways the fulcrum can operate. Thus, it is rated at 1.

The counterweight designs share similar reasoning for the assigned weights as the fulcrum, with the exception that cost was not considered significant. All designs were economical and simple enough not to have a substantial impact on the overall system price, hence cost was excluded from the criteria for the counterweights. The essential metrics are stability and ease of use. Stability of weight is key to provide good balance with the camera weight and thus quality shoot. Ease of use is defined by how quickly counterweight can be added or removed.

Once created, we utilized the Pugh chart scores to select our top designs. As shown in Table 3.A.1, we chose the scissor mechanism because it had more portability than the rail slider system. The scissor has the benefit of being compressed to a smaller size, whereas the rail-slider merely moves the location of the rail, and as such, the rail is bulky and is not a streamlined design. Additionally, we judged that the scissor could provide a more fluid shot than a rail-slider based on our previous interaction of similar mechanisms, such as cabinet drawer rails. However, after prototype 1 testing, we discovered that we had not taken into account the additional complexity of the scissors' many joints. It turns out the slider mechanism is better, as we later discovered in prototype 2. As shown in Table 3.A.2, the fulcrum designs were a tie. However, we chose the single-bearing fulcrum because it is a smaller mechanism that allows the arm to be very close to the stable base of the tripod. Additionally, the single-bearing fulcrum allows the fulcrum to operate independently from the tripod stand, ensuring that the customer could use their own preferred tripod. Lastly, as shown in Table 3.A.2, we went with the barbell clamps because they are a simple and adequate solution that meets our design criteria without requiring us to design something novel.

Product Functionality

The table and CAD models below describe in detail how our product functions and directs the reader to figures which illustrate the motion described.

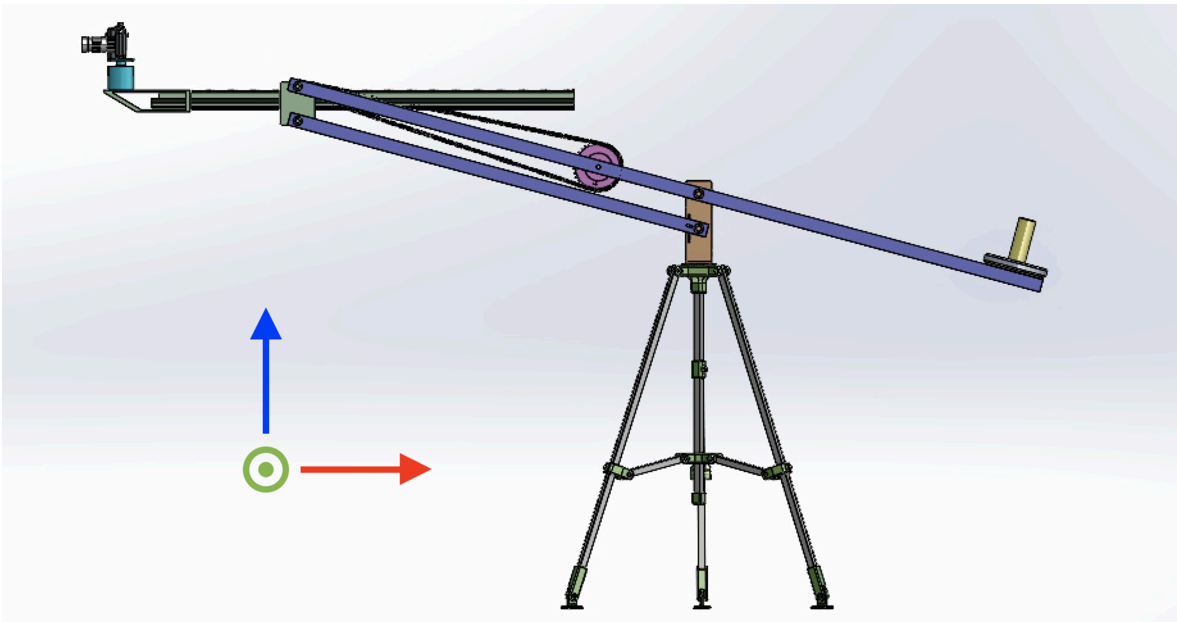


Figure 3.C.1. Right View of Detailed Final CAD. See Appendix for all Subsystems.

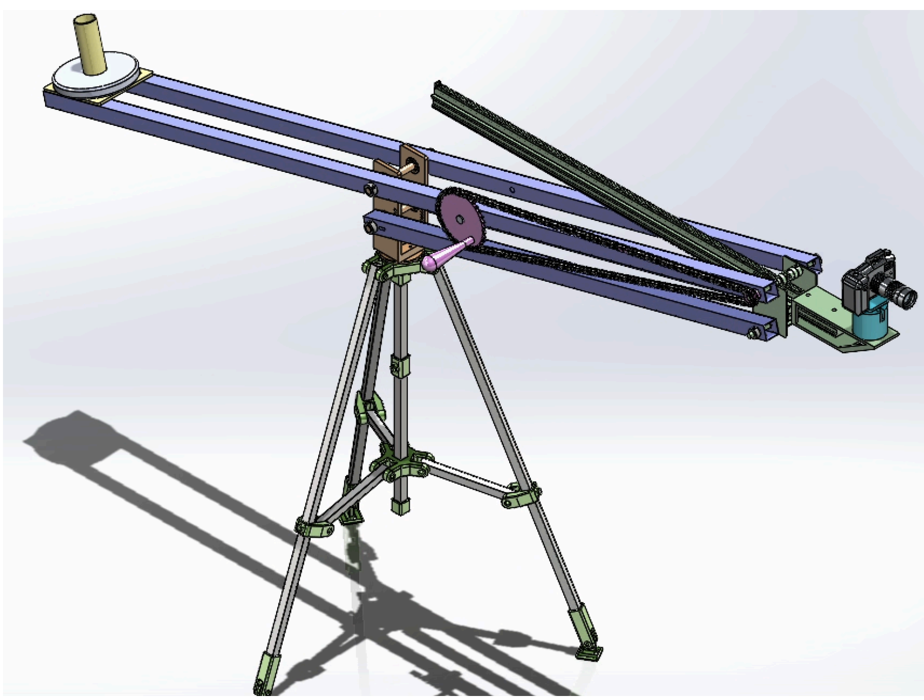


Figure 3.C.2. Isometric View of Detailed Final CAD. See Appendix for Subsystems.

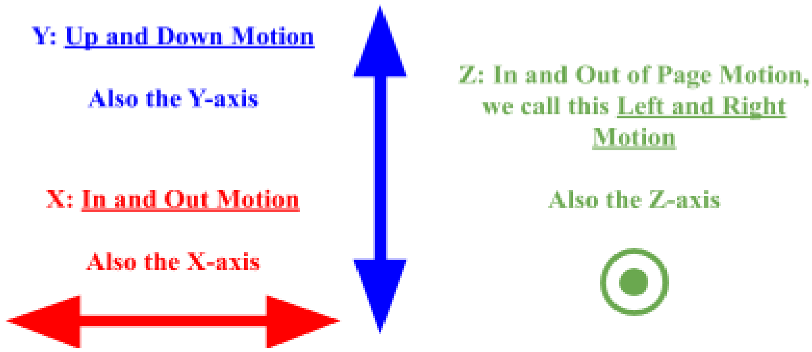


Figure 3.C.3. Motion Direction Description.

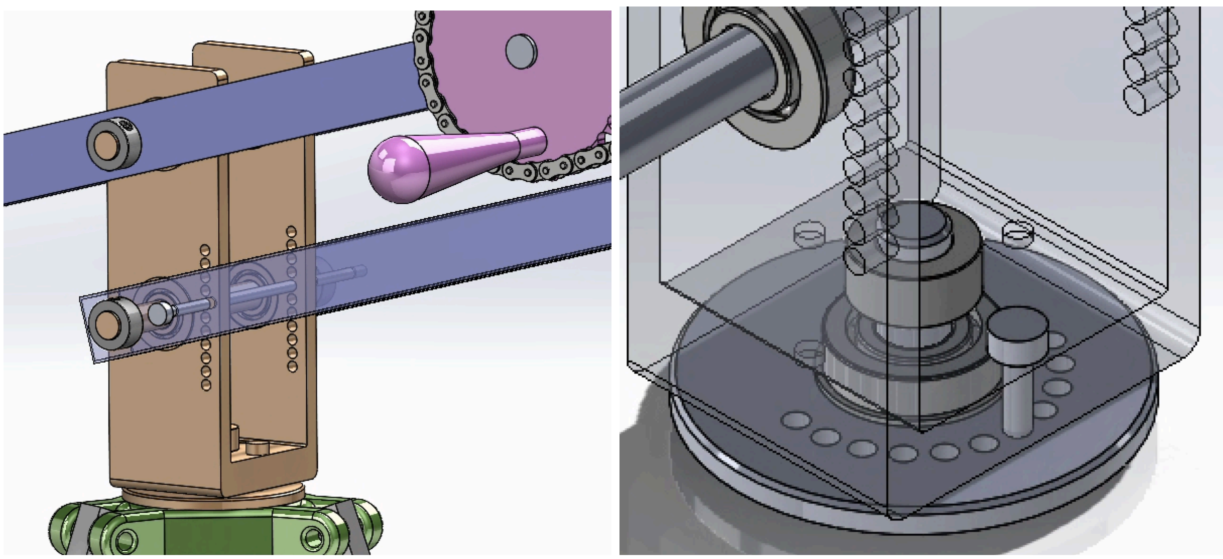


Figure 3.C.4. Locking Mechanisms. Y-locking shown on the left consists of a horizontal pin. Z-locking shown on right consists of a vertical pin.

Table 3.C.1 **S**ubsystem Color Reference and Function Description. For function description use Figures 3.C.1 and 3.C.3 to determine the directions of motion.

Subsystem	Color	Motion	Function - further description	See Figure
Rail Slider Mechanism	Green	along the X-axis	Provides the user with the ability to create an In and Out motion shot with the camera. This is a unique DOF that typical jibs do not have. This is 1 DOF.	Fig 3.C.5
Fulcrum	Orange	360˚ Rotation around Y-axis	Provides the user with the ability to create a Left and Right motion shot with the camera when using small angles. The fulcrum provides 360˚ of left and right rotation as well. This is our 2nd DOF.	Fig 3.C.6
Arm Linkage	Blue	along the Y-axis	Along with the Fulcrum, it provides the user with the ability to create an Up and Down motion shot with the camera. This is our 3rd DOF.	Fig 3.C.7
Rack, Pinion, Chain	Pink	along the X-axis	Provides the mechanism by which the user moves the Rail Slider mechanism. Clockwise/counterclockwise rotation of the large sprocket by the handle moves the Slider.	Fig 3.C.2
Locking System	n/a	Prevents motion	Allows the user to lock either the up and down (Y) motion or the left and right (Z) motion. Both can be locked at once, or just one degree of freedom can be locked, or none.	Fig 3.C.4
Counter-weight	Yellow	n/a	Balances the weight of the Rail Slider side of the Jib Arm. Meant to counter both the weight of the arm and the camera such that the Jib Arm can be easily manipulated by the user.	Fig 3.C.1
Camera Mount	Teal	X-axis transl. Y-axis rotation	Provides the connection between the camera and the Rail Slider. Also enables the camera to be positioned at a specified Up and Down angles and a specific Left and Right angle.	Fig 3.C.8
Tripod	Gray+ Green	n/a	Provides a stable base of support for all the other subsystems and keeps the Fulcrum at a reasonable height above the ground for the desired footage.	Fig 3.C.1

Note: To find more detailed CAD models of each subsystem, see Appendix A.

Physical Constraints of Functionality Diagrams

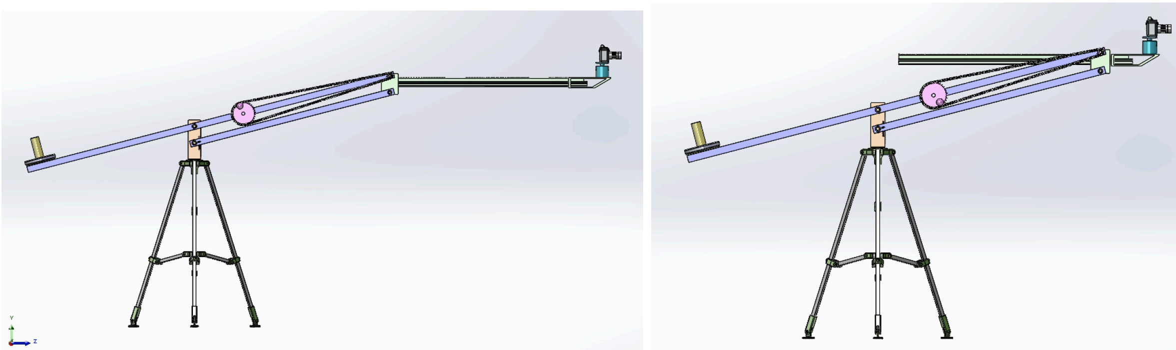


Figure 3.C.5. Maximum Slider Mechanism In and Out X-axis Motion (40 in of motion).

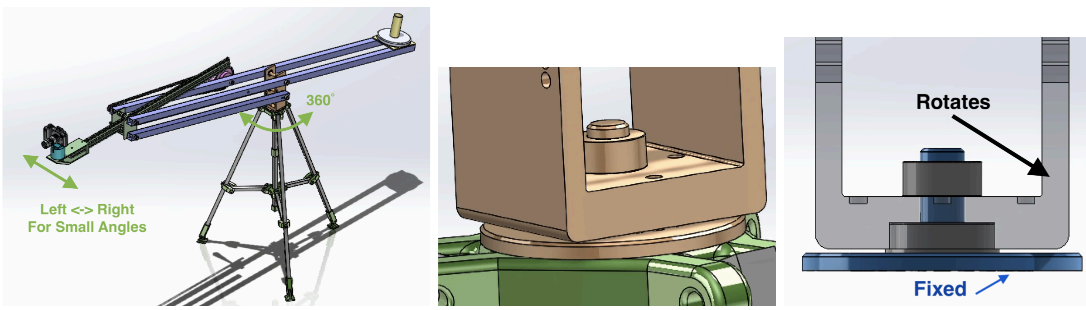


Figure 3.C.6. Max Fulcrum Rotational Left and Right Z-axis Motion (360˚ of motion).

Figure 3.C.7. Max Arm Linkage and Fulcrum Up and Down Y-axis Motion (6 ft of motion).

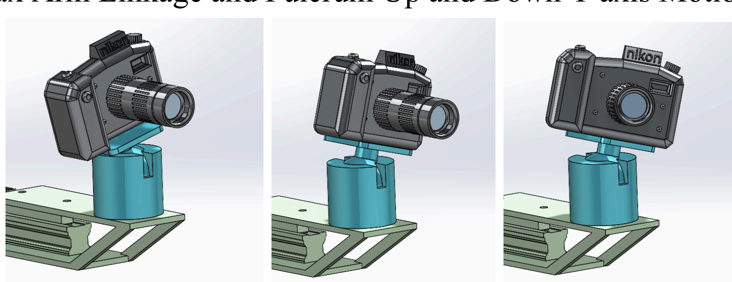


Figure 3.C.8. Camera Ball Joint Mount Positioning Motion.

4. System Functional Analysis

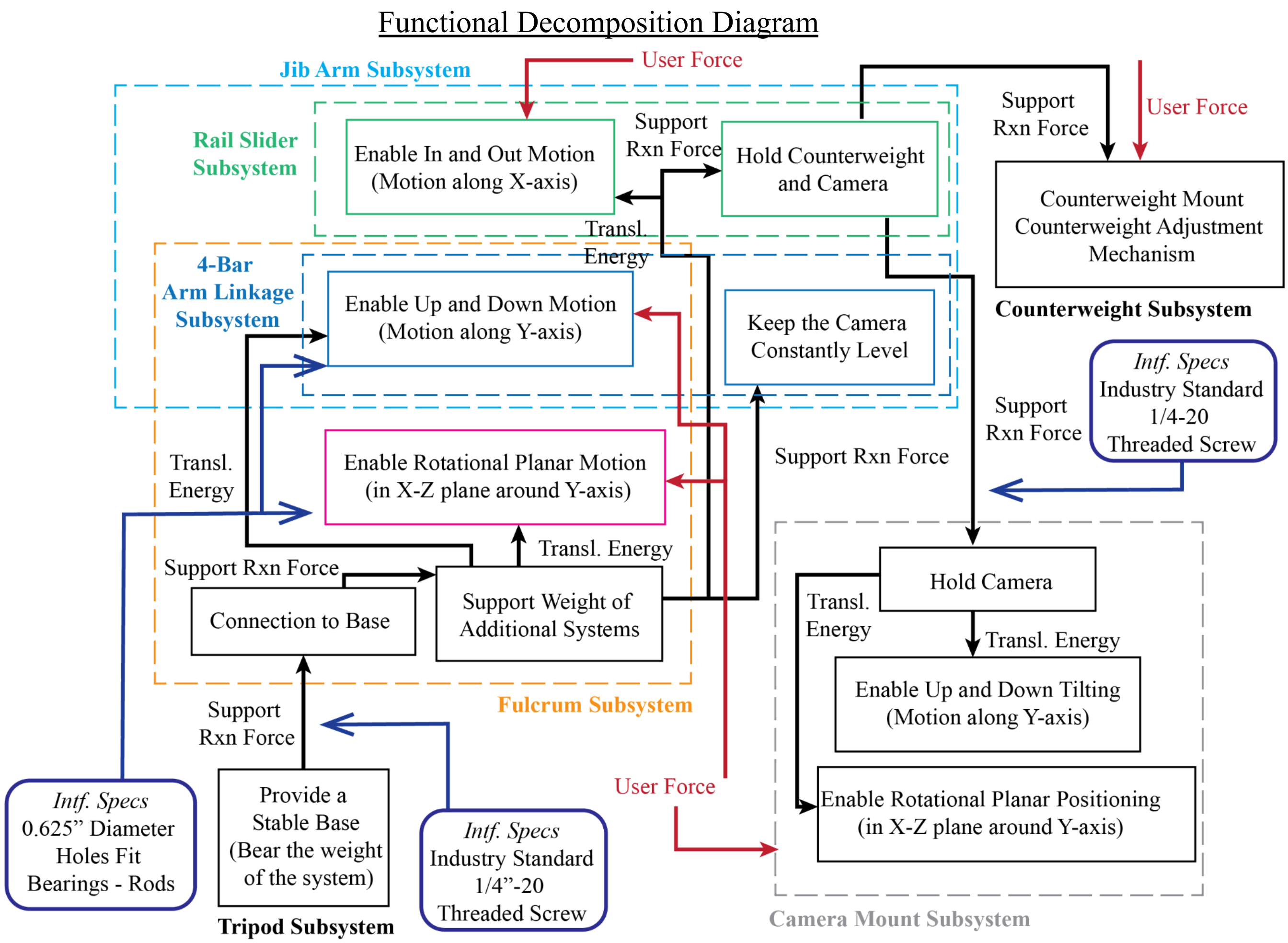


Figure 4.1. Functional Decomposition Diagram for full product. Subsystems are color-coded as shown above in the CAD Model in the Detailed Design Description.

As shown in the Figure 4.1 above, our proposed product has 5 major subsystems: the Tripod, Fulcrum, Jib Arm, Camera Mount, and Counterweight. Additionally, the Jib Arm subsystem is subsequently divided into 2 more subsystems: the Rail Slider Mechanism and the 4-Bar Arm Linkage Mechanism. The Tripod is meant mainly for support. As such, our design does not intend to improve upon the tripod, and we will instead focus on manufacturing the remaining subsystems. This decision was made in conjunction with the fact that most of our customers already own a tripod of reasonable caliber.

First, the Fulcrum (Orange) exists to connect to the tripod, support the other subsystems, and provide rotational planar motion (360˚ around the Y-axis). Note: see Fig.3.C.3 for XYZ motion description key. This is our 1st Degree of Freedom (DOF). Additionally, the Fulcrum and the 4-Bar Arm Linkage Subsystem (Dark Blue) work together to provide the up and down motion (along Y-axis). This is our 2nd DOF. Energy to both these subsystems is provided via user input force (shown in red), supporting reaction forces, and translational/rotational energy.

The 4-Bar Arm Linkage Subsystem has an additional task, namely keeping the camera mount level no matter the Y position of the Jib Arm Subsystem (Light Blue). We achieved this self-leveling mechanism by separating the Jib Arm Subsystem into the Rail Slider Mechanism and the 4-Bar Arm Linkage. Because the Arm Linkage is a 4-Bar system designed where each opposing linkage is equal in length, the opposing linkages will always be parallel to each other. So, our left and right short linkages always remain flat and level. The Rail Slider Mechanism (Green) is attached to this linkage, so the entire subsystem remains level. The Rail Slider uses translational energy to enable motion In and Out along the X-axis. This is our 3rd DOF.

The Counterweight Subsystem is a support system to hold weights on the Jib Arm. It also enables the overall system to balance against the weight on the Rail Slider end of the Jib Arm and be more easily manipulated. The Camera Mount Subsystem (Gray) has a positioning system that enables 360˚ Y-axis rotation in the X-Z plane and Up/Down Y-axis angling. The positioning of the Camera Mount is considered our 4th DOF.

The Fulcrum, Rail Slider Mechanism, and Counterweight Subsystems all have a user input force. The Counterweight requires user input to add weights and remove them, however this is not done concurrently with the other two subsystems. As such, the 4-DOF Jib Arm Product would be locked into an unmoving position at the time in which the weights are mounted onto the system.

The Fulcrum and Rail Slider Mechanism user inputs have to do with manipulating the degrees of freedom motion capabilities of our product. Generally only one input will be applied at a time. For more detail about interfaces and locking see below.

Interface Specifications

As shown in Fig. 4.1 above (Navy Blue) there are three key interface specifications. Specifically, at the connection between the Tripod and the Fulcrum and the Camera Mount and the camera we must abide by videography industry standards. Tripods come with a ¼”-20 threaded bolt that a camera can be mounted on. So, our Connection to Base on the Fulcrum must have a hole threaded to ¼”-20 to attach to a standard tripod. Similarly, our camera mount must have a ¼”-20 threaded rod/bolt to enable a standard camera connection.

Additionally, we specified the 0.625” holes needed for the Fulcrum and Arm Linkage subsystems since it was a measurement used across multiple subsystems and so our group needed to be aware of the value to avoid error.

Locking is necessary at every interface in which a degree of freedom is applied. So, the rotational motion (in X-Z plane), up and down (along Y-axis), in and out (X-axis), and camera positioning must all have the ability to be locked into a specific position. They need not all be locked at the same time. Indeed, any combination of the 4 DOFs can be locked at any one time.

5. Prototype Tests and Performance

Prototype 1 Description

For Prototype 1 we focused on designing the Scissor mechanism, the Fulcrum, and the Arm linkage. Our Prototype 1 (PT1) was designed as shown in the Appendix and below in Fig. 5.A.1. The Fulcrum is machined from three pieces of Multipurpose 6061 Aluminum. The pieces are connected by four ¼”-20 Black-Oxide Alloy Steel Socket Head Screws. The Fulcrum also contains two 0.625” Carbon Steel Rotary Shafts and five 440C Stainless Steel Flanged Ball bearings. The bearings are fixed onto the shafts via four 0.625” Carbon Steel Shaft Collars.

The Arm Linkage subsystem is made of two Multipurpose 6061 Aluminum 1.5” Square Tubes with 1/16" wall thickness. These tubes were machined in the Tech Spark shop to have the appropriate holes.

The Scissor mechanism is manufactured from ¼” MDF board. The pieces were cut with the laser cutter. The holes and slots in the Scissor mechanism pieces are ¼” diameter. The pieces are fixed to each other with ¼”-20 Black-Oxide Alloy Steel Socket Head Screws, ¼” washers, and ¼”-20 Zinc Plated Steel Hex Nuts.

Prototype 2 Description

For Prototype 2 we focused on designing the Rail Slider mechanism, the Counterweight, and the Locking System. Our Prototype 2 (PT2) was designed as shown in the Appendix and below in Fig. 5.A.1. We used the same Fulcrum created in PT1, however we used an additional two Multipurpose 6061 Aluminum 1.5” Square Tubes with 1/16" wall thickness to widen our design. The Rail Slider subsystem consists of 1” square T-slotted Framing Rails from McMaster that slide on four plastic T-Slotted Framing Rail Slides. These slides were mounted to a slider box manufactured from ⅛” flat aluminum slider box sides and flats. The slider box sides were cut with the waterjet and the flats were machined with the lathe. The sides and flats were welded together to make the complete slider box. Additionally, we created the counterweight subsystem by using a plywood platform and a 2” diameter ABS plastic rod. This was then attached to more T-slotted Framing Rails, which were attached to the opposite end of the Arm Linkage as the Rail Slider mechanism. We also machined the Fuclcrum’s bottom lock and tripod-jib connector from aluminum. We 3D printed the vertical (Y-motion) locking system and screwed it onto the Fulcrum. All pieces are fixed to each other with ¼”-20 Black-Oxide Alloy Steel Socket Head Screws and ¼”-20 Zinc Plated Steel Hex Nuts.

Figure 5.A.1. Image of the full PT1 assembly (left) and PT2 (right).

Prototype Testing

Questions we intend to test:

1) Can PT1 and PT2 pan the height of a 6 ft person?
2) Does PT and PT2 achieve at least 3 ft of in and out (x-axis) distance?
3) Does the linkage keep the camera mount level?
4) How much does each subsystem weigh?
5) How much and at what angle does the scissor mechanism droop?
6) How much does the scissor mechanism bend left and right?
7) Can PT1 and PT2 hold the desired 10 pounds of weight?

PT1 Analysis and Conclusions:

We performed tests on each of the PT1 subsystems. Overall, the tests confirmed that PT1 meets the physical constraints of panning a 6 ft person and achieving at least 3 ft of in and out (x-axis) motion. Although, the tests on the scissor mechanism showed that the prototype, without any applied loads to the scissor, has undesired droop (downward from the scissor's own weight) as well as left and right bending (any time the arm is moved left or right). Under zero applied load, this droop and bending led us to the conclusion that the assembly cannot hold our desired 10 lbs of camera weight. During testing, we also discovered an extreme tipping moment occurring at the fulcrum that nearly broke our tripod fulcrum connection. This will be improved with the addition of the counterweight subsystem, but could be even further improved with a redesigned tripod-fulcrum connection part. The testing results are shown below in tables 5.B.1, 5.B.2, and 5.B.3 below. The testing parameters are defined in Appendix III with images to show what they mean.

Table 5.B.1. PT1 Testing Results for Scissor Subsystem

Extended Length (in)	53.125
Compressed Length (in)	17.5
Compressed Droop (deg)	4.10
Compressed Left and Right Bend (deg)	20.1
Extended Droop (deg)	10.3
Extended Left and Right Bend (deg)	62.3
Weight (lbs)	6.5

Table 5.B.2. PT1 Testing Results for Aluminum Tube Arms and Fulcrum Subsystems

Counterweight End Length (in)	23.5
Camera End Length (in)	47.5
Weight of Aluminum Tube Arms (lbs)	5
Weight of Fulcrum (lbs)	8.5
Weight (lbs)	13.5

Table 5.B.3. PT1 Testing Results for Full Assembly

Maximum Height Reached (in)	50.25
Minimum Height Reached (in)	-26.0
Total Pan Height (in)	76.25
Weight (lbs)	20

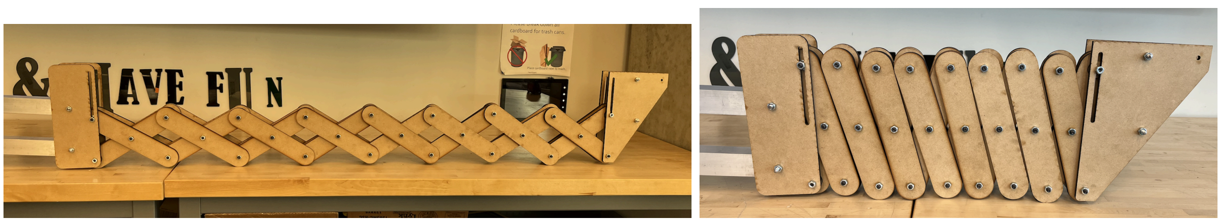


Figure 5.A.2. Maximum Scissor Mechanism In and Out X-axis Motion (3 ft of motion).

PT2 Analysis and Conclusions:

After much consideration, the undesired droop and bending led us to refine our scissor mechanism into a sliding rail mechanism instead. While our research had led us to believe that the scissor mechanism was the ideal choice, the practical results of PT1 indicate that the scissor mechanism has too many interacting parts with a potential for error, misalignment, slippage, and instability. The sliding rail mechanism of PT2 consists of two rails that are attached to the camera mount. This refinement significantly decreases the number of parts, the number of fasteners, the number of areas for possible bending to occur, and difficulty of manufacturing. In addition, The two additional aluminum tube arms for PT2 add more stability to the jib.

The testing of the PT2 subsystems confirmed that PT2 meets all of the design requirements. It can hold up to 10 pounds of weight and can be assembled in under 30 minutes. Although, there is a consistent 2 degree slant for the rail sliders due to a manufacturing error. By replacing the PT1 scissor with the PT2 slider, we have cut the droop degree in half and removed the left and right bending. The results of testing are shown in Table 5.B.4, Table 5.B.5, and Table 5.B.6 below. Additionally, by making use of an Optical Flow Algorithm, we were able to compare the stability of our jib versus just holding the camera. As seen in Table 5.B.7 below, our jib is significantly more stable than the alternative.

Table 5.B.4 PT2 Testing Results for sliding rail mechanism

Extended Length (in)	30
Compressed Length (in)	-
Compressed Droop (deg)	4
Half Length Droop (deg)	2
Extended Droop (deg)	8
Weight (lbs)	3.8

Table 5.B.5. PT2 Testing Results for Aluminum Tube Arms and Fulcrum Subsystems

Counterweight End Length (in)	23.5
Camera End Length (in)	47.5
Weight of Aluminum Tube Arms (lbs)	10
Weight of Fulcrum (lbs)	8.5
Weight (lbs)	18.5

Table 5.B.6. PT2 Testing Results for Full Assembly

Maximum Height From the Ground (in)	80
Minimum Height From the Ground (in)	8
Total Pan Height (in)	72
Weight (lbs)	26.8

Table 5.B.7. PT2 Testing Results for Optical Flow Algorithm. The algorithm analyzes the video and assigns a roughness value. A lower value is ideal.

Shot Type	Our Jib	Hand-Held Camera
Left-Right (Z-motion)	0.83	4.00
Up-Down (Y-motion)	1.13	1.44
In-Out (X-motion)	3.56	4.12

Figure 5.A.3. Prototype 2.

6. Engineering Analysis

Material Selection

In this section, we will address the justification of our material selection as an engineering analysis. Design objectives and material indices are the primary criteria to our material selection. Based on our design objectives of low weight and affordability, Cast Iron, Low alloy steel, AISI 9255, and Aluminum, 2024, T861 are initially the materials to be considered.

Since Cast Iron is a brittle material, the sudden breakage of a brittle material is characterized by little to no plastic deformation before rapid crack propagation. Cast Iron is not appropriate for use with our jib, since such a brittle break may cause severe injury to people and expensive camera equipment. Then, only Low alloy steel, AISI 9255 (low alloy steel) and Aluminum, 2024, T861 (Aluminum, 2024) are the materials with characteristics appropriate to our design.

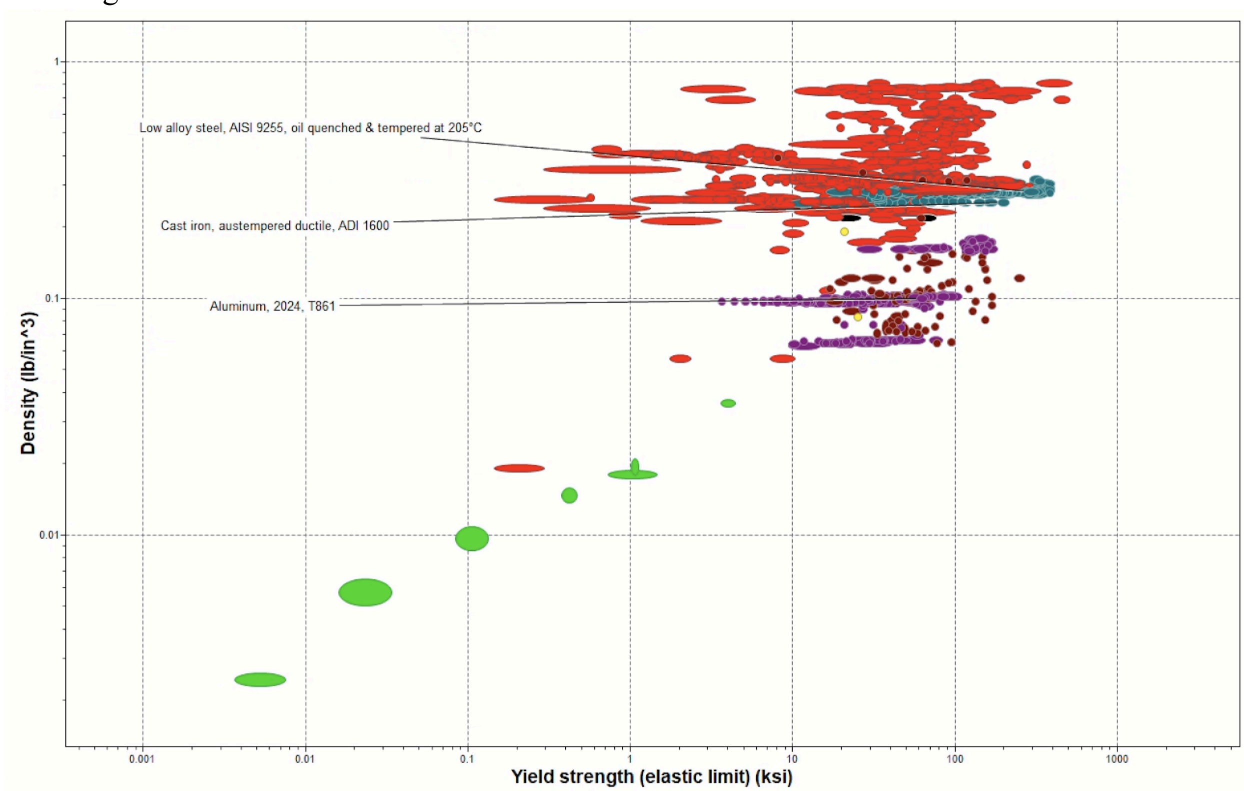


Fig. 6.1 Material indices - Density vs Yield strength

Fig. 6.1 shows the density vs yield strength distribution of Low alloy steel, AISI 9255, and Aluminum, 2024, T861. Metric stress to weight ratio is utilized for evaluation. The weight to stress ratio of Aluminum, 2024, T861, is 0.0016 lb/in^3-ksi, whereas weight to stress ratio of Low alloy steel, AISI 9255, is 0.00096 lb/in^3-ksi. In other words, taking the reciprocal of weight to stress ratio, the stress to weight ratio of Aluminum , 2024, T861, is 1/0.0016 = 623 ksi-in^3/lb,

while stress to weight ratio of Low alloy steel, AISI 9255, is 1/0.00096 = 1038 ksi-in^3/lb. The stress to weight ratio of Low alloy steel is higher than that of Aluminum, 2024, T861.
While the stress to weight ratio of Low alloy steel, AISI 9255 is higher (better) than Aluminum, 2024, T861, the machinability of these two materials is also considered. Higher machinability rating of a material implies easier machining of that material. As listed in Table 6.3.1, machinability rating of Aluminum, 2024, i.e., 4.80 - 3.20, is an order of magnitude better than that of alloy 9255, i.e., 0.36-0.08. Therefore, given that the machinability rating of Aluminum is 10 times better than that of Low alloy steel and the stress to weight ratios are only 2 times different, Aluminum 2024 stands out as the better material. Also based on the sizes of our designs it seems a higher strength material is not needed, as it already satisfies the 5 FOS requirement.

The density of Aluminum 2024 is only around 30% of that of low alloy steel, and thus this meets our design objective of low weight.

Table 6.3.1 Machinability comparison
(https://www.a-i-t.com/cnc-machining-services/machinability-rating-chart)

MATERIAL		Hardness BHN	Machinability Rating
Alloy Steels, Cast	**Material Grade**	**Range**	**Range**
Medium Carbon	1330, 4032, 4130,	175-52R_C	.36 - .08
	4135, 4140, 4145,		
	4150, 4340, 5130,		
	5140, 5147, 5150,		
	6150, 8630, 8637,		
	8640, 8642, 9255,		
	9260		
Aluminum Alloys, Wrought		30-150 (500 kg)	4.80 - 3.20
	EC, 1060, 1145,		
	1235, 2014, 2018,		
	2024, 2217, 2218,		
	2618, 3004, 4032,		
	5050, 5056, 5086,		
	5252, 5454, 5457,		
	5657, 6061, 6066,		
	6101, 6262, 6951,		
	7004, 7039, 7075, 7175		

For the other design objective of affordability, **Fig. 6.2** (below) indicates that in the lower density region, Aluminum, 2024 is among the lowest price per unit volume. This meets our design objective of affordability.

In addition, the yield strength of Aluminum 2024 is on the higher end among the group of materials of similar price per unit volume shown in **Fig. 6.3**.

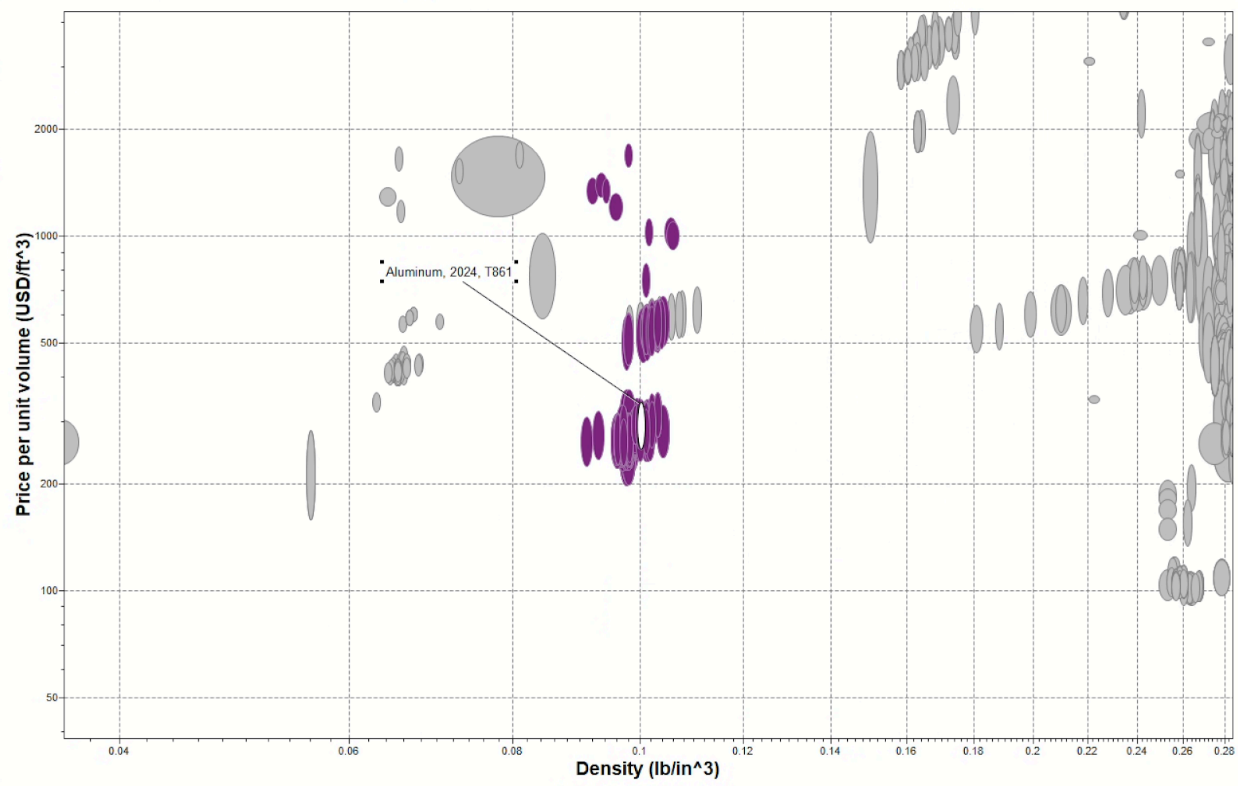


Fig. 6.2 Material indices - Price per unit volume vs Density

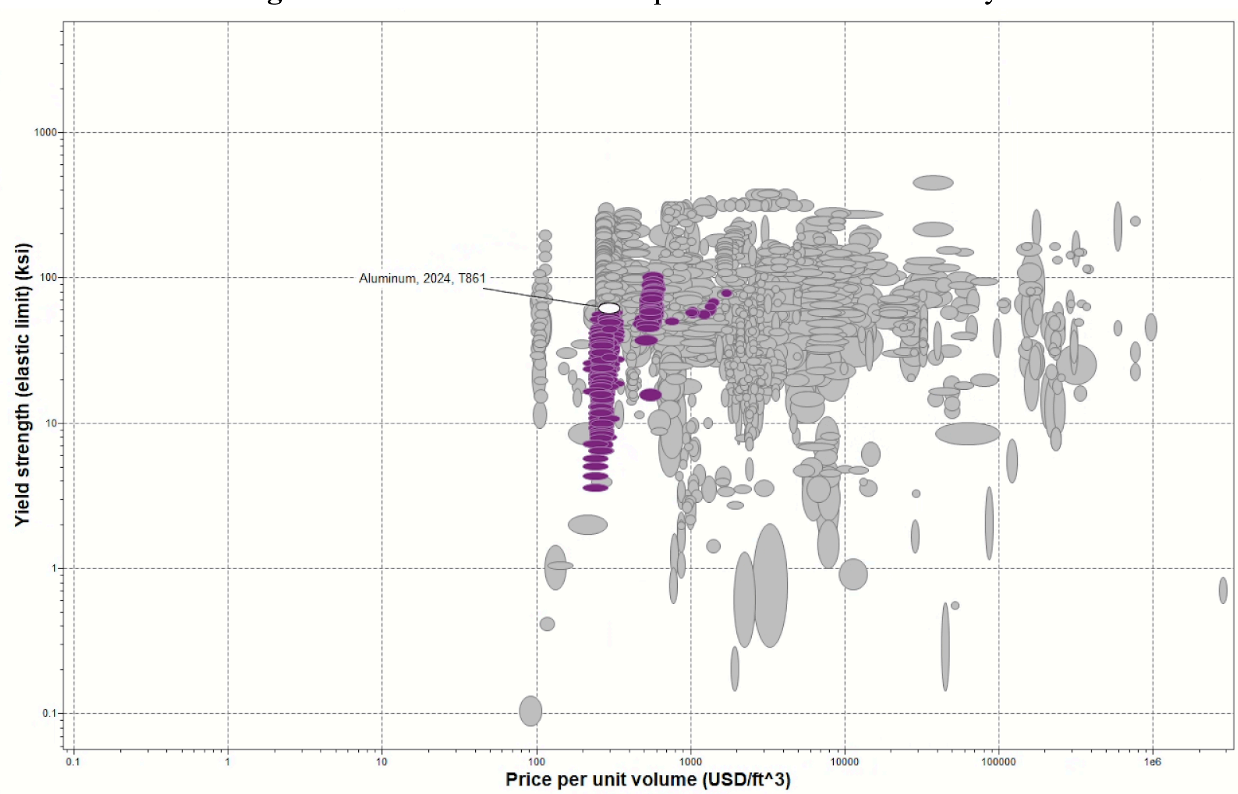


Fig. 6.3 Material indices - Yield strength vs Price per unit volume

FEA - Custom Fulcrum Rotary Shaft

To test the strength of Custom Fulcrum Rotary Shaft, a load of 610 Newton is simulated as an upward-force applied to the edge of the pin, representing a load from Custom Top Arm (Long).

This scenario is when the pin on the top of **Custom Fulcrum Structure** is carrying the most weights, such as jib, camera, and counterweight. The weights are held by the pin and apply an **upward-force** upon the edge of the pin. A load of 610 Newton distributed across the curved edge of the pin was used for FEA. The bottom part of **Custom Fulcrum Structure** was set fixed.

As shown in **Fig. 6.4**, the simulation yielded a maximum stress of 7.893e +07 N/m^2 on the pin. This results in estimations of Factor Of Safety (FOS) of 5 for Aluminum and FOS of more than 25 for Low Alloy Steel. We used OSHA's standard of FOS of 5 for Hoists and Rigging as a baseline to choose a reasonable factor of safety. See our engineering standards for more information. As such, from our analysis, both Aluminum and Low Alloy steel have sufficient FOS for the shaft.

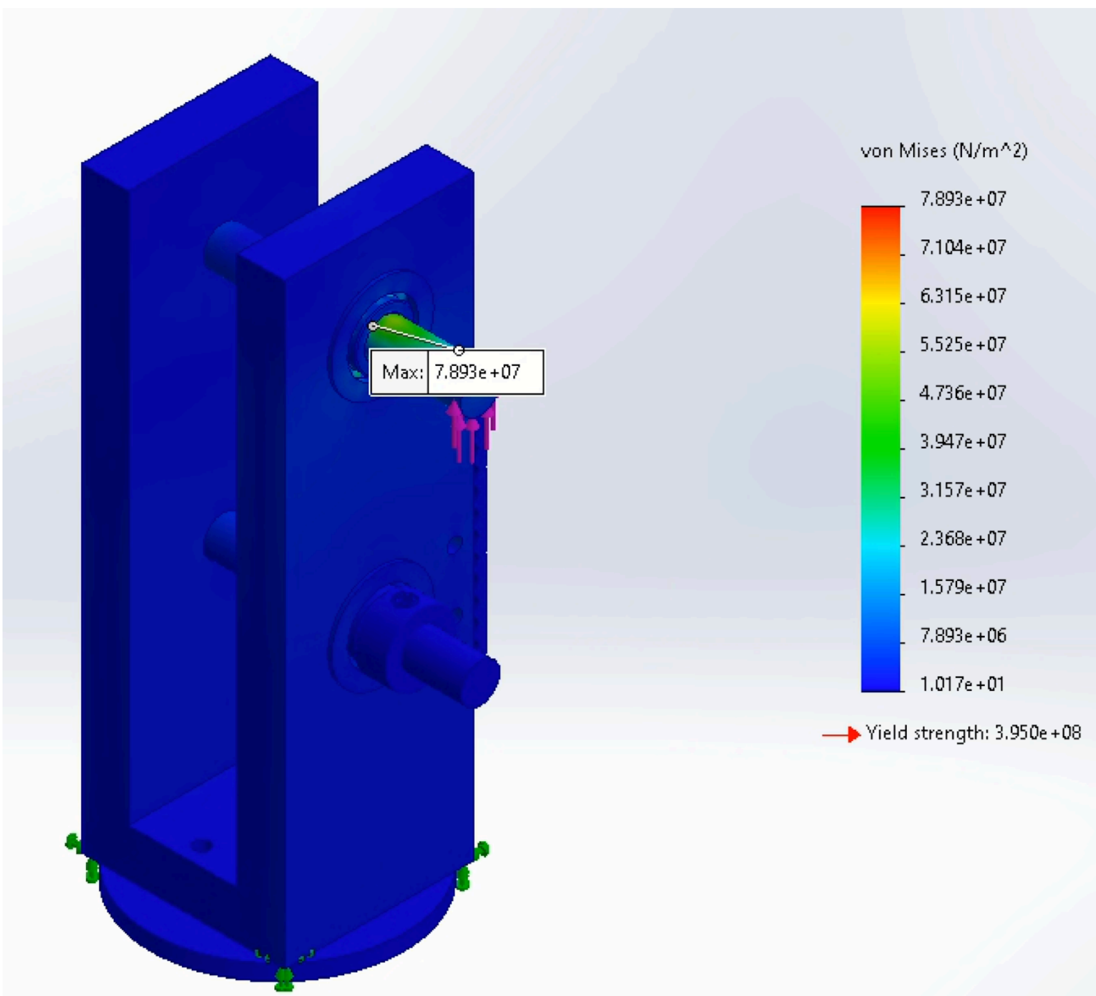


Fig 6.4 Stress distribution for the pin in Custom Fulcrum Structure

FEA - Custom Top Arm (Long)

The strength of the Custom Top Arm (Long) was under the loads from counterweight and slider mechanisms, including a camera, and therefore was our focus in testing using FEA.

Three loads are applied on the very two ends of the long arm. The loads 98 Newton, 88 Newtons, and 790 Newtons represent loads on the left in the Y directions, right in the Y directions, and right in the X directions, respectively. The center holes shown in **Fig. 6.5,** were set fixed**.**

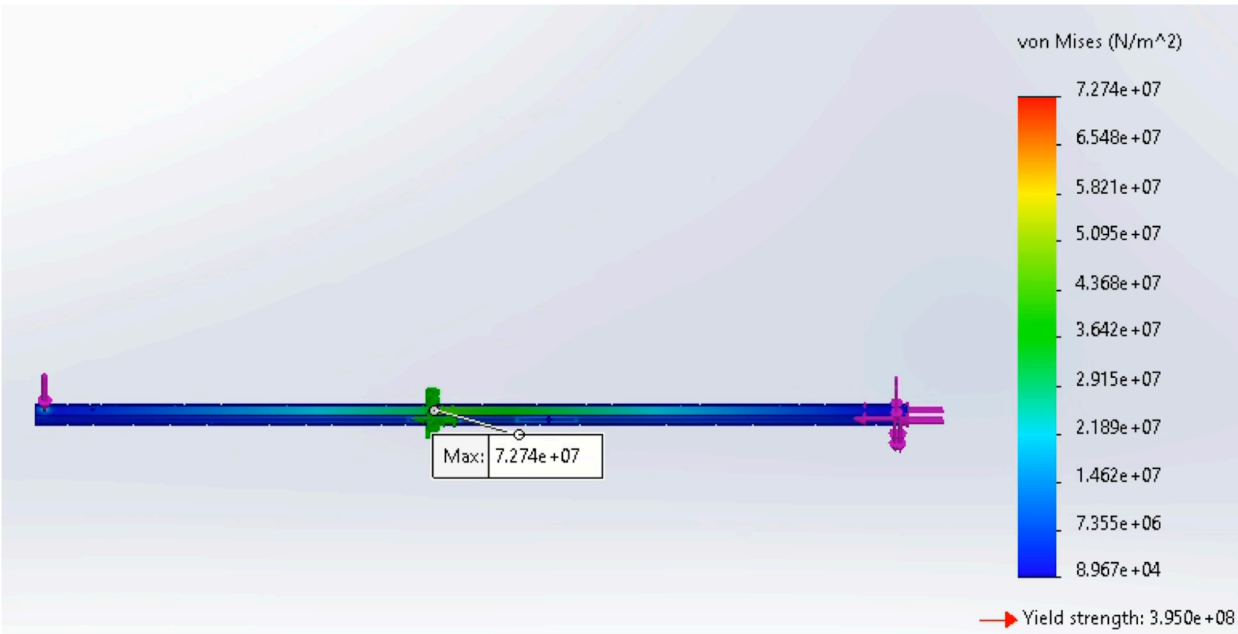


Fig 6.5 Stress distribution for the pin in Custom Top Arm (Long)

The simulation yielded a max stress of 7.274e +07 N/m^2, and this gives FOS of 5.2 for Aluminum and nearly 25 for Low Alloy Steel.

Our FEA indicates that both Aluminum and Low Alloy Steel are giving more than sufficient FOS. Because the lighter and cheaper Aluminum meets design objectives of lightweightness, affordability as well as the FOS from FEA simulation, Aluminum was chosen for the most appropriate material in our design.

7. Component and Material Selection

The following table outlines the components and material selection for our prototype. These were selected primarily based on design objectives, but also factor in other justifications.

Table 7.1. Material Choice and Justification

Part No.	Component	Material	Justification
C001	Custom Fulcrum Structure	Aluminum, 2024, T861	-Ductile - Low density - Low price per unit volume - High yield strength - Good machinability (lower price for machining) -High Strength to Weight Ratio -Yield strength was high enough to achieve a Factor of Safety of 5 - Using the same material for many parts is more affordable since we do not need to buy many different materials.
C002	Custom Fulcrum Rotary Shaft		
C003	Custom Fulcrum Bottom Lock and Left-Right Swiveling Mechanism		
C004	Custom Short Locking Pin (Left-Right)		
C005	Custom Top Arm (Long)		
C006	Custom Bottom Arm (Short)		
C007	Custom Slider Box		
C008	Custom Gear Rack and Guide Rail Connector		
C009	Custom Gear Shaft		
C010	Custom Counterweight Platform		
C011	Custom Camera Platform		
C012	Custom Handle for Large Sprocket		
C013	Custom Sprocket Shaft		
C014	Custom Long Locking Pin (Up-Down)		

8. Final Detailed Design

Figure 8.1. Final Detailed Design. Also depicted above are the tripod, counterweight, camera ball joint mount, and camera, which are sold separately.

Our final detailed design is similar to our second prototype, however it has several notable major changes and a few minor ones. Note that an in-depth description of how our product functions can be found in *Section 3* Above under *Product Functionality*.

Our first major change between PT2 and our final design is the incorporation of a more advanced and expensive linear slider. We will use a Maintenance-Free Ball-Bearing Carriage and guide rail to replace the simple plastic McMaster sliders and T-Slotted Framing Rails used in our prototype. This will effectively reduce the friction we discovered in the rail-slider subsystem. It will also reduce the gaps between the sliders to a reasonable level, giving our design a better tolerance. See Figure 8.2 below, which illustrates the new carriage, which uses recirculating ball-bearing to reduce sliding friction.

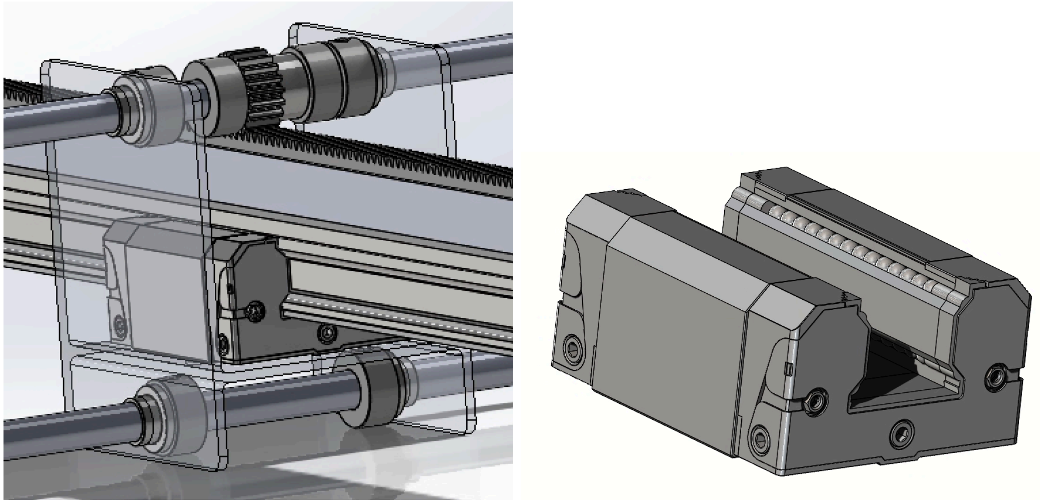


Figure 8.2. New ball-bearing carriage and guide rail for friction reduction.

Additionally, our final design incorporates a gear rack and pinion mechanism along the slider guide rail, which was not modeled in PT2. This rack and pinion mechanism is then connected to a chain and sprocket mechanism, which allows the user to wind the bottom sprocket so that the rail moves in and out. This winding mechanism enables a user to manipulate the slider-mechanism's X degree of motion from a position farther back along the Jib arm. Additionally, it allows easier use of the slider-mechanism when the jib is at an extremely high or low vertical position. See Figures 8.3 and 8.4 below.

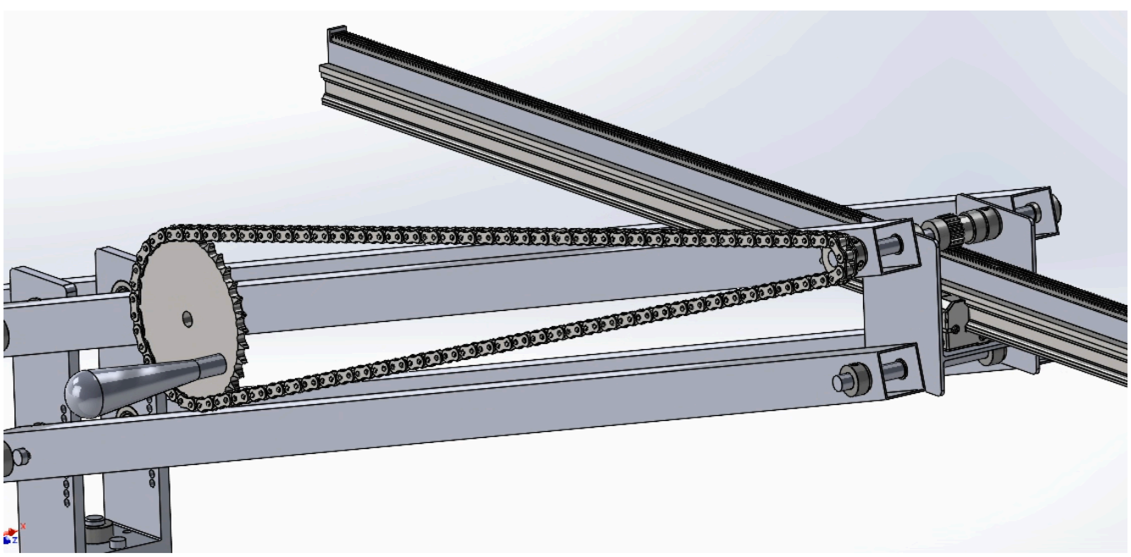


Figure 8.3. Close-up of gear rack and pinion system (shown on the right side of the image), connecting to the chain and sprocket winding mechanism (see the center and left of the image).

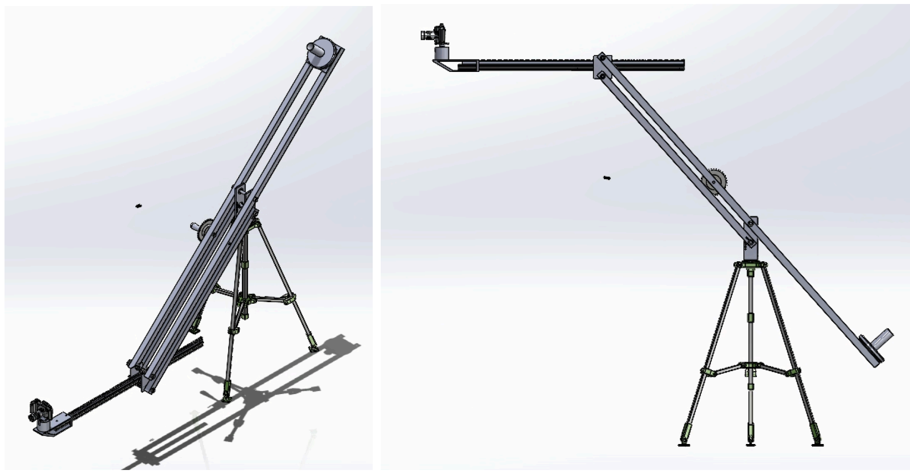


Figure 8.4. View of the jib at extreme low (left) and high (right) Y motion capabilities. Note that the addition of the chain and sprocket winding mechanism allows the X-motion rail-slider to be more easily moved in and out at these positions.

In addition to these major changes, our final model has modified the slider box to hold the new linear carriage and guide rails as well as the rack and pinion mechanism. As mentioned above in Section 7, there will be some minor material changes between our prototypes and our final detailed product design. However, the majority of our product is still made out of aluminum, so it is comparable to our prototype design.

9. Bill of Materials

Table 9.1. Bill of Materials. Note that any Part Number that begins with C is a custom part. Any other is a standard part we will purchase. The final three parts on this list are necessary for product use, but should be acquired by the customer separately.

Item No.	Part No.	Description	Material	Qty.
1	C001	Custom Fulcrum Structure	Aluminum, 2024, T861	1
2	C002	Custom Fulcrum Rotary Shaft	Aluminum, 2024, T861	2
3	C003	Custom Fulcrum Bottom Lock and Left-Right Swiveling Mechanism	Aluminum, 2024, T861	1
4	C004	Custom Short Locking Pin (Left-Right)	Aluminum, 2024, T861	1
5	C005	Custom Top Arm (Long)	Aluminum, 2024, T861	2
6	C006	Custom Bottom Arm (Short)	Aluminum, 2024, T861	2
7	C007	Custom Slider Box	Aluminum, 2024, T861	1
8	C008	Custom Gear Rack and Guide Rail Connector	Aluminum, 2024, T861	1
9	C009	Custom Gear Shaft	Aluminum, 2024, T861	2
10	C010	Custom Counterweight Platform	Aluminum, 2024, T861	1
11	C011	Custom Camera Platform	Aluminum, 2024, T861	1
12	C012	Custom Handle for Large Sprocket	Aluminum, 2024, T861	1
13	C013	Custom Sprocket Shaft	Aluminum, 2024, T861	1

14	C014	Custom Long Locking Pin (Up-Down)	Aluminum, 2024, T861	1
15	6383K247	Ball Bearing	Steel	5
16	9414T13	Set Screw Shaft Collar Size 1	1215 Carbon Steel	5
17	6338K417	Oil-Embedded Flanged Sleeve Bearing	841 Bearing Bronze	8
18	9184T453	34 mm Wide x 1240 mm Long Guide Rail for Maintenance-Free Ball Bearing Carriage	Steel	1
19	9184T105	Maintenance-Free Ball Bearing Carriage	Steel	1
20	5174T11	Metal Gear Rack - 20 Degree Pressure Angle	1018 Carbon Steel	1
21	5172T12	Metal Gear - 20 Degree Pressure Angle	1020 Carbon Steel	1
22	9414T11	Set Screw Shaft Collar Size 2	Black-Oxide 1215 Carbon Steel	10
23	6280K631	Roller Chain Sprocket (Small)	Steel	1
24	60425K78	Lightweight Chain Sprocket (Large)	Nylon Plastic	1
25	6261K173	ANSI Number 40 Single Strand Roller Chain	Steel	1
26	91251A542	Socket Head Screw 1/4"-20 Thread Size, 1" Long	Black-Oxide Alloy Steel	22
27	N/A	Tripod (weight bearing 60 lb min)	Varies	Not Sold With Our Product
28	N/A	Camera (weight bearing 10 lb max)	Varies	Not Sold With Our Product
29	N/A	Weight (weight bearing 20 lb max)	Varies	Not Sold With Our Product

10. Manufacturing and Assembly techniques

Our product consists of two main categories of parts: Custom and Standardized. Where possibly, we have made use of economies of scale to lower the cost of manufacturing by using standard parts. As such, any parts like set screws, fasteners, and our linear ball bearing carriages will be prefab purchases. For our complete list of standard parts, see the Bill of Materials above. **Table 10.1** below highlights how we determined the appropriate manufacturing method for our custom products.

Table 10.1: Manufacturing Methods for Custom Parts

Part No.	Component	Manufacturing Method	Justification
C007	Custom Slider Box	Extrusion followed by CNC Machining	The slider box has thin walls, and a more complex shape, but it has a constant cross section. This makes it manufacturable by extrusion, which is good at making complicated constant cross-sectioned parts at low cost and fast production. The part would require some post-machining anyway, at which point the holes can be added. The same goes for our custom arms. They have constant cross-sections and can have holes drilled afterwards, since the holes are not overly complicated [18].
C005	Custom Top Arm (Long)		
C006	Custom Bottom Arm (Short)		
C002	Custom Fulcrum Rotary Shaft	Extrusion	The rotary shafts we are creating have constant cross-sections, so they can be made with extrusion. Thus, it is ideal to use extrusion, which is a low cost process and has quick production [18].
C009	Custom Gear Shaft		
C013	Custom Sprocket Shaft		
C014	Custom Long Locking Pin (Up-Down)	Cold Heading	Cold heading is often used to manufacture screws, and these pins are very similar to screws, except without the threading. Cold heading would be useful for these parts since it would allow us to get a single part with a long cylindrical body and a larger head. The process has less waste and has a fast production. Additionally, it is a go-to manufacturing method for custom fasteners, which these parts are [19].
C004	Custom Short Locking Pin (Left-Right)		

C001	Custom Fulcrum Structure	Sand Casting and CNC Milling Finishing Injection Molding	Sand Casting is relatively inexpensive as far as casting processes go [20]. Additionally, it has the ability to create the strange shapes of these custom parts. However, since sand casting has worse tolerances and finishes, the addition of the CNC to the manufacturing process will allow us to ensure that some of our more delicate holes will be sized correctly. However, we will avoid the loss of material that comes from making these parts through a purely subtractive process. Thus we leverage the benefits of both casting and machining [21].
C003	Custom Fulcrum Bottom Lock and Left-Right Swiveling Mechanism		
C008	Custom Gear Rack and Guide Rail Connector		
C010	Custom Counterweight Platform		
C011	Custom Camera Platform		
C012	Custom Handle for Large Sprocket		

With our new methods of manufacturing, several of our parts have been redesigned under DFMA guidelines. For instance, our prototype of our Fulcrum Structure was created in three parts that screwed together so that we could manufacture an aluminum structure of that size in the machine shop. However, the new design has minimized the part (and fastener count) by making the structure one piece and by cutting down the width of the part. We did a similar consolidation of parts for the new Slider Box, the Fulcrum Bottom Lock, and the Counterweight System, all of which were originally designed as multiple parts with additional fasteners. Their new designs have minimized our part count.

Additionally, our final parts have standardized design features, meaning we have used common dimensions when possible. For example, all our fasteners are ¼”-20 for simplicity of manufacturing and assembly. Additionally, our locking pins and locking hotels are also ¼” since it was acceptable for weight-bearing purposes and it has the benefit of being a standard size and a common dimension with our chosen fasteners.

We did our best to design for manufacturing by keeping our parts simple. As you can see from **Table 10.1** above, many of our more complex custom parts have constant cross-sections so we can use extrusion for ease of manufacturing. Additionally, from the table you can observe that we chose manufacturing processes that would minimize the amount of material removal, so as to provide an ease of fabrication.

In conclusion, in the creation of our prototype we took into account DFMA principles to create a truly manufacturable product.

Assembly Techniques:

The following images and descriptions detail how the camera Jib would be assembled. The first image shows what a user would have to do to assemble the product for use. The images following that one show what would need to be assembled by the manufacturer prior to sale of the product.

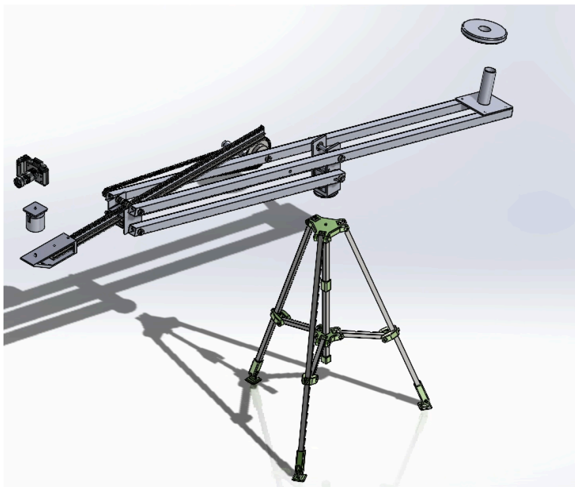


Fig 10.1. Final Assembly for Use
To use the fully assembled product, you first attach the Jib arm to your tripod.This connection is achieved via a ¼”-20 threaded post. Then you slide the counterweight onto the vertical post. Next, you can choose to use a camera head mount. This piece attaches to the camera platform and can be used to position the camera. After that, you can attach your camera of choice. Both these attachments are achieved with a ¼”-20 threaded post.

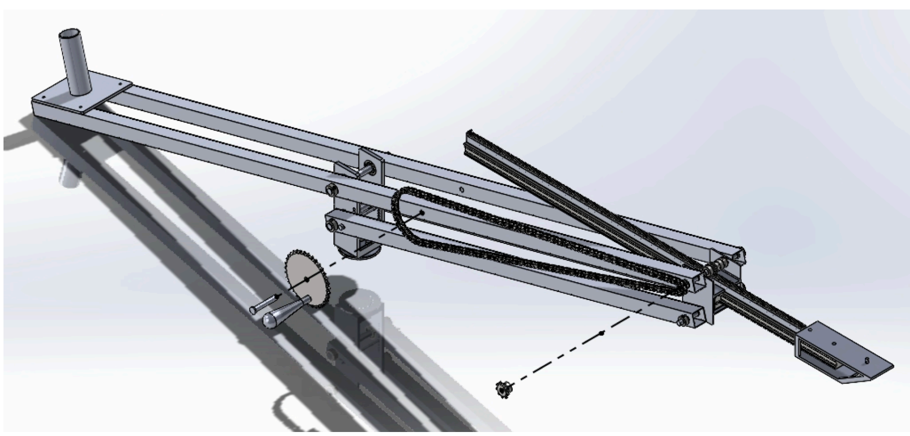


Fig 10.2. Chain Assembly
Attach the smaller sprocket to the front rotary shaft via a built-in set screw. Attach the larger sprocket to the arm via the sprocket shaft and set screw collar.

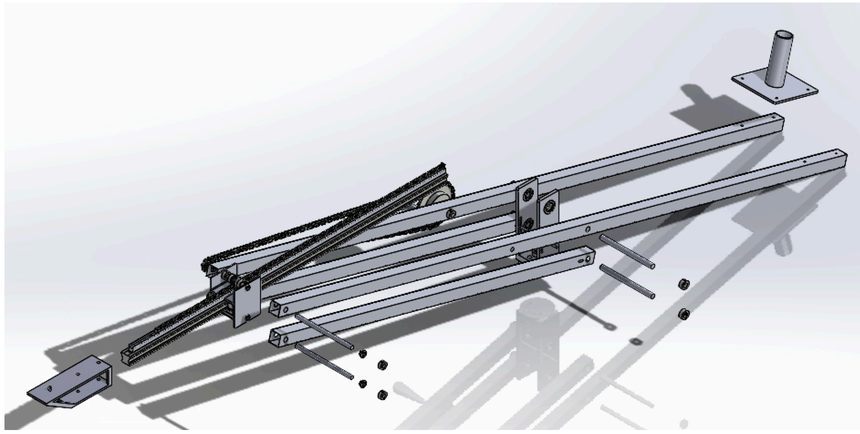


Fig 10.3. Major Assembly

The shafts go through the respective holes, bushings are inserted between the front shafts and the arms. The bushings and shafts are held in place by set screw collars inserted on the shafts. The camera platform goes over the guide rail and is screwed down. On the back, the counterweight platform is screwed to the arms.

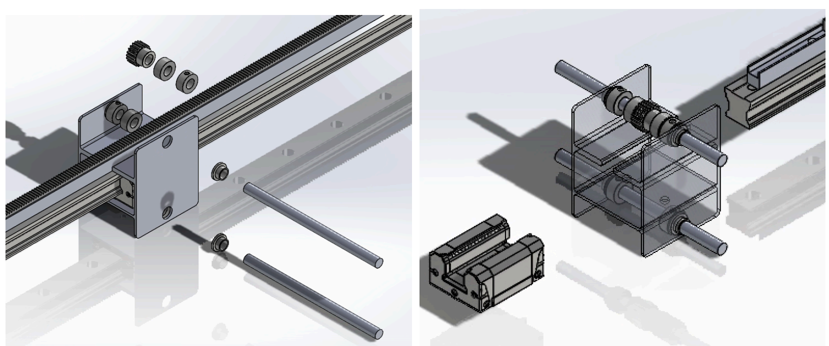


Fig 10.4. Slider Box Assembly

The shafts go through the respective holes, bushings are inserted between the shafts and the slider box. The pinion gear goes on the top shaft. The bushings, pinion gear, and shafts are held in place by set screw collars inserted on the shafts inside the box. The guide rail goes into the linear ball bearing carriage. The ball bearing carriage is screwed onto the slider box in the holes shown above in the transparent box (right image).

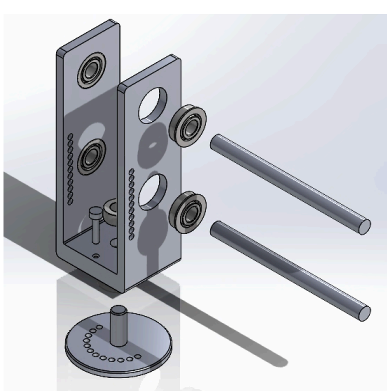


Fig 10.5. Fulcrum Assembly

The shafts go through the respective holes, ball bearings are inserted between the shafts and the fulcrum body. The bushings and shafts are held in place by set screw collars inserted on the shafts (not pictured here, see Major Assembly). The locking base plate is inserted through a hole in the bottom of the Fulcrum body. Another ball bearing is inserted in that bottom hole (not in view on this image). The bottom lock and ball bearing are held in place by a set screw collar.

11. Cost Estimate

Table 11.1. Cost Estimate for Material and manufacturing by part.

Item No.	Part No.	Description	Material (Mat.)	Qty.	Price for Mat.	Price of Manufacturing
1	C001	Custom Fulcrum Structure	Aluminum 2024	1	\$3.11	Extrusion/CNC \$50 - \$100
2	C002	Custom Fulcrum Rotary Shaft	Aluminum 2024	2	\$6.11	Extrusion \$20 - \$40
3	C003	Custom Fulcrum Bottom Lock and Left-Right Swiveling Mechanism	Aluminum 2024	1	\$1.37	Sand Casting and CNC Milling Finishing \$80 - \$150
4	C004	Custom Short Locking Pin (Left-Right)	Aluminum 2024	1	\$0.50	Cold Heading \$0.30 - \$1.50
5	C005	Custom Top Arm (Long)	Aluminum 2024	2	\$33.55	Extrusion/CNC \$60 - \$120
6	C006	Custom Bottom Arm (Short)	Aluminum 2024	2	\$16.75	Extrusion/CNC \$30 - \$60
7	C007	Custom Slider Box	Aluminum 2024	1	\$4.12	Extrusion/CNC \$40 - \$80
8	C008	Custom Gear Rack and Guide Rail Connector	Aluminum 2024	1	\$21.34	Sand Casting and CNC Milling Finishing \$100 - \$180
9	C009	Custom Gear Shaft	Aluminum 2024	2	\$29.52	Extrusion \$50 - \$100
10	C010	Custom Counterweight Platform	Aluminum 2024	1	\$4.05	Sand Casting and CNC Milling Finishing \$60 - \$120
11	C011	Custom Camera Platform	Aluminum 2024	1	\$0.81	Sand Casting and CNC Milling Finishing \$10 - \$30

12	C012	Custom Handle for Large Sprocket	Aluminum 2024	1	$0.19	Sand Casting and CNC Milling Finishing $10 - $30
13	C013	Custom Sprocket Shaft	Aluminum 2024	1	$1.09	Extrusion $20 - $40
14	C014	Custom Long Locking Pin (Up-Down)	Aluminum 2024	1	$0.65	Cold Heading $0.30 - $1.50
Cumulative Custom Costs					$130.36	$1,053.00
15	6383K 247	Ball Bearing	Steel	5	$12.91/ each	N/A
16	9414T 13	Set Screw Shaft Collar Size 1	1215 Carbon Steel	5	$2.92/ each	N/A
17	6338K 417	Oil-Embedded Flanged Sleeve Bearing	841 Bearing Bronze	8	$1.98/ each	N/A
18	9184T 453	34 mm Wide x 1240 mm Long Guide Rail for Maintenance-Free Ball Bearing Carriage	Steel	1	$15.03 $178.00 [23]	N/A
19	9184T 105	Maintenance-Free Ball Bearing Carriage	Steel	1	$143.93 [24]	N/A
20	5174T 11	Metal Gear Rack - 20 Degree Pressure Angle	1018 Carbon Steel	1	$56.86	N/A
21	5172T 12	Metal Gear - 20 Degree Pressure Angle	1020 Carbon Steel	1	$31.59	N/A
22	9414T 11	Set Screw Shaft Collar Size 2	Black-Oxide 1215 Carbon Steel	10	$2.45	N/A

23	6280K 631	Roller Chain Sprocket (Small)	Steel	1	$3.02 $17.58	N/A
24	60425 K78	Lightweight Chain Sprocket (Large)	Nylon Plastic	1	$2.07 $27.04	N/A
25	6261K 173	ANSI Number 40 Single Strand Roller Chain	Steel	6 ft	$9.83 $5.88/ft	N/A
26	91251 A542	Socket Head Screw 1/4"-20 Thread Size, 1" Long	Black Oxide Alloy Steel	22	$12.36 / 50	N/A
Cumulative Costs For McMaster and Other Custom Parts					$622.12	N/A

*Note that Price of manufacturing is only based on the cost of the manufacturing method, and is not cumulative per product. It is the startup and die making costs, essentially.

We consider labor costs for assembly to be a $24.45 hourly wage, as given by the US Bureau of Labor Statistics [25]. We can estimate one hour of assembly per product. For any machining costs, there will be startup costs for die creation and overhead to keep things running. From above, the cost of startup for the parts is around $1,053.00 for machining. So, it will take some time for our product to become profitable. From above, we see that the cost of purchasing prefab parts is around $622.12 without taking into account that we will be purchasing parts in bulk (and not necessarily from McMaster which can be more expensive). If we consider a wholesale discount of 50% then we have a cost around $311 [26]. With custom material costs of $130.36 per product and $311 for prefab parts plus $24.45 for labor, we get a cost per product of $465.81. If we consider a 50% markup for retail that gives us around $698.71 per product. Rounding this to a nicer number and we can sell our product for a total cost of **$699.99 per unit**. This allows us to offset the $1,053.00 machining costs for fabrication with the markup and become profitable more quickly, while still remaining much lower than our competitors on the market. Our competitors are around $2,000 to $15,000, so our product is much more competitive and affordable, which fulfills our customer requirements. With an estimate of 450,000 full time youtube creators in the US (and many other amateur filmmakers and film students) and assuming ¼ of them might purchase our product we anticipate an initial production run of 112,500 products [27].

12. Failure Mode and Effects Analysis

Table 12.1. Failure mode and effects analysis.

Item	Failure Mode	Effects of Failure	Sev.	Cause of Failure	Occ.	Design Controls	Det.	RPN	Recommended Actions
Rail Slider	Elastic deformation	Camera will no longer be level	5	Use of a camera that is too heavy	7	Use of materials that do not deform at desired max. camera weight	2	70	Give weight limits in instructions for use and assembly
Rail Slider	Yielding	Jib cannot be used	8	Use of a camera that is too heavy	7	Use of materials that do not yield at desired max. camera weight	1	56	Give weight limits in instructions for use and assembly
Jib Arm	Elastic deformation	Camera will be hard to aim	5	Use of a camera and/or counter-weight that is too heavy	6	Use of materials that do not deform at desired max. camera weight	2	60	Give weight limits in instructions for use and assembly
Jib Arm	Yielding	Jib cannot be used and could fall on user	10	Use of a camera and/or counter-weight that is too heavy	6	Use of materials that do not yeild at desired max. camera weight	1	60	Give weight limits in instructions for use and assembly
Fulcrum	Elastic deformation	Jib may fall	8	Torques and forces being applied to the fulcrum	6	Thickness of fulcrum walls	1	48	Perform analysis to determine needed dimensions for desired FOS
Fulcrum	Yielding	Jib may fall	10	Torques and forces being applied to the fulcrum	6	Thickness of fulcrum walls	1	60	Perform analysis to determine needed dimensions for desired FOS
Entire Jib	Corrosion	Jib may eventuall y fall	8	Long term exposure	4	Choice of material and possibly paint over material	1	32	Perform analysis to determine materials lifetime for corrosion

A large majority of our failure modes are either elastic deformation or yielding. These are dependent on the dimensions and material of the different subsystems within our product. To account for these failure modes for the rail sliders and the jib arms, we have chosen dimensions and materials that complete the design requirements, such as, panning the height of a 6 ft person and bearing the weight of a 10 lb camera. In order to ensure that the jib arms and rail sliders do not fail during use, a camera weight limit will be given in the instructions for use and assembly. To account for failure modes for the fulcrum, we have performed FEA simulations to determine the dimensions needed for an aluminum fulcrum to reach the desired FOS.

Section 13: Engineering Standards

In order to ensure the safety of our product, we should ensure that our jib arm follows the guidelines outlined by the ASME B30.22 Safety Standards for Articulating Boom Cranes [15]. For instance, under guideline 22-1.3 we should ensure that our product has appropriate swing control, capable of being stopped and locked. This is one of our key design requirements for our jib from customer research, so it is reasonable that we will follow ASME standards for testing this motion capability. As such, we will follow the guidelines in section 22-2.2 of the ASME B30.22 Safety Standards regarding the testing of our products. Some highlights of these regulations involve testing all new products in load lifting and lowering, arm extension and retraction, and swing mechanism by a designated person who can verify the compliance of our design.

Additionally, when designing our product's custom components and conducting FEA simulation tests we used OSHA's Standard number 1926.753(e)(2) for Hoisting and Rigging [16]. According to the Occupational Safety and Health Administration standard above, our parts should have a factor of safety of 5:1. As such, we used this number as a baseline for our part design, as mentioned in Section 6 above.

Another important ISO standard to consider as we start the manufacture of our product, is how our production method will impact the environment. Since we have not begun production, it is the best time to plan how we will follow the instructions indicated in the IWA 42:2022 Net Zero Guidelines [17]. Thus, to do our part to limit the temperature increase to 1.5˚C we will attempt to reach net zero Green House Gas (GHG) emissions. As such, we will be sure to consider how our shopping and transportation of supplies and products affect GHG emissions as mentioned in the Net Zero Guidelines.

These guidelines give a small example of how we will use engineering standards to ensure our new product is acceptably designed for appropriate safety, is tested for safety compliance, and does not have an adverse effect on the environment.

Section 14: Life Cycle Analysis

	Production Items that compose your product		**Material Collection Items consumed during the material collection**	
	Item 1	*Item 2*	*Item 1 (aluminum)*	*Item 2 (steel)*
a) Item purchased	Aluminum	Steel	Electricity & Fuel	Electricity & Fuel
b) Best match economic sector # and name	331313 Alumina Refining and Primary Aluminum Production	3311100 Steel Mill	212299 All other metal ore mining	3311100 Steel Mill
Confidence that sector represents item (low/high)†	High	Fair	Low	Low
c) Reference unit (e.g.: 1 kg or 1 kWh)	1 kg	1 kg	1 kWh	1 kWh
d) Units consumed per product life	25.1	1	1604 (63.9 kWh per kg)	2.4 (2.4 kWh per kg)
e) Cost per unit ($2022)*	$2.22	$0.79	$0.16	$0.16
f) Lifetime cost =(d)×(e) ($2022)	$55.72	$0.79	$256.64	$0.38
g) Economy-wide kgCO2e released per $1 output of industry (b)**	1.41 kg	0.979 kg	1.233 kg	0.979 kg
h) Implied mtonCO2e per product life =(g)×(f)/$1M	0.0786	0.0007734	0.31643712	0.000376

We have low confidence in our material collection findings and are fairly confident with our production findings. However, the analysis done on material collection revealed to us that the mining and extracting of aluminum is the most dominant contributor to the GHG emissions for the life cycle of our product. With this in mind, we decided to go back to our material selection phase and look further into materials with lower GHG emissions. We came to the conclusion that aluminum is still the best material to meet our design requirements.

15. Conclusions

Our project began with the goal of providing an effective solution that combines various fluid video shots that amateur filmmakers can utilize to convey the emotions they intend in their art. Understanding that the market for professional video equipment is likely unaffordable to an average customer, we sought to manufacture a 4-degree-of-freedom video jib system that could include the various shots needed at an affordable price range.

After conducting customer research from surveys, we created standards that would be used to evaluate the success of our endeavor. We aimed to have a vertical range of motion capable of panning a 6 ft adult, an in-out X range of motion of around 3 ft. We aimed to have an easily assembled jib that can be put together in around 30 minutes. Finally, we aimed to design the jib so that it can comfortably hold a camera and other attachments totaling up to 10 pounds. After testing our product, we were able to accomplish all of the standards we initially set for ourselves. We were able to pan a group member that was 6 ft tall; we were able to assemble the device in around 10 minutes, and we tested our device for ten pounds, and it did not succumb to any of the failure modes. Utilizing the 2-bar linkage, we were able to create smooth vertical motion, and utilizing custom-designed sliders, we were able to create a planar degree of freedom. In terms of our competitors, having the 4 degrees of freedom for the same price point separated us from the existing solutions, and we were able to successfully accomplish that feature. Additionally, using Aluminum 2024 as the primary material allows us to have a strong product that also optimizes lowering manufacturing costs, ensuring that the cost of our overall product is low. One of the primary design choices of ensuring that our jib remains fully mechanical allowed us to lower the cost while also functioning in silence as electronic components often introduce noise.

All design choices were made based on our survey feedback and ultimately allowed us to incorporate the best functionality for the jib. As a part of our testing, we asked CMU School of Drama actresses to act in a brief scene to compare and contrast the differences between the Jib and hand-held filming. Anecdotally we saw that the jib offered a much more fluid and stable shot than hand-held. However, anecdotal evidence was not enough to verify this observation, so by utilizing an optical flow algorithm, we compared the two shots and found a numerical reference for the stability of the shot. The Left - Right shot on the Jib had a rating of 0.83, while hand-held had a rating of 4.00. The Up - Down shot had a rating of 1.13 while the hand-held rating was 1.44. Finally, the In - Out shot using the jib had a rating of 3.56, and the hand-held rating was 4.12. In all of the motions, the jib consistently performed better than hand-held, further underscoring its functionality.

In terms of our financial viability, we determined that there is a cost per product of $465.81. When considering a 50% markup for retail, that gives us around $698.71 per product. Rounding this to a nicer number, we can sell our product for a total cost of $699.99 per unit. This allows us to offset the $1,053.00 machining costs for fabrication with the markup and become profitable more quickly, while still remaining much lower than our competitors on the market. Our competitors are around $1,500 to $15,000, so our product is much more competitive and affordable, fulfilling our customer requirements. If 25% of our target market purchases our product, we will bring in revenue of close to $78,750,000. While this is an unlikely outcome to capture that percent of the market, with further refinements of our product and much more rigorous testing, there is potential for our product to be profitable.

Overall, our product was able to meet the initial design requirements we intended to achieve. By using customer research, engineering design principles, iterative prototyping, not only were we able to accomplish our goal, but we were also able to build upon our existing knowledge of engineering and skills that we will carry on into our future careers involving engineering.

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17. Appendices

Appendix I: Notes for Future Teams

a. What we have learned as a team:
    i. It can be difficult to come up with a truly important/interesting design problem or idea. It can be helpful for people to start thinking about options much earlier than the start of class, since we did not have much time to brainstorm.
    ii. It was very helpful to make all our fasteners the same size, this way when we came up with new parts to manufacture we always had plenty of screws and never had to worry about having the wrong sized part.
    iii. The machinists in Tech Spark's machine shop are very helpful to talk to about how to manufacture parts for your prototype. They are also helpful when trying to decide what materials are better choices. They have lots of other information that they know from experience that can be confusing when trying to research it yourself.
    iv. Manufacturing things in the machine shop can take a long time. It's best to be ready to work a week ahead of time. Additionally, part drawings are very helpful if you plan to manufacture parts in the machine shop.
    v. The machine shop has a lot of scrap material and some stock material that you can buy from them directly and avoid the delivery time associated with ordering from McMaster.

b. How we dealt with problems we didn't know how to solve:
    i. We found the most useful people to go to for help were the machinists in Tech Spark. They are helpful in suggesting more affordable fastening options and material choices we would not have even thought of to research.
    ii. McMaster was very helpful to peruse when looking for ideas. Also, they had a very fast delivery time.

c. What we would have done differently:
    i. Our product was very large, which meant it was expensive to manufacture and also difficult to manufacture larger parts. Our fulcrum had to be made in three pieces and re-designed so we could actually make it in Tech Spark. A smaller product design would have been better.
    ii. Additionally, our product had many subsystems. This made it hard to make each subsystem truly optimized and well-designed since we had to make so many different systems. We would recommend that future teams not choose a design that requires more than two major subsystems so they can focus most of their effort on those designs.

d. Suggestions for teams who would continue our project:
   i. Our design works, but it is not the most aesthetic. Some industrial design choices could be helpful.
   ii. Our locking systems are functional, but are simple. They could be more complicated of a mechanism, but more easily used if someone had more time to prototype and design.
   iii. We never got the chance to prototype the chain sprocket rack and pinion extension mechanism. A team continuing our project would want to implement that design and see if they could optimize it.
   iv. Our product has not been designed to have straps or clips for when it is not in use and requires easy transportation. This is an intriguing feature that would make our product better if a team had time to further investigate it.

Appendix II: Full CAD diagrams

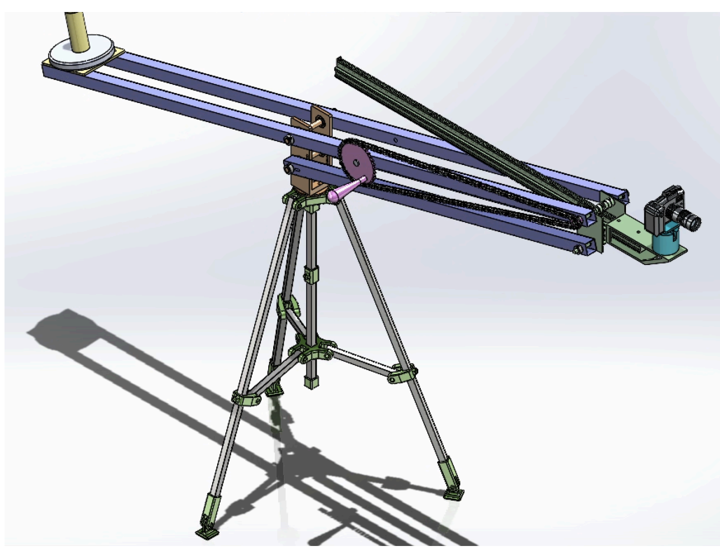


Figure Final.1 Full assembly CAD of Final Product. (Color Coded subsystem image on bottom).

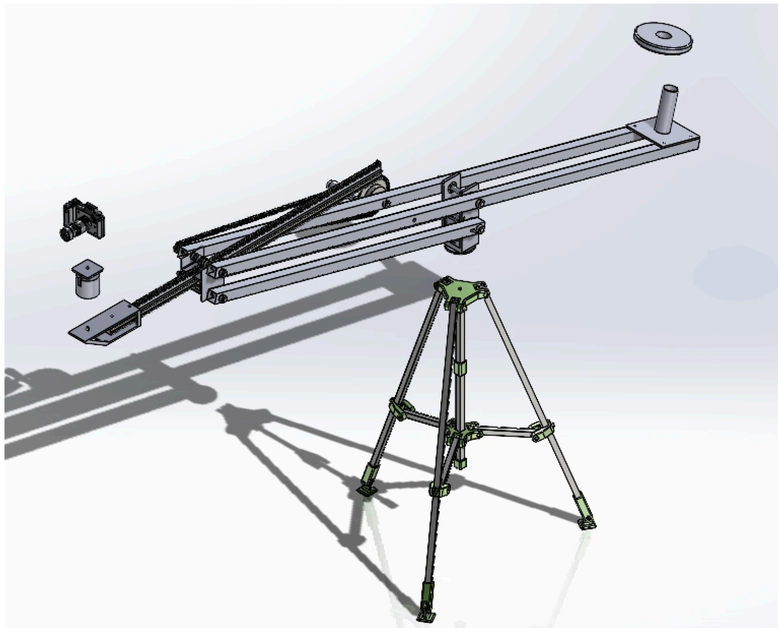


Figure Final.2 Full assembly CAD of Final Product along with attachments sold separately (i.e. the counterweight, camera head mount, camera, and tripod).

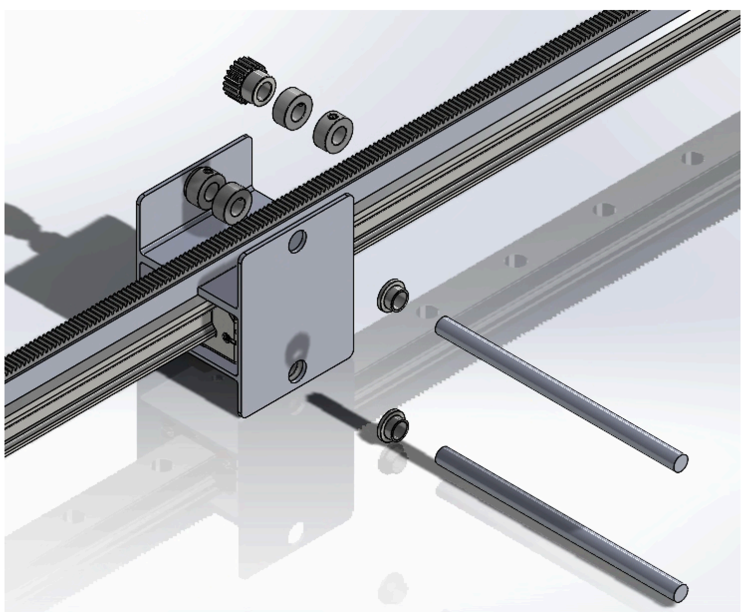


Figure Final.3 Exploded view of slider box assembly to illustrate assembly techniques.

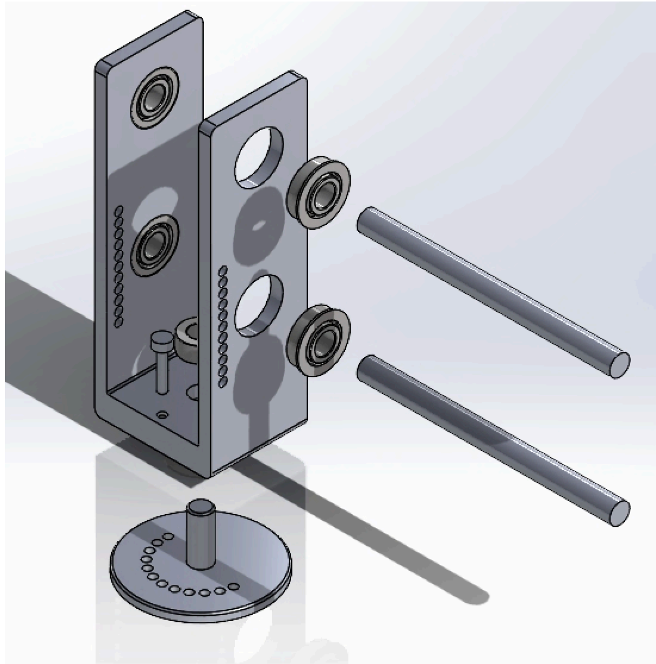


Figure Final.3 Exploded view of Fulcrum assembly to illustrate assembly techniques.

<u>Prototype 1 CAD Models</u>

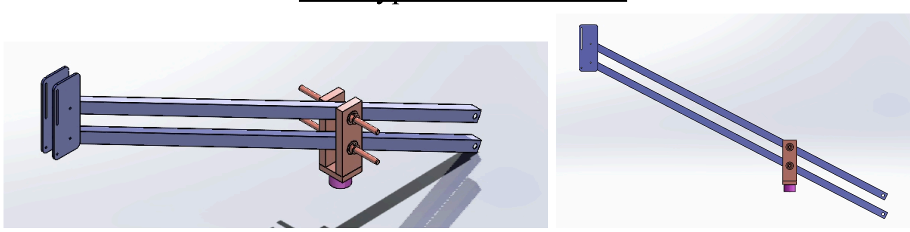


Figure PT1.1 4-bar arm linkage subsystem.

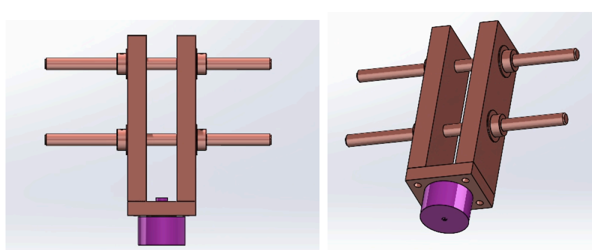


Figure PT1.2 Fulcrum subsystem. Bottom image shows the ¼”-20 threaded connector (pink piece) which attaches to the standard tripod connector.

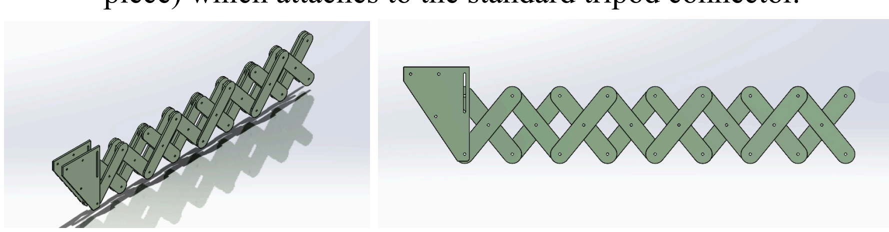


Figure PT1.3 Scissor mechanism subsystem.

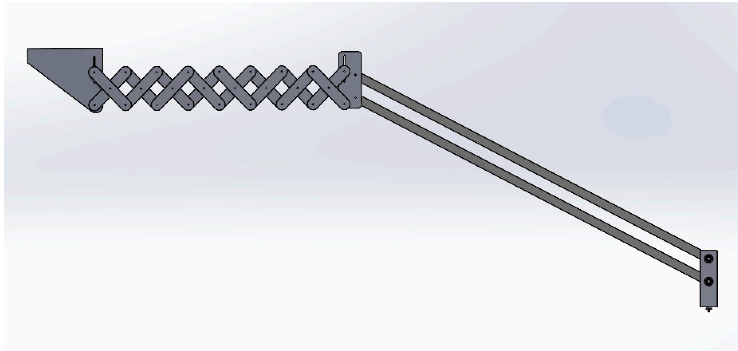


Figure PT1.4 Full assembly CAD of PT1.

Prototype 2 CAD Models

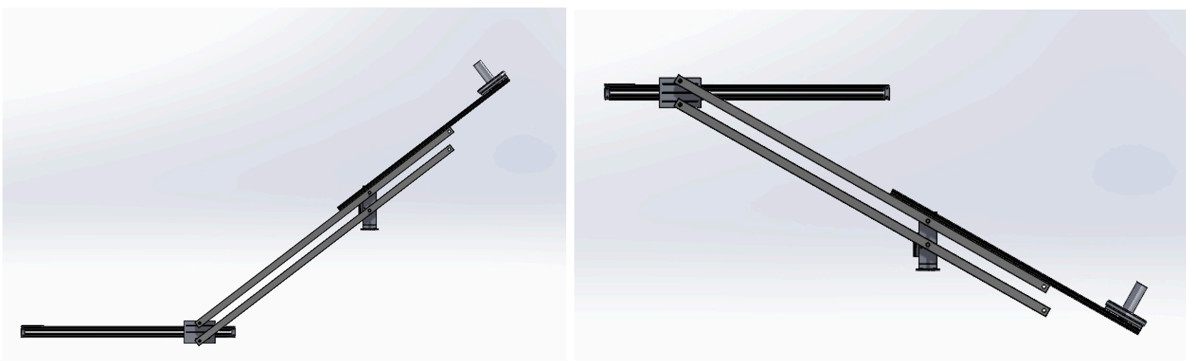


Figure PT2.1 Full assembly of PT2.

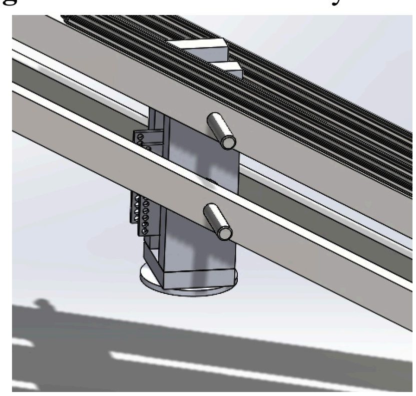
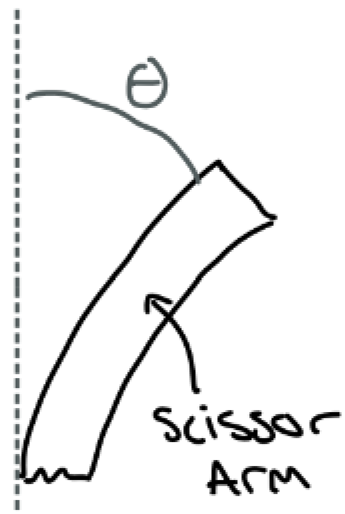


Figure PT2.2 Up-down locking system for PT2.

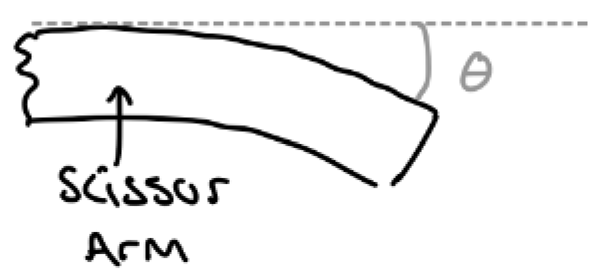
Appendix III : Prototype Testing Parameters

Scissor Subsystem

Angle for the measured degree of left and right bend (simplified from top view of PT1):



Angle for the droop measurements (simplified from left view of PT1):



Aluminum Tube Arms and Fulcrum Subsystems

"Counterweight end length" and "camera end length" measurements (simplified from left view of PT1 and is not to scale):

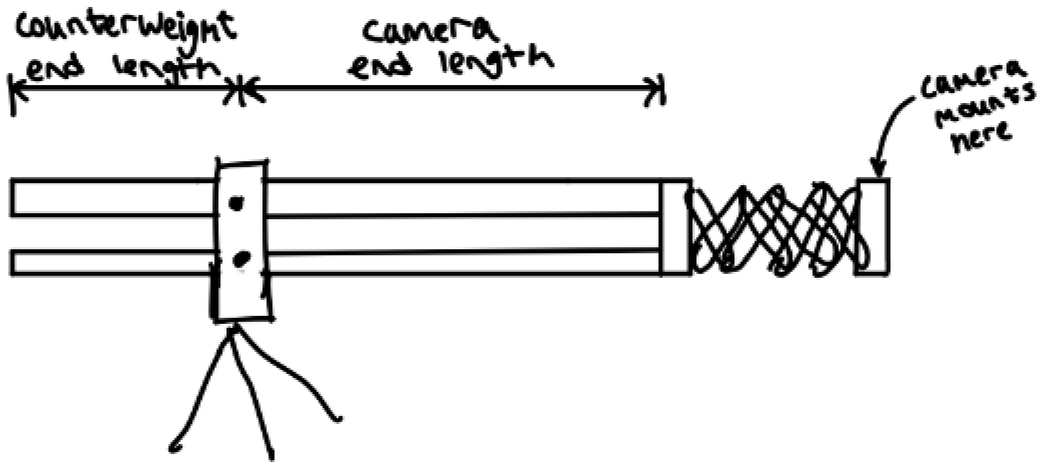


Figure Appdx.6 Example of bending in our prototype 1.

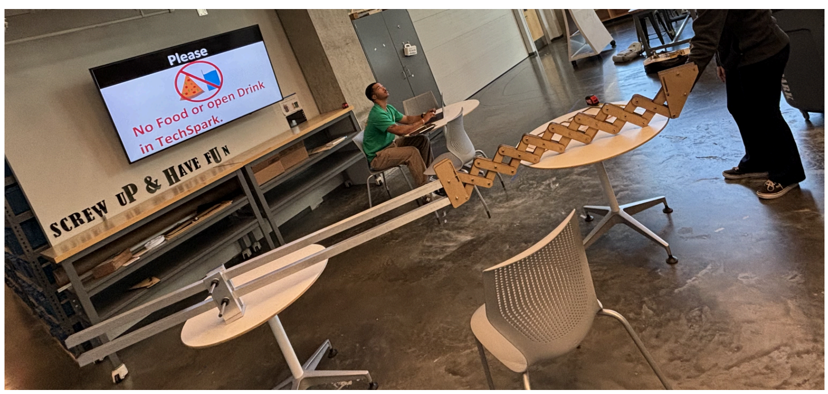
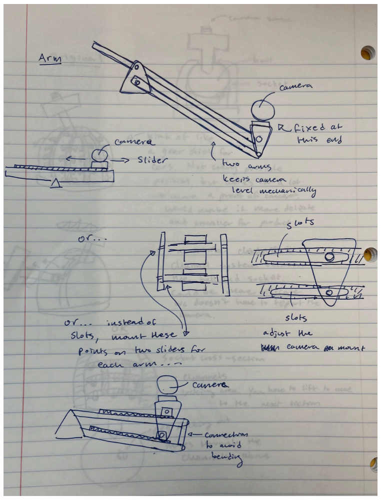
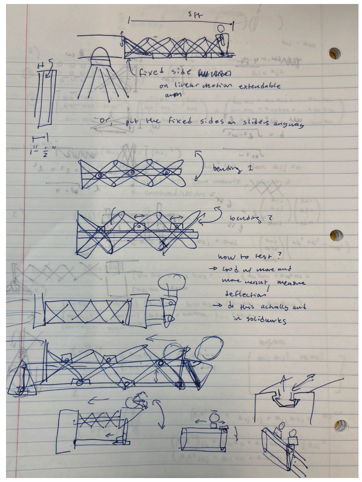


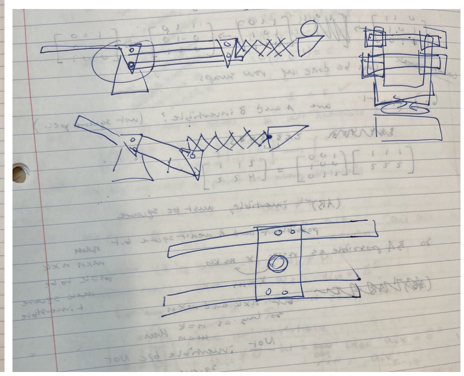
Figure Appdx.7 Image of PT1.

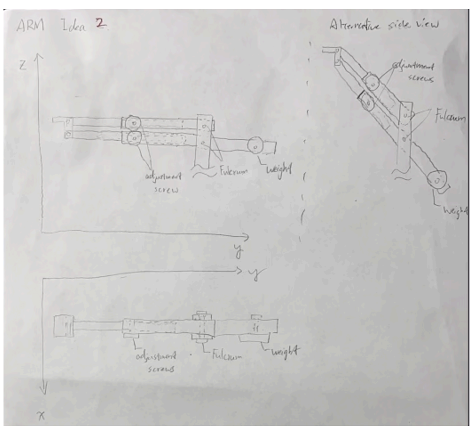
Appendix IV: Ideation Sketches

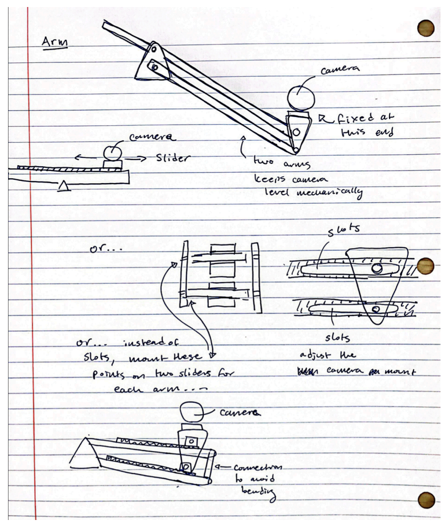
Brainstorm Sketches for Arm Subsystem:

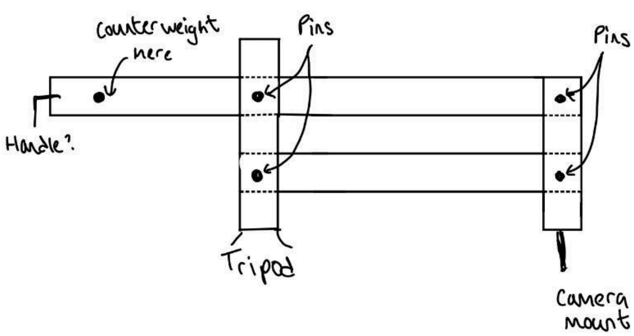


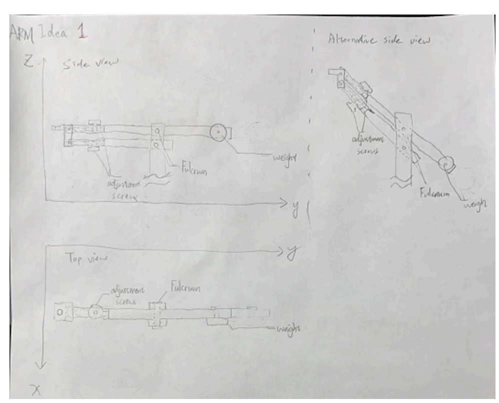




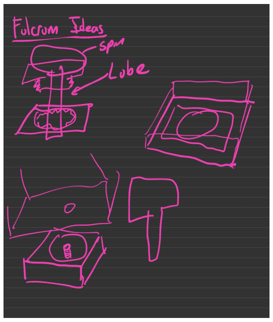


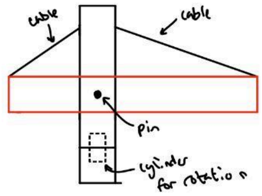


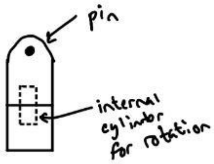


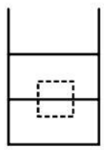


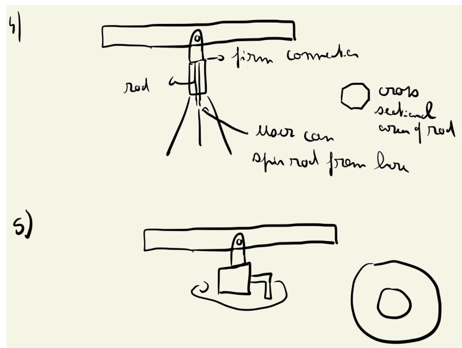
Brainstorm Sketches for Fulcrum Subsystem:

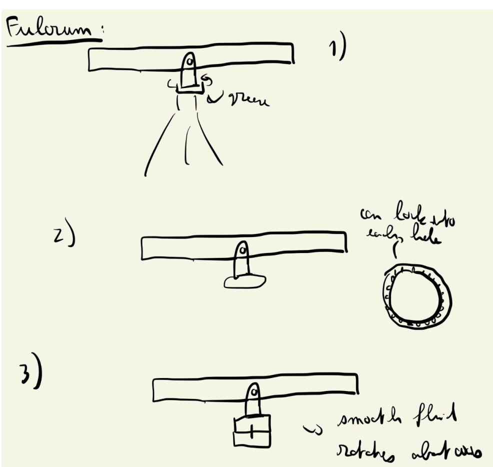


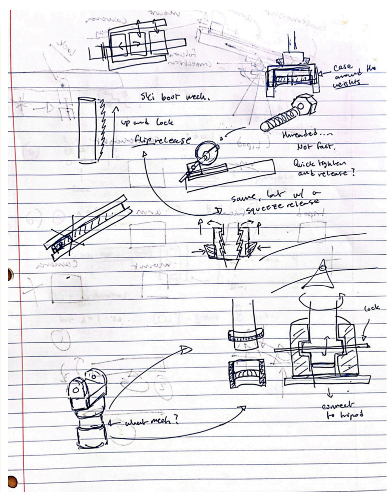


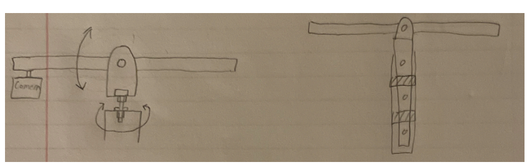




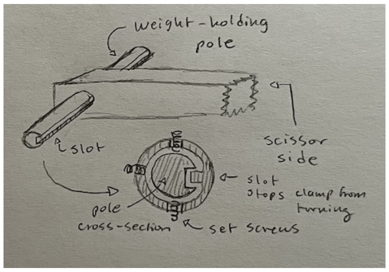


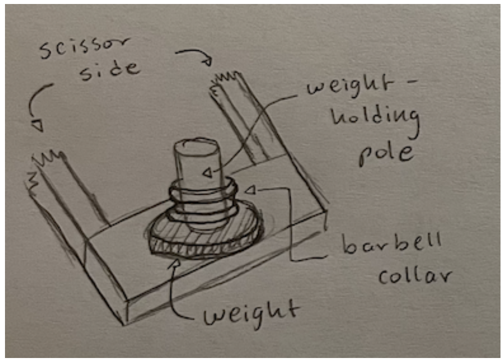


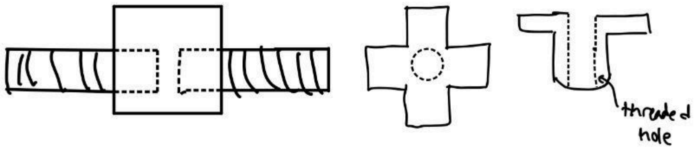


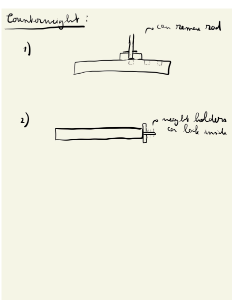


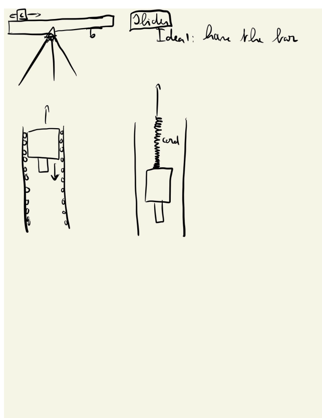
Brainstorm Sketches for Counterweight Subsystem:

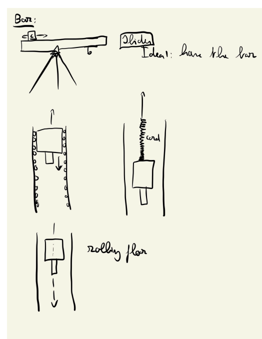












Brainstorm Sketches for Camera Mount Subsystem: