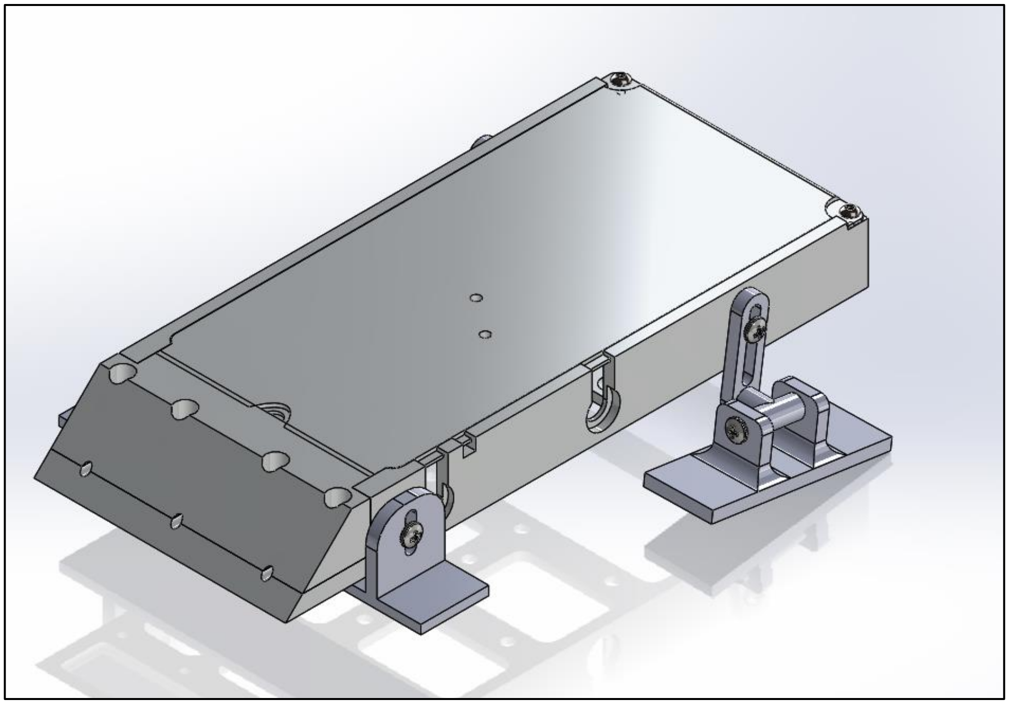
Final Project Report

Articulated Mounting Feet for BLDS



B.L.D.S.
"Big League Design Solutions"
June 6th, 2014

Sponsored by:
Dr. Russ Westphal, Cal Poly ME, and

NORTHROP GRUMMAN

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Statement of Disclaimer

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I. Introduction

This final report summarizes all of the efforts of the Senior Project aimed at creating Articulating Mounting Feet for the BLDS. The project focuses on improving the design of the mounting feet for the current Boundary Layer Data System at Cal Poly, San Luis Obispo. Dr. Russ Westphal, the project's sponsor, wishes that our team focus primarily on a reliable and lightweight mount design for a curved wing, with only transverse curvature. Dr. Westphal is currently researching the boundary layer effects on airplane wings at Cal Poly, and the ability to mount to a multitude of surface contours would increase the range of data he would be able to collect.

This project's Principal Investor is Dr. Westphal, and he is supported by Northrop Grumman. Dr. Westphal's grant from Northrop to fund this project allows us to freely experiment and rapid prototype multiple concepts in the shops at Cal Poly. The successful completion of this project will improve both Northrop Grumman and Dr. Westphal's ability to study the effect that the boundary layer has on a variety of airplane wings and surfaces.

Our team is made up of two senior mechanical engineering students at Cal Poly in San Luis Obispo. As students close to graduation, we will be using the culmination of our education at Cal Poly to achieve the best possible solution to this problem. Cal Poly's "Learn by Doing" philosophy has prepared our team for the successful completion of this project. Our previous experience working with larger teams of people will allow our small team to maintain productivity, while also taking appropriate responsibilities for this project.

After the first ten weeks of team building, idea generation, and concept development, the BLDS team generated concept designs to solve Dr. Westphal's problem. With further evolution and improvement upon the concept designs, we presented our Critical Design Report. Multiple solutions have been designed and analyzed, and the final solution has now been manufactured and tested. We are confident that our prototype will solve the assigned problem.

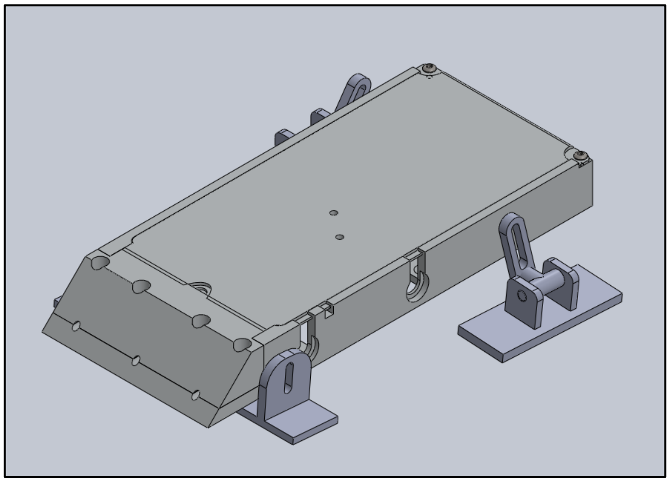

Figure 1. Potential BLDS Assembly

II. Background

1. Existing Information

The BLDS is a data system which is used for autonomous flow measurement while in flight. The system must be flight compatible, small, self-powered and attach onto a plane wing by matching its contours. Through our research, we have found very little information on mounts specifically comparable to the BLDS. This caused us to focus on various other mounting devices, as well as the range of articulation that the customer has decided is necessary. Seeing how these tasks are performed by other objects gives us a better idea of how to complete our own main objective.

Figure 2. Dr. Westphal bonding the BLDS

Dr. Westphal demonstrated the current BLDS mounting process to our team during the initial stages of this project. The device, shown to the right in Figure 2, applies a minimum of 90 pounds of force down onto the top of the BLDS box. This procedure is used to activate the bonding capability of the 3M4868F Visco Elastic Tape. Using the device in Figure 2, the BLDS and mounting device are held in position for a time to allow the tape to fully bond under the applied load. The force required to activate the elastic tape is the greatest load the BLDS will see during its testing process. This fact makes the mounting method and load application an important part of the success of our designs.

2. Existing Products for Similar Problems

There are a couple of existing products that utilize an articulating mechanism for mounting. One example is the base-articulating mount, shown in Figure 3, which connects a flat screen television to a wall [2, 3]. These are of interest to us in how the load is transferred through the brackets of the mount and how the arms articulate, because it can rotate around two axes. This provided us with insight on how previous designers have accomplished articulation of mounts in multiple directions.

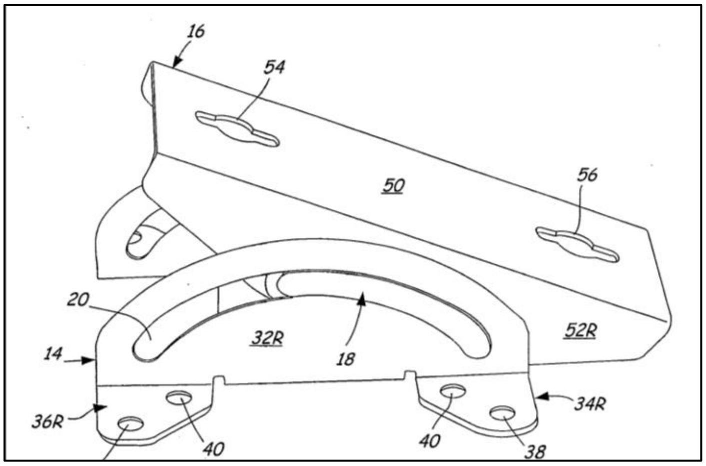

Figure 3: Base-Articulating Mount [2,3]

There was also an attachment assembly for mounting a seat to the floor of an airplane [1]. It absorbs some of the dynamic load due to the aircraft experiencing both negative and positive G forces.

The second concept we analyzed were the various ways to create a locked ball and socket joint. The basic principle used to make the joint lock is by friction. One way this is done is by putting a clamp around the ball and engaging it when necessary [4].

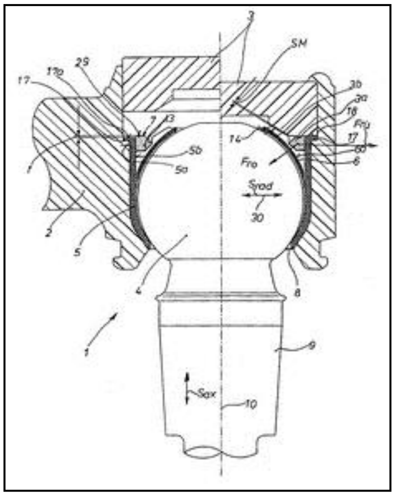

Figure 4: Lockable Ball and Socket Joint [5]

Figure 4 (above) depicts another way to lock a ball and socket joint. This concept uses a spring and connects it to both the upper half and lower half of the bearing shell, along with grooves and ridges on the inside of the shell [5].

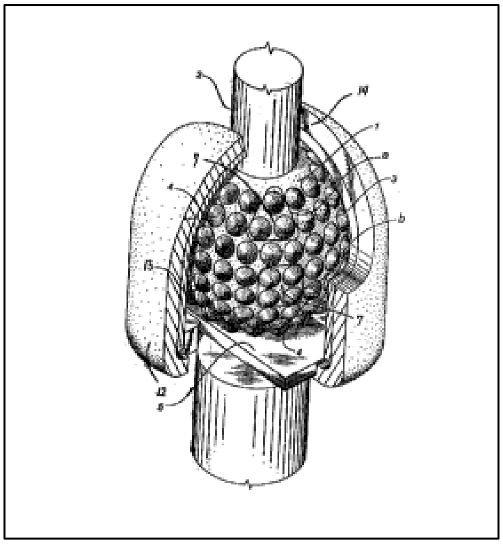

Figure 5: Lockable Ball and Socket Joint [6]

The next method is shown above in Figure 5. It is used for locking a prosthetic limb, but is very interesting. The ball bearing has multiple dimples on the inside and there are rods on the bearing cover that will insert into these dimples and provide a friction holding force to lock the joint in place [6].

3. Literature Review

The principles and methods presented in Shigley's design book, *Mechanical Engineering Design*, will be used to perform the stress analysis on the mounting feet and ensure that failure will not occur. The feet are expected to experience approximately 10 pounds of shear during flight and 90 pounds of compression during the adhesion process. A safety factor of 3 will be utilized.

4. Applicable Codes and Standards

Due to flight regulations, it is in our best interest to keep the entire BLDS assembly under one pound, including the mounting feet. To achieve this, our mounts should add no more than 50 grams. This is the only code that the customer specifically required us to follow.

5. Other Background Info

The customer has requested that there must be up to 10 degrees of articulation in the horizontal axis (curvature) and 40 degrees of articulation in the vertical axis (sweep). Previous work has been conducted on this design by other Cal Poly groups. Some of the design ideas from these groups include creating shims that have fixed sweep positions at both zero and 30 degrees, a contoured foot and a pivot/arc rear with a hinged front.

III. Original Objectives

1. Overall Goals

We plan to design, build and test different mounting concepts for the BLDS in order to accommodate surfaces with different contours. We will design multiple concepts to solve for surface contours in respect to curve, sweep, and taper about multiple axes. In Figure 6, the coordinate system's axes have been illustrated. These axes help to visualize each category of surface adaptability. The four categories are listed below:

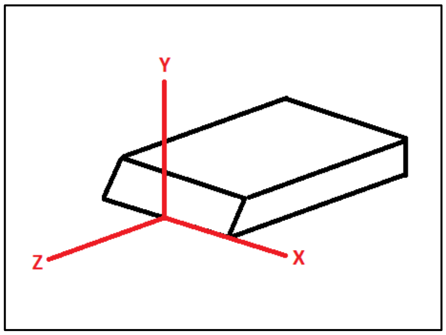

Figure 6. Established Coordinate System for BLDS

1. ***Standard Transverse***
   This curvature is most similar to a standard wing. The surface curves along the length of the BLDS, so feet must pivot about the X-axis.
2. ***Swept***
   For swept surfaces, the feet must pivot about the Y-axis.
3. ***Tapered***
   For tapered wings, the feet must pivot about the Z-axis.
4. ***Fuselage Transverse***
   If the BLDS needs to mount to a cylindrical surface or fuselage, the mounting feet must pivot around the Z-Axis.

Multiple designs will be considered and conceptualized in order to successfully address one or more needs associated with the BLDS mounting. Through this process, there will ideally be one final solution that can accommodate every type of surface change, although multiple solutions for specific surface changes will be acceptable. The mounts will use 3M4868F Visco Elastic Tape for adhesion to the surface. This high-grade tape set specific engineering requirements, which are incorporated into the following Specification Table and QFD.

2. Customer Requirements vs. Engineering Specifications

Our BLDS team of designers met with Dr. Westphal for the first time on October 3rd of 2013 to discuss the goals of the project. These customer requirements are listed in Appendix A. As engineers, it is important to be able to relate customer requirements to engineering specifications. Fortunately, Dr. Westphal's engineering experience made it possible for the customer requirements and engineering specifications to be easily related and identified. In Appendix B, the QFD (Quality Function Deployment) table displays the relationships between each customer requirement and engineering specification. The QFD allowed our team to apply weights to each relationship in order to determine the most critical engineering specifications. The outcome of this exercise is our engineering specifications shown in Table 1 below. A more detailed description of the table is on the following page.

Table 1. Engineering Specifications Table

Articulated Mounting for BLDS Formal Engineering Specifications					
Spec. #	**Parameter**	**Target**	**Tolerance**	**Risk**	**Compliance**
1	Weight	50 (grams)	Max.	H	A, T
2	Contact Area	3.0 (in^2)	Min.	M	A
3	Temperature	-60 (deg C)	Min.	L	A
4	Compression Strength	90 (lbs)	Min.	H	A, T
5	Shear Strength	10 (lbs)	Min.	H	A, T
6	Strength (in flight)	3g (lbs)	Min.	H	A
7	Height	0.3 (in.)	Max.	M	A, T
8	Mat. Strength	TBD (MPa)	N/A	L	A
9	Deflection	TBD (in.)	N/A	L	A, T

A key skill in engineering is the ability to convert the requests of the customer into quantifiable engineering specifications. A lot of these conversions were simplified due to Dr. Westphal's engineering experience. For instance, we were essentially given the specifications for weight, contact area, temperature, and strength. These specifications were pre-determined from Dr. Westphal's experience with the BLDS. Due to FAA regulations, the entire Data System must weigh less than one pound, meaning our feet should not add more than 50 grams. Dr. Westphal also informed us of the minimum area required for the adhesive (3.0 in^2) and the force that each foot would need to withstand during bonding (90 lbs). These three specifications are our highest risk items, and greatly influenced our decision making process.

The remaining customer requirements needed more interpretation. Dr. Westphal wishes to keep the BLDS as low profile as possible, so we set a maximum height of 0.3 inches. During flight, the pilot cannot accelerate more than 3g (three times the acceleration of gravity). This is important to keep in mind, even though the forces to survive bonding will be much larger than the forces from the in-flight accelerations. The specifications for material strength and mount deflection are still up for interpretation. Customer requirements did not immediately rule out a flexible mount, but our group is leaning towards rigid articulated mounting. We will focus on these parameters more during the testing stage. In regards to the compliance, the A denotes specifications that require analysis and the T denotes that testing is required.

IV. Concept Design Development

1. Methods Used

As seniors at Cal Poly, our team has learned and practiced the design process through numerous classes and labs. The design process is always changing and open to interpretation, but having a flowchart will help the team stay on track. In general, we will follow the Formal Design process presented in our Senior Project Lab. The process is iterative, and we will likely restart the process several times in order to achieve an optimal final design.

With all projects, communication with the customer is key to success. In our case, we have the luxury of constant communication with Dr. Westphal because he works on the Cal Poly campus. Designing to customer requirements is simplified and facilitated by frequent communication. We plan on maintaining communication with Dr. Westphal through the duration of the project and actively involving him in our review process.

With customer needs identified and engineering specifications documented, we plan to move forward with conceptual design and analysis of the current mounting process. Our conceptual designs that are deemed as valid solutions to at least one of the surface categories will then be prototyped and tested. The tested prototypes will then be reviewed and new designs will be generated. This process repeated until a practical solution or group of solutions is found.

2. Top Conceptual Designs

In comparison to a majority Cal Poly senior projects, designing articulated mounting feet for the current BLDS leaves less room for creativity. The design of the BLDS casing is fixed, therefore a majority of the design process focuses on how the flat feet will be attached, and the range of motion that the attachment allows.

Following ideation sessions and discussions with Dr. Westphal, four concepts evolved to a point where they could be evaluated: Pivoting Flat Foot, Slot Slider, Piano Hinge Foot, and Locking Ball and Socket. Each concept will be described along with a discussion of how it meets the customer's requirements.

a) Pivoting Flat Foot

The Pivoting Flat Foot is a simple design that could be attached at the front or the rear of the Data System box. The design will require new holes in the sides of the BLDS in order to mount the foot, but this will allow us to easily lock and unlock the angle. Other key advantages to this design include its low profile and large range of angles along the curved axis. A picture of the model for this design can be found in Figure 7, and a detailed design drawing is in Appendix C.

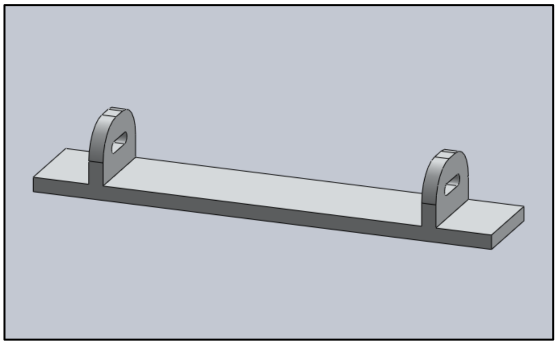

Figure 7. Concept Model of Pivoting Flat Foot

b) Slot Slider

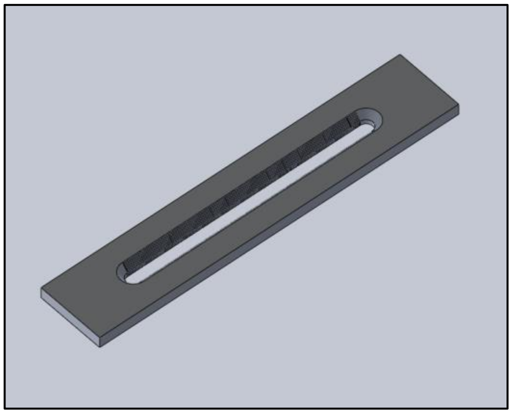

Figure 8. Concept Model of Slot Slider

The slot slider (Figure 8) is a very simple foot design that can adapt to swept surfaces. The foot can rotate to any angle, and can slide into different positions. After speaking with Dr. Westphal, we determined that this design is not feasible because we would need to tap into the bottom of the BLDS. The bottom frame of the BLDS is too thin to tap. In order to attach anything to the bottom, the screw must come through the inside of the frame—which has a countersink—and tap into the underlying foot.

Because of this limitation, we plan on modifying the design of this foot. The concept will be similar, but the slot will be replaced with a series of tapped holes. Please see the critical design section for further details and analysis of the new concept.

c) Piano Hinge Foot

The Piano Hinge Foot came straight from our project sponsor, Dr. Westphal. This foot design is truly as simple as the title makes it out to be—a piano hinge. The hinge is low profile, and can adapt to similar surfaces as the Pivoting Flat Foot. The main issue with this foot involves the difficulty locking the hinge at the right angle. As per Dr. Westphal's advice, we plan on deforming the joint of the hinge to keep it stiff and/or locked. We could also use small set screw. A SolidWorks solid model of this design is shown below in Figure 9.

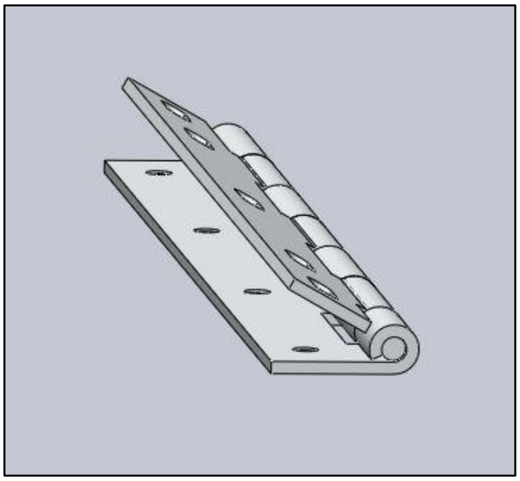

Figure 9. Concept Model of Piano Hinge Foot

d) Locking Ball-and-Socket

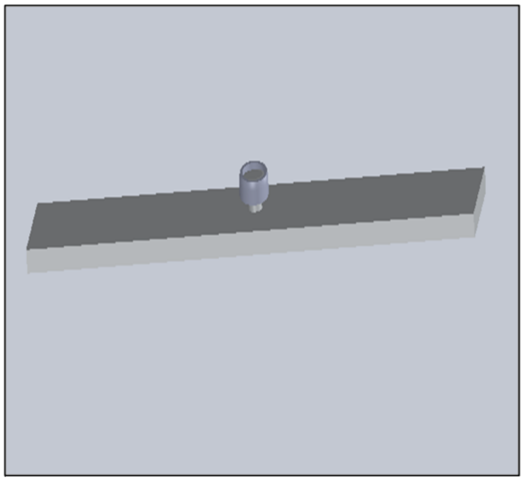

Figure 10. Concept Model of Ball Joint

The Locking Ball-and-Socket (Figure 10) was our preferred concept for the rear mounting feet on the BLDS. The ball and socket joint allows for a full range of motion so that we may adapt to the contours of the airplane wing. Unfortunately, we believe that this design will require more space than allowable at the front of the BLDS so it is planned to be used only in the rear.

When considering the interface with the BLDS, this joint can be mounted to the BLDS in multiple ways. This makes the ball-and-socket an ideal adaptable concept. The proposed design will be custom made to limit the free motion of the ball and socket so that the parameters of the design are met and extra weight and material is eliminated. The final layout of the Ball-and-Socket joint is still to be determined through experimentation and optimization.

3. Design Challenges

Each parameter given for the design of the articulated mounting feet presents its own challenges during the design process. Some parameters are more difficult to address and had a larger impact on the design. Maintaining a maximum of 0.3 inch above the surface of the wing is one such parameter. To achieve this goal we plan on using two different foot designs in the front and the rear, so that the rear foot can provide the adaptability that the front foot lacks due to the height limit.

Another parameter that has a large effect on our design process was the material choice. Originally, we had started out with no restriction on material choice and wanted to research flexible materials so that we could mount the feet flush to the surface of the wing, regardless of curvature. From that point, our design would be focused around attaching these flexible feet to the BLDS. However, after discussing more with Dr. Westphal, it was determined that the material would need to be rigid and preferably aluminum. This, in turn, makes the focus of the design around the locking capability and geometry of the feet in respect to the BLDS.

When overcoming these challenges, there are infinite solutions that we could have produced. After conceptualization of different mounting feet, the final challenge associated with designing the feet is to choose the design that best fulfills the requirements. A decision matrix and in-depth group discussion is often needed to choose a final design.

4. Concept Decision Matrix

Below, in Table 2, you will see the decision matrix that was initially used to determine the best conceptual design. Each design addresses the customer requirements differently. In a Pugh decision matrix, we compare the potential concepts with a currently accepted concept, or a *datum*. The concepts are then rated on a three-level scale. Each concept receives a "+" if it satisfies the criteria better than the datum, a "-" if the concept is worse, and an "S" if there is no difference between the concept and the datum. From months of ideation, our team came up with four top concepts to compare to the datum. The datum, a simple flat foot, is the standard mounting foot for the current Cal Poly BLDS.

Table 2. Original Pugh Decision Matrix

Concept **Criteria**	Piano Hinge	Modified ball-and-socket	Flat Foot	**Slot Slider**	Pivoting Flat Foot
Low Profile	**-**	**-**	DATUM	**S**	**S**
Curve Adaptability	**+**	**+**		**+**	**+**
Sweep Adaptability	**S**	**+**		**S**	**S**
Taper Adaptability	**S**	**+**		**-**	**S**
Strength of Feet	**S**	**-**		**S**	**S**
Locking Capability	**-**	**+**		**S**	**+**
Complexity	**-**	**-**		**-**	**-**
Ease to attach/detach	**S**	**S**		**S**	**S**
Ease to bond	**-**	**S**		**S**	**S**
Total +	**1**	**4**		**1**	**2**
Total -	**4**	**3**		**2**	**1**
Total + & -	**-3**	**1**		**-1**	**1**
Total S	**4**	**2**		**6**	**6**

By completing and analyzing the above matrix, we are able to conclude that the modified ball-and-socket is our top concept. All of the concepts presented have better adaptability to a curved surface, but certain feet are best for different situations. Out of all five concepts, the modified ball-and-socket has the most versatility in regards to surface adaptation. The locking ball joint allows adaptation to all three possibilities of surface contour.

We can also conclude that the pivoting flat foot concept has the potential of becoming a legitimate solution. The pivoting flat foot will lock in place better than the piano hinge. Furthermore, the pivoting foot does not have to be detached and flipped in order to accommodate a curve in the opposite direction.

5. First Chosen Concept

Our team will employ the use of our Pivoting Flat Foot in the front with the Ball-and-Socket Foot in the rear. This concept allows for the most adaptability to a curved surface while still maintaining a low profile. The front needs to be as close to the contoured surface as possible, and with this in mind we determined for the front feet this parameter should be addressed first. The low profile of the Pivoting Flat Foot makes it a perfect choice for the front mount. The pivoting action of the mount will allow for the front to incorporate certain degrees of rotation about the horizontal axis, but more importantly, the mount is designed to meet the low profile requirement.

For the rear, we determined the mounting feet had more room for vertical expansion, which increased our possible design envelope. That being said, low profile was still a main concern in the design consideration of the rear. We decided that a custom made Locking Ball and Socket joint would allow for the BLDS to mount over a larger curvature than other concepts. With a larger range of motion, the ball-and-socket joint would allow our mount to adjust to different contours while the front mount maintains a low profile. The interface between the BLDS, the joint, and the mounting feet are still to be determined through testing so that we may find the optimal design. After discussion with Dr. Westphal during our Concept Design Review, we have determined that the actual preferred method of mounting the ball and socket joint would be on the sides of the BLDS. This mounting feature would enable minimal interference with the underside and overall height of the BLDS.

The solid model of our first conceptual solution can be seen in Figure 11. Testing and design iterations will determine the final layout of our solution. There is the possibility of multiple solutions—concepts that will solve specific cases of curvature and solutions that will incorporate adaptability to multiple contours.

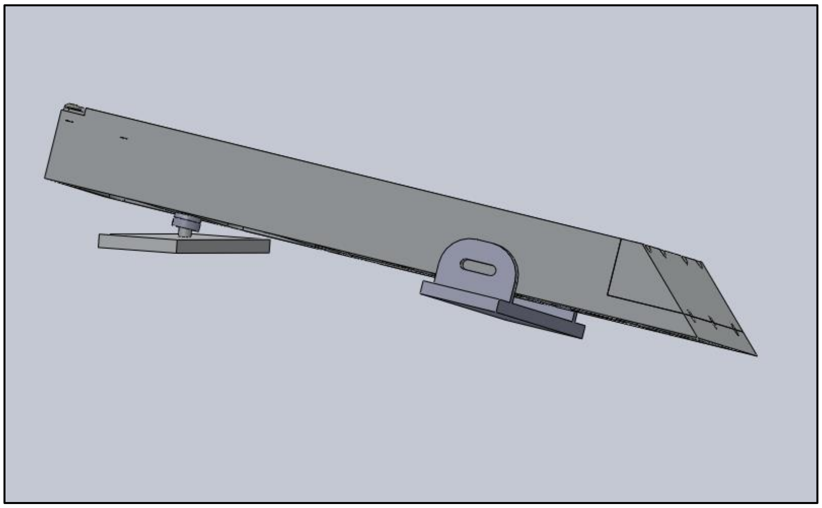

Figure 11. BLDS Mounting feet proposed Concept I

6. Concept Manufacturing and Testing Plans

We plan on completing the designs of several different mounting feet concepts to solve for different types of curvature in different arrangements. During the month of January, our team plans on completing a full detailed design of our concept. This will include exact geometries, tolerances, materials, and manufacturing processes. We plan to conduct hand-calculations to analyze the forces and stresses on our design.

While the official manufacturing plans are not yet decided, we have a general process plan. In all likelihood, the feet will be machined from aluminum. This will likely be completed by a mill. We must also pay careful attention to long-lead items, such as the locking ball-and-socket joint. These joints, especially in the size we require, are not readily available. Further planning and manufacturing preparation will take place over the winter break and through January.

After the design is complete, prototypes will be constructed of the design in order to test our overall concepts. Testing will include geometrical analysis of the feet in relation to model airplane wings. This initial geometrical analysis will allow us to evaluate the profile of the BLDS. The range of curvature that the feet can adapt to will be tested along with the clearance of the nose on the BLDS. After we have determined the validity of the solution we will test our calculated strengths with Aluminum and test a final solution to verify that our calculations were correct.

When testing our prototypes, we must always keep safety in mind. Although our project involves minimal safety risks, a Safety Hazard Checklist has been attached in Appendix E. The checklist shows that no real safety hazards exist on our end of the project. Safety concerns will arrive in the actual mounting and flight of the BLDS assembly.

7. Concept Design Review

On December 3rd, our team presented this concept to Dr. Westphal and our project advisor Sarah Harding, who both provided valuable questions and suggestions. Later, the team met with Dr. Westphal to discuss the Concept Design Report in depth. Through these interactions, we were able to confirm most of our concepts and begin to plan further.

After the review, Dr. Westphal stressed that each type of surface contour must be individually identified. Each solution must then be clearly labeled as a solution to a specific curvature. We implemented this new concept and the four curvature capabilities are presented in the Overall Goals section of the Objectives.

Dr. Westphal also provided helpful suggestions based off his experience with the BLDS. Per his advice, we plan to look into using a shoulder bolt to tighten down the pivoting feet from the sides. Our team should also plan on using 4-40 screws, because they seem to tap into the thin Aluminum better than other screw or bolt sizes. Further limitations and suggestions on modifications to the BLDS frame are presented in the next section.

V. Critical Designs

1. Introduction

This project is unique because we will not have one final solution. Instead, we have designed and analyzed multiple solutions for each of the curvature categories. Due to the lack of long-lead items and short manufacturing times, we plan to manufacture and test prototypes for each of our designs. After multiple design iterations, eliminations, and additions to our concepts, our team has six detailed designs to move forward with. This section describes the designs from our Critical Design Report in detail.

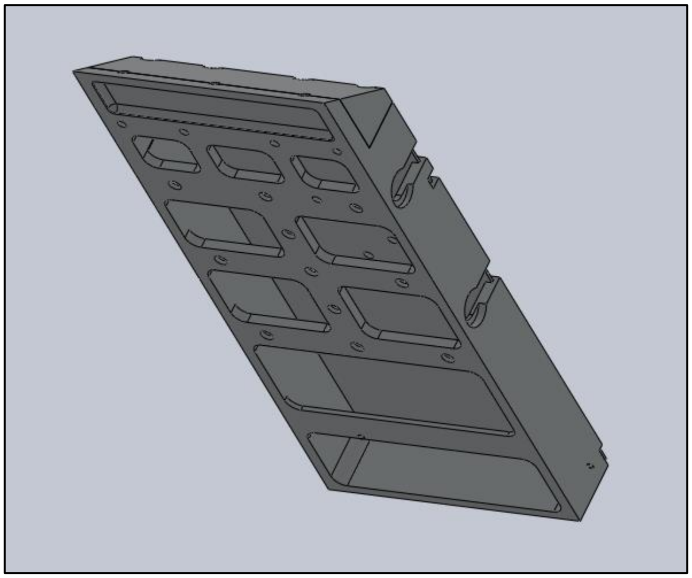

Figure 12. Underside of Dr. Westphal's BLDS Solid Model

The frame of Dr. Westphal's current BLDS creates certain design limitations and concerns. The entire frame has been machined from Aluminum, and is very thin in certain areas. The holes in the bottom frame cannot be tapped, so screws must come through the inside of the box and into our mounting feet. The sides of the BLDS are thicker, but we cannot drill through the bottom up into the side walls. Dr. Westphal recommends tapping 4-40 holes through the side walls.

2. Detailed Critical Design Descriptions

Design A: Pivoting Horizontal Slotted Foot

The Pivoting Horizontal Slotted Foot (Figure 13) involves a basic, low-profile design that has been iterated from the Pivoting Flat Foot Concept. It will be attached with 4-40 screws into the side frame of the BLDS. The horizontal slot allows for adjustments in placement, but results in poor height adaptability. This design may help to multiple degrees of Type 1 curvature, but cannot account for any of the remaining curvature categories.

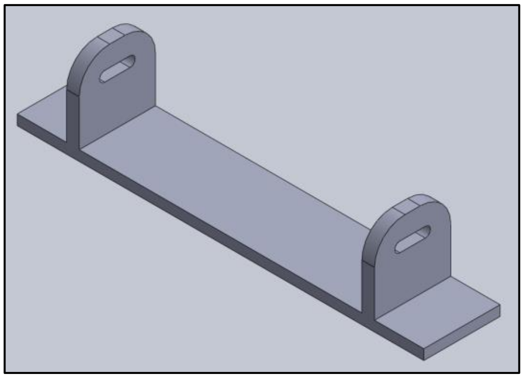

Figure 13. SolidWorks Model of Design A

We plan to continue the iterations of this part until we have the optimal design. Our first change involves adding countersinks to the outsides of the slots. Countersinks will allow for increased contact area with the screws and a higher ease of assembly.

Design B: Pivoting Vertical Slotted Foot

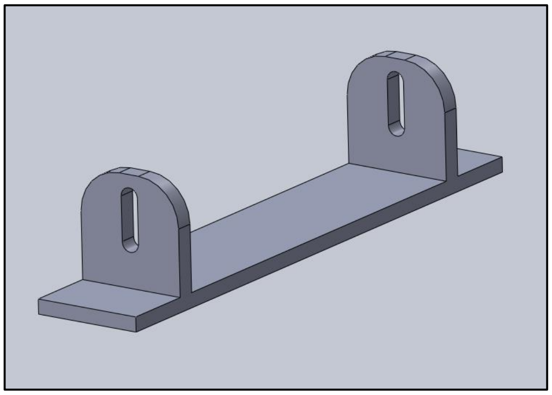

Figure 14. SolidWorks Model of Design B

Our team designed this mounting foot with inspiration from the previously discussed design. As illustrated in Figure 14, the vertical slots are advantageous because they allow for adjustments in height. This height variability opens the possibility of using Design B as the front foot or back foot. This design also displays the potential to solve Type II curvature due to the nature of its parallel vertical slots that could be locked at different heights on each side of the BLDS.

In comparison with the Horizontal Slotted Foot, we believe this design may outperform the previous and display better results for Type I curvature adaptability. However, the horizontal slotted feet provide more vertical support, which is essential during the mounting process. The assembly will rely on the support of the tightened screws. Also, we plan to countersink the outsides of the vertical slots for the same reasons presented in Design A.

Design C: Versatile Flat Foot

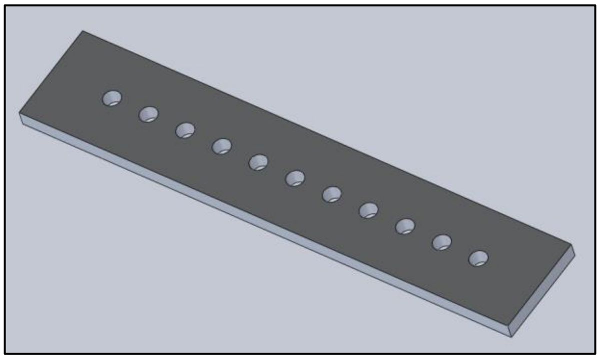
Figure 15. SolidWorks Model of Design C

The Versatile Flat Foot design, displayed in Figure 15, was originally intended to solve Type II and III curvature. If attached with one screw to the bottom frame, the foot can easily pivot about the Y-axis, accounting for swept curvature. This is the only simple foot that does not require new holes in the BLDS frame. The thickness has yet to be determined; it will be chosen based on geometrical analysis of the screws used and range of motion that added thickness will give the foot.

The real advantage of this foot would be the ability to pivot around the Z-axis. Our team originally planned to have two screws attached at varied heights, allowing the foot to adapt to Type III curvature. However, due to limitations on threading the bottom of the BLDS, this design may not be able to function as we initially hoped. After some testing, we hope that this design can do more than serve as just a spacer.

Design D: Locking T-Joint Foot

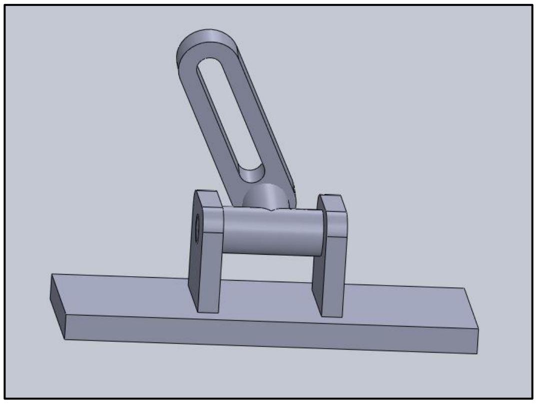
Figure 16. SolidWorks Model of Design D

The Locking T-Joint (Figure 16) is meant to utilize a dual axis of rotation to solve every curvature from Types I to IV. The foot will be able to rotate about the Z-axis, and the joint connected to the foot is then connected to a leg placed on the BLDS and this allows it to rotate about the X-axis. Setscrews can lock the pivoting axes. Furthermore, the vertical slot allows for a wide range of height variability. When the chosen position is found and force is applied to compress the Elastic tape this joint should maintain the desired position.

Similar to the slots on the two slotted feet (Designs A and B), the next evolution of this design will incorporate a countersink along its vertical slot. The volume and weight of this foot have been calculated in the Analysis section in order to determine how many feet of this type we could add without going overweight. We are the most optimistic about this design. This design will not only have a higher ease of manufacturing than the locking ball-joint, but will also have a stronger locking mechanism.

Design E: Large Flex Foot

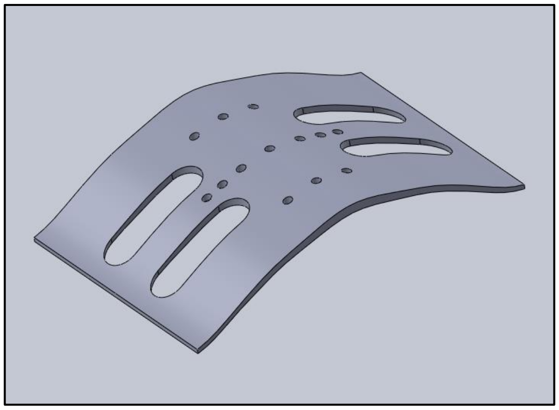

Figure 17. SolidWorks Model of Design E

The Large Flex Foot is intended to solve every curvature from Type I to VI, and has been modeled in SolidWorks (Figure 17). This design will have multiple thicknesses across its area. The middle and most raised part of the foot will a maximum of an eighth inch thickness so that screws may be used to attach it to the BLDS. As the curve progresses the thickness of the Aluminum thins out to a sixteenth of an inch so that the compression force can deflect the material to the shape of the curve on which it was placed. The thickness and geometry of this design will provide the maximum contact area and highest contour adaptability.

Design F: Locking Ball-Joint Foot

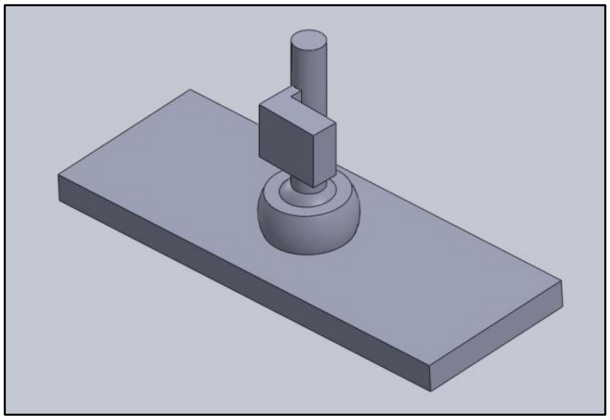

Figure 18. SolidWorks Model of Design F

The Locking Ball-Joint was originally our most promising design that used to solve curvature from Types I to IV. After the initial the concept design was discussed, we have modified this foot to mount with 4-40 screws through dimensions required to create a locking joint might be too large and too heavy for a valid design. We are currently changing the design of this to eliminate unneeded material and limit movement even more.

3. Material, Geometry, and Component Selection

All of the mounting feet designs will be machined from 6061 aluminum. We chose this material because it is cheap, lightweight, and easy to work with. We could purchase 1” x 1” 6061 aluminum stock for around 50 cents per cubic inch, according to *Online Metals.* We factored this cost estimate into the Direct Material (DM) Costs of each design. One aspect that we must remain wary of is the soft nature of aluminum. We need to take extra precautions when tapping into the BLDS, and when tightening down the steel screws.

The rigidity of aluminum limits the amount of shapes we can use to mount to the surface. The rigidity of the BLDS box makes it so that in order to keep the front end flush with a curved surface, the rear of the BLDS must be able to mount to a surface that’s initial distance from the BLDS increases with increasing curvature.

The team plans to purchase and use 4-40 sized taps and screws for each mounting point. Dr. Westphal has experimented with many different screws and hole sizes, and he strongly recommends only using 4-40 screws. Other than the attaching screws/bolts, the actual mounting feet are the only other component that we must select. Dr. Westphal certainly simplified this selection process.

4. Analysis Results

During the first three years of the mechanical engineering curriculum, we have learned to perform detailed analysis on complex machinery components. We now have the opportunity to verify our own designs with that analysis experience. Using these techniques and Shigley’s *Mechanical Engineering Design* textbook, we performed several hand calculations. The safety risk is very low for this project, but we have still included a factor of safety of 3.0 in each calculation. The sections on the following pages summarize the results of the detailed analysis performed on each design. The actual analysis can be found in Appendix F.

Design A: Pivoting Horizontal Slotted Foot

As engineering students, we initially thought that performing detailed analysis on these simple feet would be superfluous. However, due to class requirements we performed analysis on each and every foot. It turns out that our suspicions were correct, and both Design A and Design B will experience minimal stresses, even though we performed calculations of the worst possible cases. We are far more worried about the strength of the screws than the strength of our aluminum parts. After performing stress calculations by hand, we achieved the following results:

- Material: 6061-T6 Aluminum
- Contact: 3.0 in^2
- Volume: 0.420 in^3
- Weight: 0.0410 lb / 18.60 grams
- DM Cost: $0.21/part
- Max Shear: 480 psi
- Max Bending: 3840 psi
- Buckling $P_{cr:}$ 66825 psi
- Deflection: Negligible

The most important results to look at here are the maximum stress and deflection. Our engineering specifications require our feet to withstand a vertical load of 90 lb (mounting) and a shear load of 10 lb. Primarily, our goal is to achieve a maximum stress concentration that is less than the yield strength of 6061 aluminum, which is around 8,000 psi. As you can see, the maximum stress (which was calculated with a safety factor of 3.0) is far less than the yield strength of aluminum. The deflection experienced is minimal as well. Design A passes our analysis tests with flying colors.

Design B: Pivoting Vertical Slotted Foot

We performed analysis identical to Design A for the Vertical Slotted Foot. The mounting and shear forces are identical at the worst case scenario. The results have been reported below, and Design B passes the analysis tests with ease as well.

- Material: 6061-T6 Aluminum
- Contact: 3.0 in^2
- Volume: 0.419 in^3
- Weight: 0.0409 lb / 18.55 grams
- DM Cost: $0.21/part
- Max Shear: 480 psi
- Max Bending: 3840 psi
- Buckling $P_{cr:}$ 66825 psi
- Deflection: Negligible

Design C: Versatile Flat Foot

We deemed analysis calculations to be unnecessary because this foot is flat and flush to both contacting surfaces. With simpler and stronger geometry than the previous two designs, we can ignore these analysis calculations with confidence. Below, we have provided the basic specs of the Versatile Flat Foot.

- Material: 6061-T6 Aluminum
- Volume: 0.357 in^3
- Weight: 0.0348 lb / 15.79 grams
- DM Cost: $0.18/part

Design D: Locking T-Joint Foot

The Locking T-Joint was one of the more complex designs we came up with. The analysis that was completed on it evaluates the buckling of the leg, the shear stress on the T-Joint, and the deflection seen at the foot. Each one of these calculations was done to verify that the design would not fail when subject to theoretical stresses.

- Material: 6061-T6 Aluminum
- Volume: 0.291 in^3
- Weight: 0.0284 lb / 12.88 grams
- DM Cost: $0.15/part
- Buckling: 135 lbs < 50720 lbs
- Deflection: 0.26 inches (insignificant)
- Shear: 4,125 psi < 8,000 psi

None of the calculations indicated that the design would fail when subject to these loads at a safety factor of 3. The values indicated above show the comparison between the maximum allowable and the calculated values for the specific design and material. After the analysis this design is ready to be prototyped and then built to proceed with more in depth testing.

Design E: Large Flex Foot

The Large Flex Foot is designed to deflect and conform to a curved surface. The analysis done on the foot was to determine the amount of deflection the maximum load would cause. The deflection found was smaller than we had hoped but not unexpected. The analysis was done with the assumption that the material was solid. Our design features slots cut into the material to reduce the overall stiffness of the design. The simplistic design of the Flex foot allows for a manufactured test part to be continually changed until the desired effect is achieved without requiring a new part. With that in mind, the analysis shows that a greater force is needed to properly deflect the aluminum foot proving that the foot requires slots to reduce rigidity.

• Material:	Aluminum
• Volume:	0.575 in^3
• Weight:	0.0561 lb / 25.45 grams
• DM Cost:	$0.29/part
• Deflections :	9.025×10^{-4} inches

Design F: Locking Ball-Joint Foot

Because this design is still in iteration, it doesn't make sense to perform detailed analysis. The dimensions and capabilities of this part will have to evolve in order to meet specifications and allow feasible manufacturing. Once we finalize the dimensions of this design, we plan to perform detailed analysis before manufacturing any aluminum prototypes.

• Material:	Aluminum
• Volume:	0.230 in^3
• Weight:	0.0224 lb / 10.16 grams
• DM Cost:	$0.12/part

5. Cost Breakdown

In the end, this project can be completed at extremely low costs for a Mechanical Engineering Senior Project. The team hopes to fabricate each design in the machine shops on campus. The machine shops in both Bonderson and The Hangar have several mills and lathes, allowing us to manufacture the parts essentially for no cost.

This project also came with the added benefit of a sponsor that works on Cal Poly's campus. Our team should be able to easily purchase the raw materials and set up rapid prototyping sessions. We have estimated the few costs for this project on Table 3.

Table 3. Cost Estimation

Component	Cost
Raw Material	$0.50 / in3
Design A	$0.21 (DM)
Design B	$0.21 (DM)
Design C	$0.18 (DM)
Design D	$0.15 (DM)
Design E	$0.29 (DM)
Design F	$0.12 (DM)
RP Session 1	$140
RP Session 2	$150
Manufacturing	Free
½" 4-40 screws	$4.61

6. Design Development

Our team utilized several design development methods throughout the last two quarters. Prior to the Concept Design Review, our team analyzed customer requirements through QFD (Appendix B), and brainstormed designs through concept modelling.

The design of multiple mounting feet requires numerous iterations and evolutions. We plan on conducting a series of rapid prototyping, followed by testing and analysis, laid out in Figure 19. This analysis will then become the basis to iterate and improve designs in SolidWorks. Once springtime approaches, we will manufacture actual aluminum parts. These prototypes will then go through our in-depth Design Verification Plan. The DVP&R is discussed in the following Manufacturing Plan section.

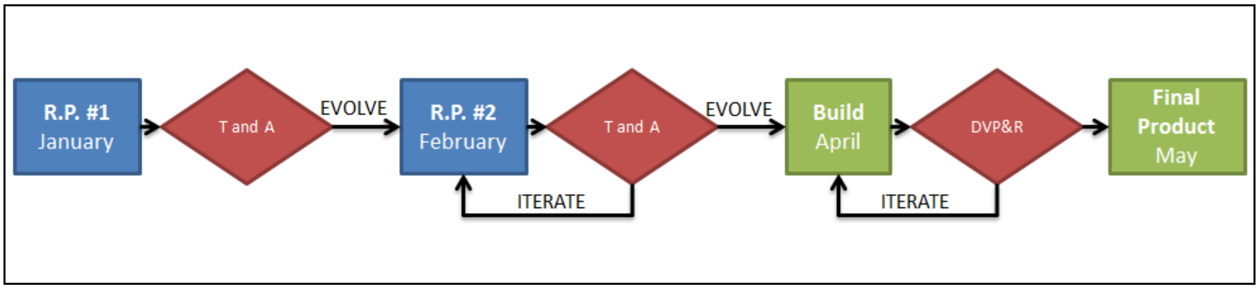

Figure 19. Design Evolution Flowchart

7. Rapid Prototyping Session 1

On January 17th our team produced the first round of rapid prototyping. Using the FDM 3-D Printer in the Mechanical Engineering building, we printed four prototypes from our concept design report. These solid representations of our designs helped to visualize the capabilities of each foot.

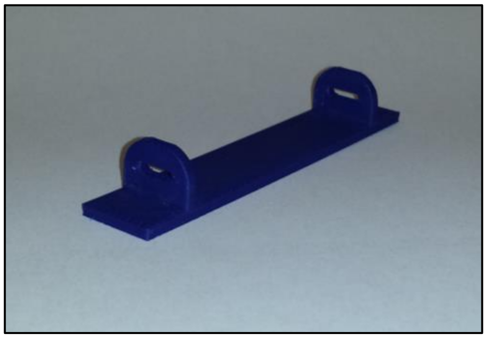

Figure 20. Slotted Pivoting Foot Concept RP

Results

- Found that the height of the slots were not high enough to give a sufficient range of motion.
- Lacks articulation desired out of design.
- Design iteration, Vertical slot may solve the lack of articulation.

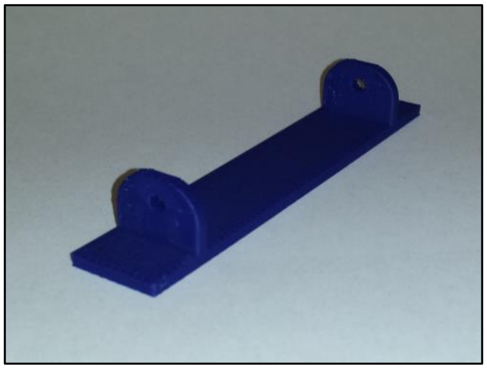

Figure 21. Pivoting Flat Foot Concept RP

Results

- Found that the height of the slots were not high enough to give a sufficient range of motion.
- Simple design shows the need for slots to increase range of feet mounted to the side of the BLDS.
- Design iteration, Feet designated to attach to the side of the BLDS should have a slotted connection to increase articulation.

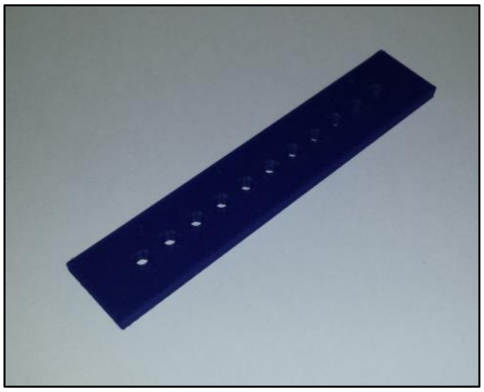

Figure 22. Versatile Flat Foot RP

Results

- Designs mounting to the bottom of the BLDS must be able to use tapped holes to secure position

- Design iteration, Feet designed to mount to the bottom of the BLDS must be done so with careful consideration to using tapped holes.

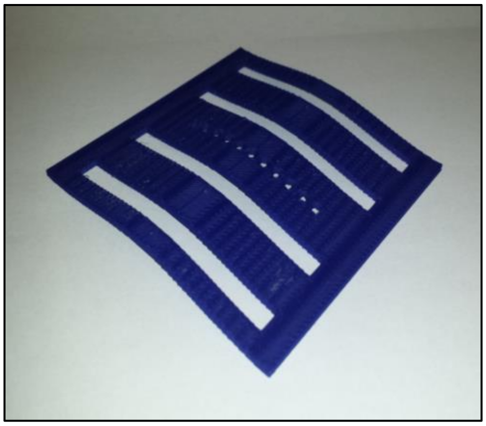

Figure 23. Flexible Flat Foot RP

Results

- Thickness of large flex plate must vary from thickest in the middle area to thinnest at the edges.
- Securing at multiple locations a possibility
- Dimensions of the feet do not compliment the current mounting process, refined dimensions will prevent a need to mount differently.
- Design iteration, Feet will taper in thickness and feature a more aggressive curve and more fitting dimensions.

VI. Manufacturing Plan for Critical Design

1. Fabrication Methods

The three simple designs (i.e. Designs A, B, and C) have fairly straightforward manufacturing methods. First, our team needs to obtain the raw materials. We plan to purchase 6061 Aluminum stock from a local metal distributer, or from McMaster online.

After the needed material is purchased we will then use the tools available in the lab to produce the desired foot. For our more simple designs such as A, B and C we plan on using the Mill and a 4-40 tap to achieve the desired outcome. The more complex designs may require more effort to complete. The T-joint, with its compact design may require pieces to be welded together as well as initial machine work. The Flex Foot will not be complicated to fabricate requiring only a sheet metal bender and varied plate thickness, the simplistic material needs of this design will allow for continual iteration as we test this foot. The most complicated design to make will be the customized ball and socket. Currently we do not possess the capability to manufacture the Ball and Socket Foot in house, however the design iteration of the current design may solve this concern.

2. Outsourced Manufacturing

We wish to minimize the use of outsourced manufacturing because it can be time consuming and expensive. Our team plans to manufacture each design in the machining labs on Cal Poly's campus. However, we anticipate difficulties in the fabrication of the complex designs. Creating a miniature T-joint (Design D) and miniature ball-joint (Design F) will certainly provide a challenge. If the resources provided on campus cannot provide us with the precise manufacturing of these designs, we plan to contact a prototyping company. Maglio Inc. is a local engineering company that takes pride in its manufacturing services, and could be of great assistance to our group.

3. Safety Considerations

As previously stated, safety is a priority, but not a huge concern for this project. Most of the danger arises in the use of the machinery in the Cal Poly machine shops. Please see Appendix E for our team's Safety Hazard Checklist. This checklist shows all "No's" for each safety hazard, and our design will be easier to use safely than unsafely.

VII. Management Plan for Critical Design

1. Team Responsibilities

As with every team, each team member has specific skills and strengths that they will draw upon to facilitate the completion of this project. In Table 4 we have provided a division of the responsibilities based on our perceived strengths. Despite the division of responsibility, we are collectively responsible for the entire project and each other's success.

Table 4. Team Member Responsibilities

Responsibility	**Leader**
Documentation of Progress	Chris Mazzucco
Communications	Mitch Conn
Research	Mitch Conn
Manufacturing Considerations	Chris Mazzucco
Prototype Fabrications	Chris Mazzucco
Testing Plans	Mitch Conn
Design Review	Team

2. Design Subsystems

In our design, we will likely only see one subsystem. The subsystem will be the mounting design, and if this design requires specific pressure application, we will have a second subsystem in the form of a mounting mechanism. Our plan is to design feet that work with the current equipment, in order to avoid designing our own pressure applicator. Both designs will be considered and worked on by all team members because the pressure application design is directly dependent on the initial design of the mount.

3. Timetable of Milestones

Our team is not only working to create a great project to for Dr. Westphal but we are also working towards graduation from Cal Poly. As part of our senior project class requirements, there are certain dates that we must adhere to so that we may stay on track. The completion of these milestones, shown in Table 5, will allow us to check our progress and assess the situation.

Table 5. Project Milestones

Date	Milestone tasks
11/05	Conceptual Model Presentation
11/21	Yellow Tag completed
12/5	Concept Design Review
1/30	Critical Design Review
2/04	Critical Design Report Submittal
3/11	Project Update Memo
4/24	Prototype Manufacturing
5/31	Senior Project EXPO
6/06	Final Report Submittal

The above table lists the main milestones for the overall project. A more detailed plan can be found in our Gantt chart. The Gantt chart—found in Appendix D—plans out the timetable for each important task that we will need to complete if we wish to stay on track. At the time of the Critical Design Report, we were maintaining the schedule laid out in the Gantt chart, and hoped to continue to stay ahead of schedule for the remainder of the project.

VIII. Product Realization

1. Final Design

The previous sections of this report consist of the plans and design decisions from our Critical Design Report. As we have already admitted, there is always room for improvement and further design iterations. The Critical Design Report was submitted and presented to our sponsor at the end of January. Following discussions with Dr. Westphal, the final designs of our mounting feet changed slightly from the critical designs.

Our final designs consist of three different mounting feet iterations. Dr. Westphal was pleased with our simple Pivoting Slotted Feet, and approved them for production. Dr. Westphal also approved of the Locking T-Joint design, but suggested one small design change. Per his advice, we decided to finalize two different versions of the T-Joint feet. Version 1 (V1) is essentially the same design of the T-Joint from our Critical Design Report. Following the suggestion from Dr. Westphal, the second version (V2) was designed with the foot rotated 90 degrees from our critical design. The differences between these designs are shown below, side-by-side in Figures 24 and 25. Both designs lock in place using the torque from 4-40 screws. Analysis on the pull-out force of these threads is presented in Appendix F.

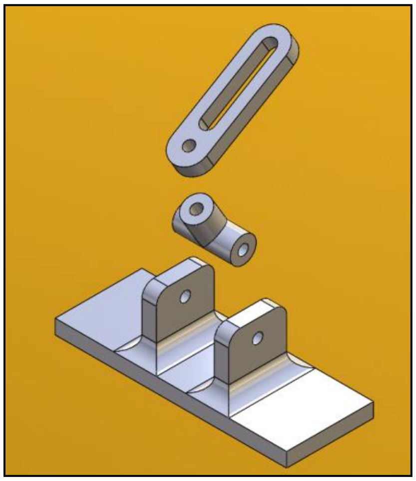

Figure 25. Final T-Joint V1

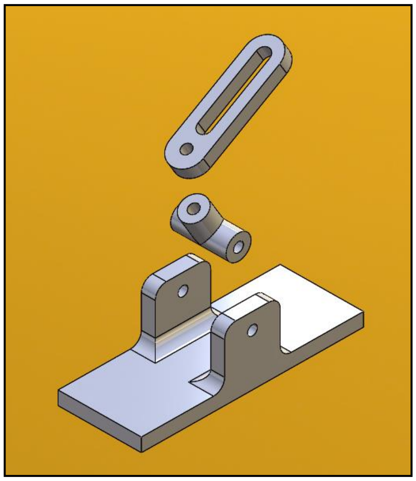

Figure 25. Final T-Joint V2

In addition to the creation of the second version of the T-Joint, we performed one more small iteration by adding fillets to the feet. Fillets will increase the overall strength of the part. This will slightly increase the weight, but we were more concerned about the shear forces around the eighth-inch thick feet.

With the three final foot designs in mind, two potential final assemblies were determined and are presented below in Figures 26 and 27.

Assembly 1 (pictured right) utilizes a Simple Pivoting Foot in the front to maintain a low profile, and T-Joint feet in the back for both height and curvature adaptation. This assembly is capable of adapting to all curvatures with the exception of a fuselage. Tapped holes in the sides of the frame allow the feet to tighten down with 4-40 screws, and lock at any desired angle.

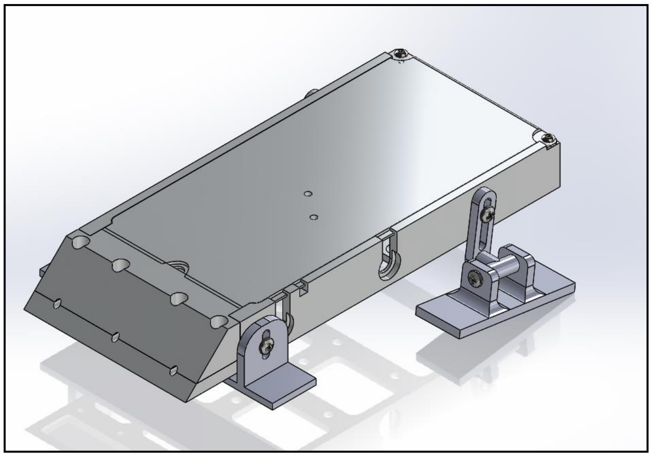

Figure 26. BLDS Final Assembly 1

Assembly 2 (pictured right) utilizes four T-Joint feet to allow for the greatest height variability and curvature adaptation. Like Assembly 1, this concept utilizes the same tapped holes in the side of the BLDS frame. This assembly is the design we are most proud of, as it can accommodate all four specified curvature possibilities.

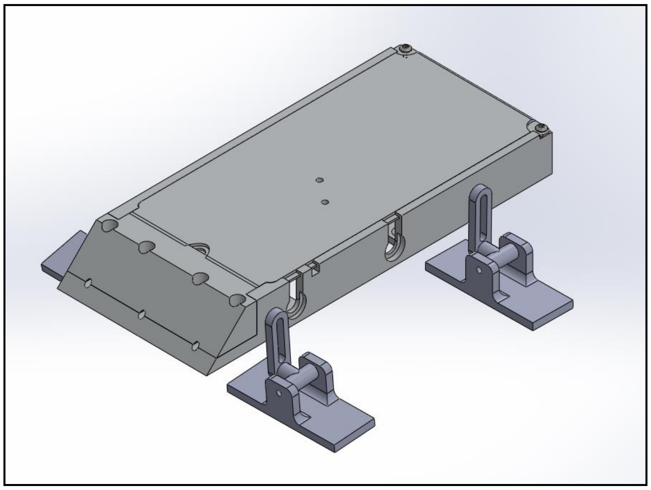

Figure 27. BLDS Final Assembly 2

Our thread pull-out analysis confirmed that we could tighten down the 4-40 screws with a torque of 162.56 in-lb$_f$. This gave us the confidence to tighten down the screws as much as possible when mounting the foot assemblies during testing. We will present the results of said testing in the following Design Verification section.

2. Rapid Prototyping Session 2

On February 18th our team produced the second and final round of rapid prototyping. Using the EDEN 250 3D Printer in the Mechanical Engineering building, we printed the six parts needed to assemble both versions of the T-Joint feet. The first rapid prototyping session, using the cheaper Stratasys printer, resulted in fairly inaccurate parts. When prototyping our final T-Joint foot designs, we needed increased accuracy to ensure all of the moving parts would mesh properly. In the end, we were extremely happy with the turnout of both feet prototypes, and were excited to move on to the production of the actual feet. Pictures of the 3D-printed feet are shown below in Figures 27 and 28.

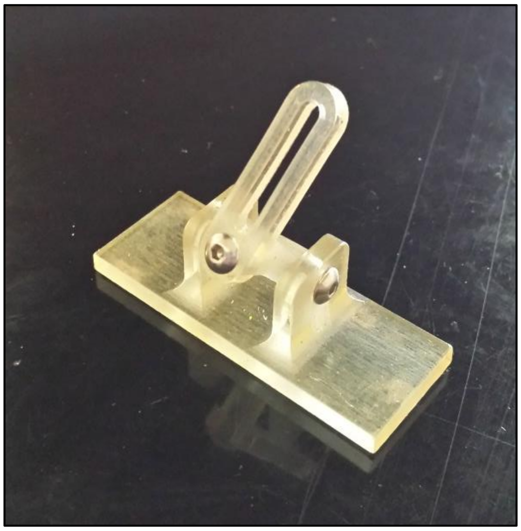

Figure 28. T-Joint V1 RP

Version 1 Results

- Excellent quality prototypes
- Very precise detail and dimensions
- Possible Design Iteration
- Orientation allows for better mounting to fuselage-like surfaces
- Solves all curvature possibilities

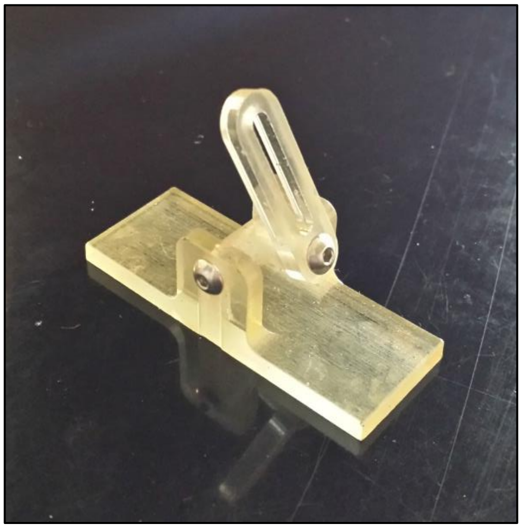

Figure 29. T-Joint V2 RP

Version 2 Results

- Excellent quality prototypes
- Very precise detail and dimensions
- Possible Design Iteration
- Orientation allows for mounting on more common surface curvatures for a wing
- Solves all curvature possibilities

3. Manufacturing Methods

After successfully evaluating the second rapid prototyping session and the materials were ordered, manufacturing began. The two most used tools were the band saw and the end mill. The horizontal band saw, shown to the right in Figure 30, was used to cut the aluminum stock into manageable lengths, close to that of the final product. After the raw stock was roughly cut to size, the end mill, shown below in Figure 31, was used to remove material and precisely shape the designed mounts.

Figure 30. Chris on the Horizontal Band Saw

Figure 31. FEM Milling a T-Joint V2 Foot

We followed the design drawings from our 3-D models to mill each foot to its precise size, and compared them to previous renditions of the same milled part. Figure 32 (right) shows different stages of production placed on top of the drawing used to make them. Figure 32 shows the aluminum stock on the right moving towards a finalized product on the far left.

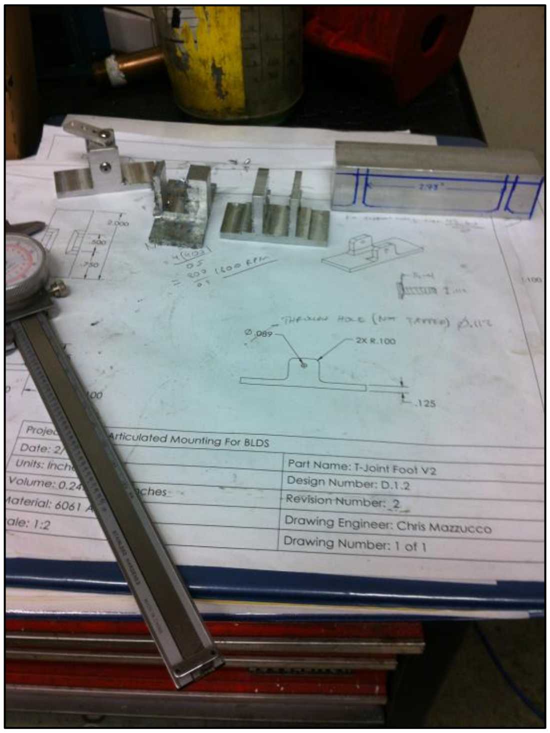

Figure 32. Stages of Aluminum Part Production

Most of our time in the shop revolved around milling the feet down to their exact shape. Once the shape was finalized, the only remaining steps were to drill through-holes in the feet, and tap the 4-40 holes in the T-Yokes. We utilized a vertical drill press with a #33 drill to create the through-holes in both the feet. This operation is shown to the right in Figure 33.

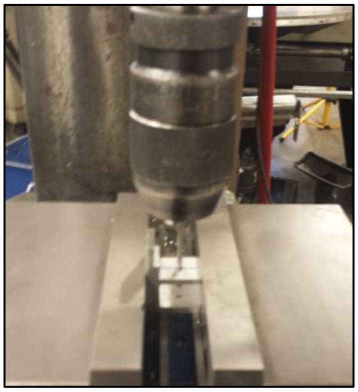

Figure 33. Vertical Drill Press creating through-holes

Figure 34. 4-40 Tap for T-Yokes

For the T-Yokes, we used the same drill press to drill the initial holes for the 4-40 taps with a #43 drill. We then tapped each hole with a 4-40 tap in the Bonderson machine shop. This step is pictured to the left in Figure 34.

Our team developed a manufacturing plan to lay out the step-by-step goals for our project. These steps are presented below in Table 6. We successfully completed these goals, and produced a functioning final product. Pictures of the final product are presented in the next section.

Table 6. BLDS Manufacturing Steps

BLDS Feet Manufacturing Plan				
Operation	**Method**	**Completed**	**Desired**	**%**
V1 Foot		2	2	100%
Cut to Shape	Band Saw	2	2	100%
Rough Cut	Mill (FEM)	2	2	100%
Finishing Pass	Mill (BEM)	2	2	100%
Through Holes	Drill (33 Bit)	2	2	100%
V2 Foot		4	4	100%
Cut to Shape	Band Saw	4	4	100%
Rough Cut	Mill (FEM)	4	4	100%
Finishing Pass	Mill (BEM)	4	4	100%
Through Holes	Drill Press (33 Bit)	4	4	100%
T (Yoke)		6	6	100%
Cut to Shape	Band Saw	6	6	100%
Rough Cut	Mill (FEM)	6	6	100%
Drill Holes	Drill Press (43 Bit)	6	6	100%
Tap Holes	4-40 Tap	6	6	100%
Vertical Support		5	5	100%
Cut to Shape	Band Saw	5	5	100%
Through Holes	Drill Press (33 Bit)	5	5	100%
Simple Foot		2	2	100%
Cut to Shape	Band Saw	2	2	100%
Rough Cut	Mill (FEM)	2	2	100%
Finishing Pass	Mill (BEM)	2	2	100%
	Total:	**83**	**83**	**100%**

4. How Prototype Differed from Final Design


Figure 35. Manufactured V2 T-Joints

During the manufacturing process, it became apparent that some of the parts could not be completed as designed. The slots on the mounts became through holes to increase the strength of each desired position, while only slightly decreasing the variability of placement. Through-holes are also much easier to manufacture than slots. The T-Yokes that were designed to be rounded were manufactured with square edges because a FEM (flat end mill) was used to remove material. Fillets that were designed to increase strength of the design were attempted, but were ultimately too difficult to achieve with a mill, and therefore remained imperfect during manufacturing.

The final manufactured and assembled V2 T-Joints are pictures above in Figure 35. Below, Figure 36 shows the remaining T-yokes, an extra vertical support, and the two manufactured V1 T-Joints. By the end of our manufacturing process, we had used about half of the material purchased from McMaster. We plan to give the material back to Dr. Westphal for use on future BLDS projects. Our Bill of Materials is presented in Appendix G.

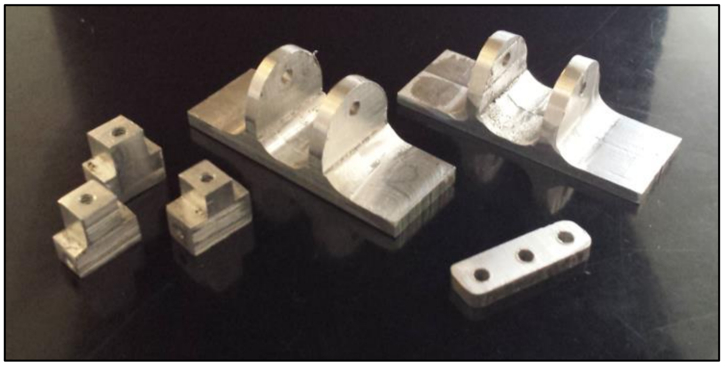
Figure 36. Manufactured V1 Feet, Yokes, and Vertical Support

5. Recommendations for Future Manufacturing

From our experience in manufacturing products for these designs, we have a few recommendations to streamline the process and eliminate possible error in the process. The easy answer is to write a program to automatically CNC the parts. Generating CNC code and manufacturing the mounting feet will not only reduce the total manufacturing time, but will increase the accuracy of each part. This will decrease the time to make each part, allowing for quicker recovery times if future iterations are required. An automatic program increasing the accuracy of each cut will enable a more uniform production of mounting feet and more exact weight results for the overall assembly. This will increase the tolerance of the machined parts, eventually leading to a stronger locking mechanism that is easier to assemble.

Furthermore, utilizing lock-washers is important when assembling the mounting system. Lock washers were not in our original design considerations, but they are extremely helpful. Not only do they provide better spacing between the feet and the BLDS frame, but they create a stronger locking force. This strong locking force is essential when mounting the BLDS to a surface. With the heavy load needed to activate the adhesive, the joints must not rotate at all. Any changes in the position of the BLDS—specifically the height—can lead to errors in the data collection.

IX. Final Design Verification

1. Test Descriptions

The validation of our designed required testing after manufacturing. There are three major tests that cover the four engineering specifications that require testing. The first test performed was the weight verification to ensure the full assembly does not exceed one pound force. The next test performed determined the strength of the design. The first part of the test examined compression strength while mounting the BLDS to a surface. After the BLDS is mounted, the second part of the test determined the shear strength of the bonded BLDS. The final test took place after the design had passed the previous two tests. With the BLDS still mounted from the compression and shear test, the height of the front in relation to the surface must be measured to insure a low profile was maintained. If the testing of any design is successful it will be recorded with the appropriate values as well as the identification of what surface types it can articulate to.

The main three test plans are listed on the three following pages. A complete Specification Checklist was filled out upon the completion of these tests, and presented later in this section. This checklist organizes our tests by engineering specification, assuring that our solution has accounted for each of the customer requirements.

1. **Weight Test**
    - Equipment
        - SolidWorks Volume Calculation
        - Material Data
        - Scale
    - Location: Mitch’s House
    - Engineers: Mitch and Chris
    - Engineering Specification
        - Maximum weight
    - Instructions
        - Take designs in SolidWorks and dimension them on a 1:1 scale with the actual model. Use the mass properties stored within the SolidWorks program to give you the volume of the given design. Use this volume and multiply it by the density of Aluminum to find the weight of the design. If the design makes the full assembly exceed one pound force it fails the test.
        - If the SolidWorks model passes the initial test, the manufactured part will then be weighed with the full assembly. If the actual weight of the manufactured assembly exceeds one pound force, it fails the test. The summary of the weights is shown below in Table 7. The results are analyzed in the following section of the report.

Table 7. Measured Weight of Each Manufactured Component

Part	Average Weight (grams)
T-Joint V1 Foot	13.8
T-Joint V2 Foot	11.375
T Piece	2.1
T Leg	1.5
Simple Foot	27.5
4X40 screws	0.3

2. Compression and Shear Test

- Equipment
    - 100 lbs of Weights
    - BLDS Assembly
    - 3M4868F Visco Elastic Tape
- Location: Mitch's House
- Engineers: Mitch and Chris
- Engineering Specifications
    - Shear and Compression Strength
- Instructions
    - Attach the finalized and manufactured design to the BLDS. Place the appropriate amount of Visco Elastic tape on the feet and the place the feet on the surface at the desired orientation. Use the compression device (or weights) to apply a force on the top of the BLDS and compress the feet and tape together with the surface. After the force has been applied long enough for the tape to activate, remove the compression device and inspect the mounting. If the tape is not activated and the BLDS can be separated from the surface, the design has failed.

Figure 37. Compression Testing

    - Designs that pass the compression test are subject to testing the shear strength of the bond. Attach the Fish scale (or weight) to the BLDS to ensure the shear strength holds. If the BLDS holds, then they pass the test and satisfy the shear and compression strength engineering specifications.

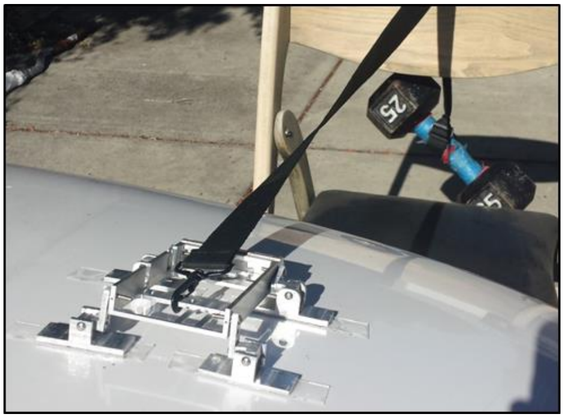

Figure 38. Shear Testing

3. Mounted Height Verification

- Equipment
  - Length Measuring Device
  - Mounted BLDS from previous Tests
- Location: Mitch's House
- Engineers: Mitch and Chris
- Engineering Specification
  - Height
- Instructions
  - After successfully completing the weight and strength tests, the BLDS should remain mounted to the chosen surface. Using the measuring device, measure the distance between the top of the contact surface to the Front tip of the BLDS. This distance should not exceed 0.3 inches, if it does it fails the test. An example of the test is shown below in Figure 39.

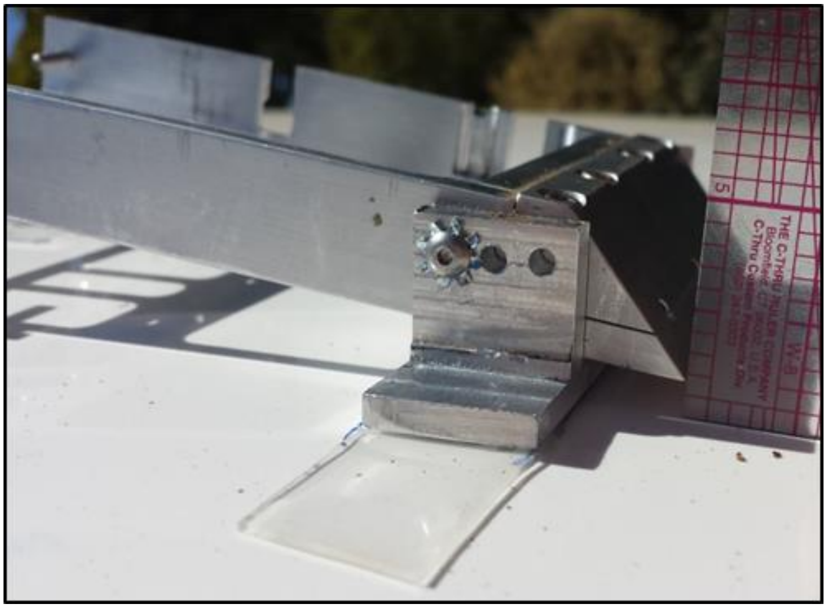

Figure 39. Mounted Height Verification Testing

2. Testing Results

From the tests performed we conclude that the final manufactured designs satisfy the conditions for which they were made. Initial testing of the mounting feet unfortunately did meet specifications. This result led to a failure analysis of thread strength and allowable torque based on material strength. After the completion of these calculations, shown in Appendix F, we found that we could increase the amount of torque used to lock the mounts in place without fear of pulling out the threads. Another addition to the design used to increase the friction force was the addition of lock washer's in-between the BLDS and leg interface. This increased the clearance between the screw heads and BLDS as well as increasing the total friction available for locking.

The second round of testing was a complete success. Two different mount arrangements (Assembly 1 and Assembly 2) withstood 100 pounds in compression as well as 25 pounds in shear while maintaining the required height range of the BLDS nose. The second round of testing is shown in the pictures in the previous section. Additional test can be conducted with different mount arrangements and ranges of curvature.

3. Specification Verification Checklist

A table was generated to summarize the results of our testing. This table lists the engineering specifications that we were able to physically test. As you can see in Table 8, our two assemblies passed each of the required tests.

Table 8. Specification Verification Checklist Table

BLDS Engineering Specification Verification					
Spec. #	**Parameter**	**Target**	**Tolerance**	**Risk**	**Result**
1	**Weight**	**50 (grams)**	**Max.**	**High**	**Pass**
2	**Contact Area**	**3.0 (in^2)**	**Min.**	**Med**	**Pass**
3	**Temperature**	**-60 (deg C)**	**Min.**	**Low**	**Pass**
4	**Compression Strength**	**90 (lbs.)**	**Min.**	**High**	**Pass**
5	**Shear Strength**	**10 (lbs.)**	**Min.**	**High**	**Pass**
7	**Height**	**0.3 (in.)**	**Max.**	**Med**	**Pass**
9	**Deflection**	**0.3 (in.)**	**Max.**	**Med**	**Pass**

X. Conclusion

This report serves as an explanation for our approach to solving this problem and manufacturing the solution. The delegated responsibilities were fulfilled by each team member in order to ensure success. Although our designs have been finalized, there is always room for possible iterations. We know that there will be room for improvement, and we hope to see our solution utilized and improved upon in the future. As a team, we were thrilled to take on this challenge and put our best effort forward to completion.

We can offer a few recommendations for moving forward should these designs be iterated or the problem revisited. Generating CNC code and automatically manufacturing the mounting feet will not only reduce the manufacturing time, but will increase the accuracy of each part. We encourage future iterations and testing of our designs.

At the completion of the testing portion of the project we can confidently conclude that our designs meet and fulfill every requirement specified by Dr. Westphal. The final successful designs consist of both T-Foot configurations and the Simple Foot design. The final tests were conducted on two different arrangements of feet, the first was an arrangement of the simple foot in the front and two T-feet (Assembly 1), the second was arranged with all four T-feet (Assembly 2). Both configurations successfully passed all the tests, and we are excited to see them used in flight.

We owe much of our success to the efforts of our project advisor, Sarah Harding. Special thanks go out to Dr. Russ Westphal for providing our team with this awesome opportunity. We hope our BLDS assembly will soon be seen flying overhead.

XI. Bibliography

1. Anglese, Kurt, Scott Cummings, and John Williamson. Attachment Assembly for Mounting a Seat to the Floor of a Vehicle. BE Aerospace Inc; Williamson, John; Anglese, Kurt; Cummings, Scott, assignee. Patent WO2005037594 A3. 13 Apr. 2006. Print.

2. Pfister, Jowel W., James Wohlford, and Dominic Grey. Articulated Tilt Mount. Milestone AV Technologies LLC, assignee. Patent EP1618329 B1. 6 Mar. 2013. Print.

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5. Broker, Klaus. Ball Joint. ZF Lemforder Metallwaren AG, assignee. Patent US6821047 B2. 23 Nov. 2004. Print.

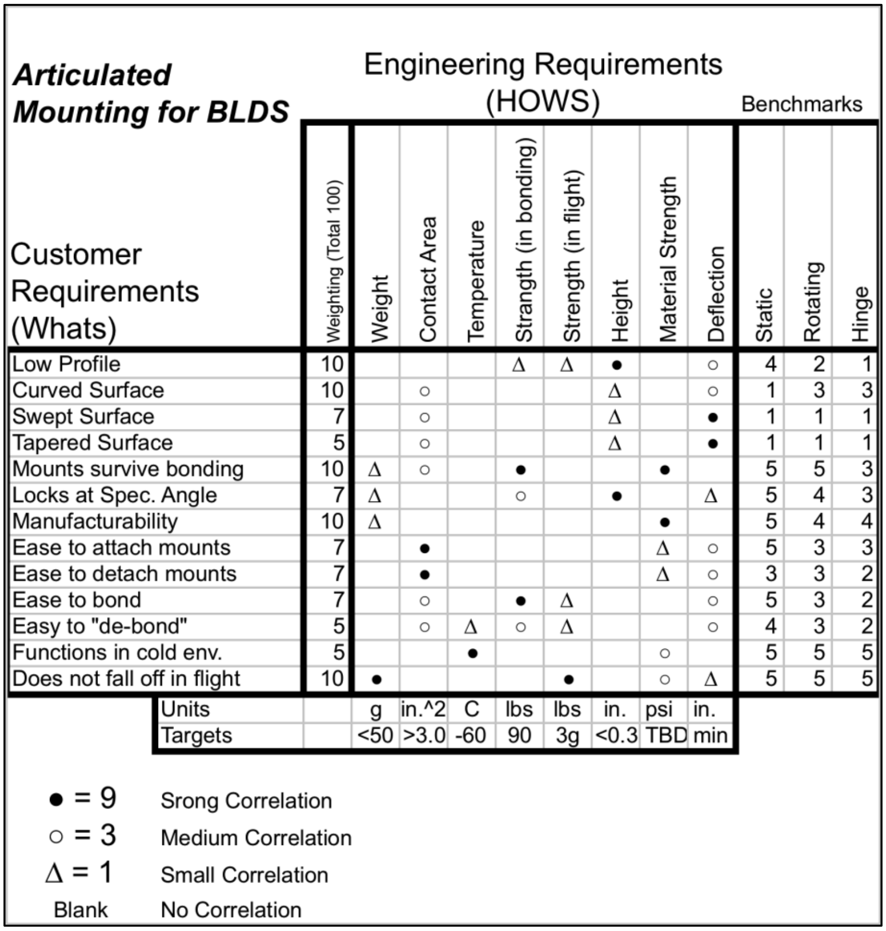
6. Merlo, Werner O. Ball Joint and Mechanisms for a Prosthetic Limb. Werner O. Merlo, assignee. Patent CA2197932 A1. 19 Aug. 1998. Print.

Appendices

Appendix A: Original Customer Requirements (From meeting on 10/3/13)

- The new mount design should not drastically change the current BLDS box design. The current box design is fixed; our focus us entirely on the mounts
- Mounts should not raise the box much higher than previous designs; Low profile is key
- Mounts should ideally be able to accommodate for curved, swept, and tapered surfaces (Types 1, 2, 3, and 4).
- Apparatus needs to withstand a force required to activate bonding in the adhesive.
- If using hinged/rotating mounts, they must have locking capability.
- Using 4 separate mounts is still an option.
- Using a flexible material for the mounts is a potential option.
- If necessary, we must design our own load fixture to properly distribute the forces for adhesive bonding.

Appendix B: Original QFD Table



Articulated Mounting for BLDS

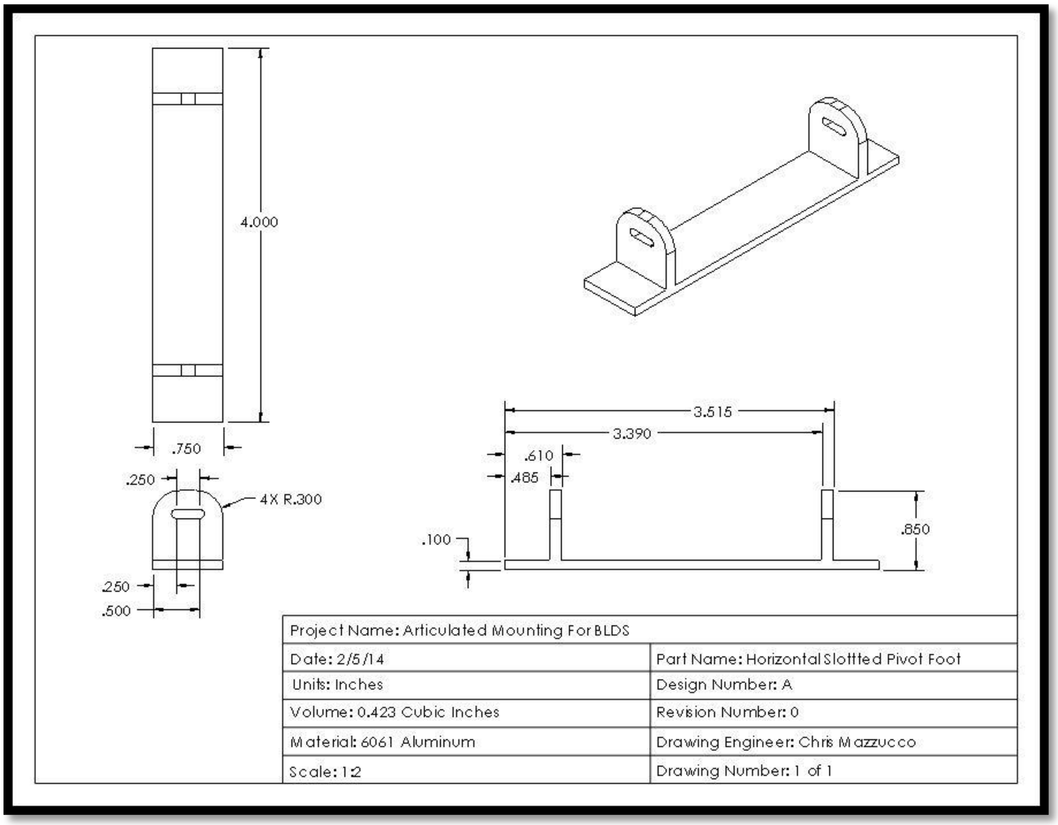
Engineering Requirements (HOWS)

Benchmarks

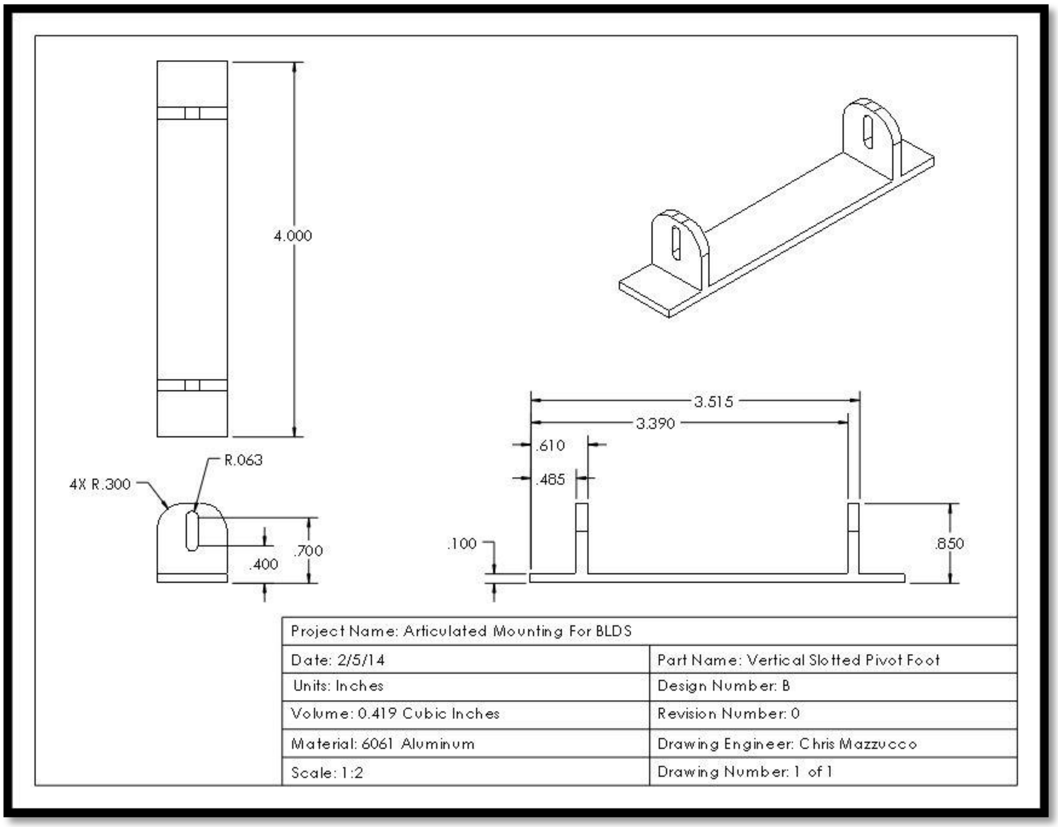
Customer Requirements (Whats)	Weighting (Total 100)	Weight	Contact Area	Temperature	Strangth (in bonding)	Strength (in flight)	Height	Material Strength	Deflection	Static	Rotating	Hinge
Low Profile	10				Δ	Δ	●		○	4	2	1
Curved Surface	10		○				Δ		○	1	3	3
Swept Surface	7		○				Δ		●	1	1	1
Tapered Surface	5		○				Δ		●	1	1	1
Mounts survive bonding	10	Δ	○		●			●		5	5	3
Locks at Spec. Angle	7	Δ			○		●		Δ	5	4	3
Manufacturability	10	Δ						●		5	4	4
Ease to attach mounts	7		●					Δ	○	5	3	3
Ease to detach mounts	7		●					Δ	○	3	3	2
Ease to bond	7		○		●	Δ			○	5	3	2
Easy to "de-bond"	5		○	Δ	○	Δ			○	4	3	2
Functions in cold env.	5			●				○		5	5	5
Does not fall off in flight	10	●				●		○	Δ	5	5	5
Units		g	in.^2	C	lbs	lbs	in.	psi	in.			
Targets		<50	>3.0	-60	90	3g	<0.3	TBD	min			

● = 9 Srong Correlation
○ = 3 Medium Correlation
Δ = 1 Small Correlation
Blank No Correlation

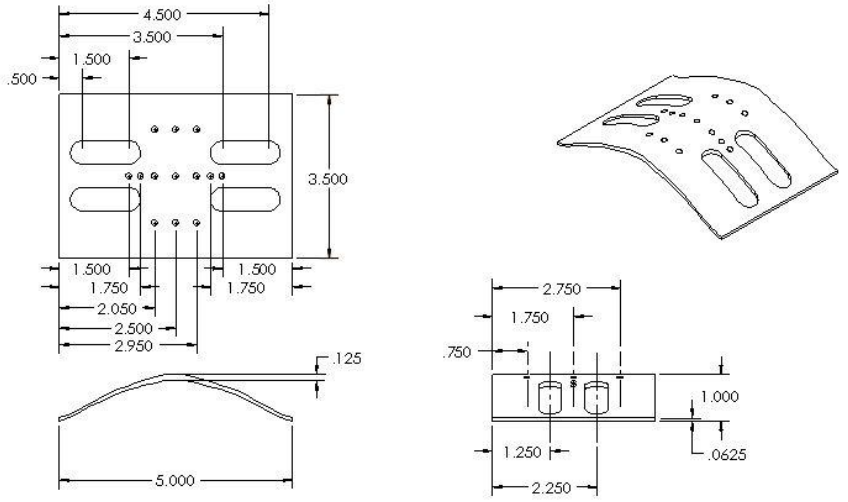
Appendix C: Solid Model Drawing Packet



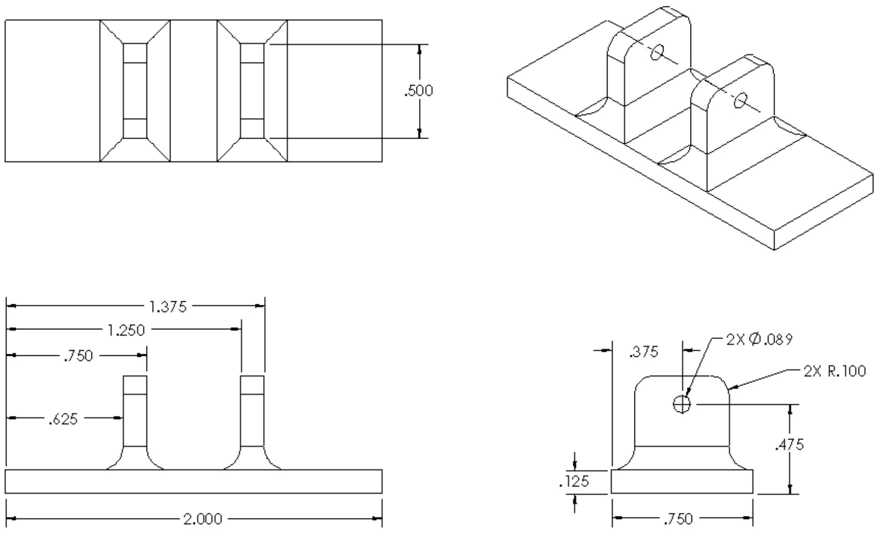
Project Name: Articulated Mounting For BLDS	
Date: 2/5/14	Part Name: Horizontal Slotted Pivot Foot
Units: Inches	Design Number: A
Volume: 0.423 Cubic Inches	Revision Number: 0
Material: 6061 Aluminum	Drawing Engineer: Chris Mazzucco
Scale: 1:2	Drawing Number: 1 of 1



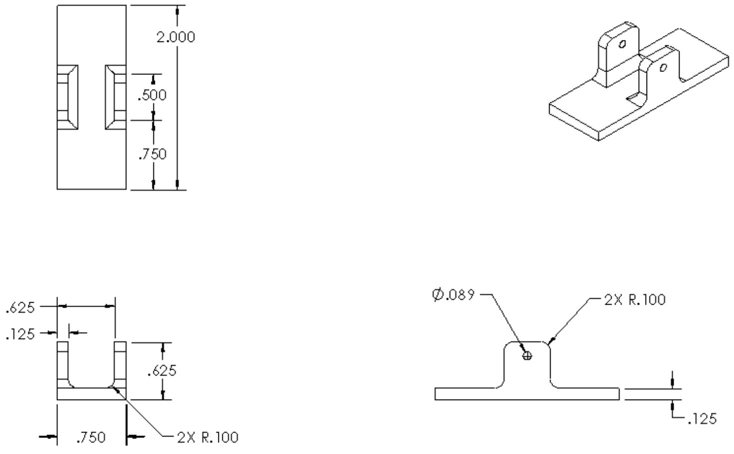
Project Name: Articulated Mounting For BLDS	
Date: 2/5/14	Part Name: Vertical Slotted Pivot Foot
Units: Inches	Design Number: B
Volume: 0.419 Cubic Inches	Revision Number: 0
Material: 6061 Aluminum	Drawing Engineer: Chris Mazzucco
Scale: 1:2	Drawing Number: 1 of 1



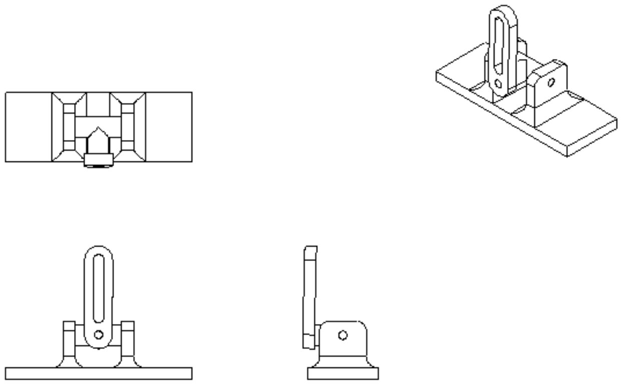
Project Name: Articulated Mounting For BLDS	
Date: 2/5/14	Part Name: Flex Foot
Units: Inches	Design Number: E
Volume: 0.575 Cubic Inches	Revision Number: 1
Material: 6061 Aluminum	Drawing Engineer: Mitch Conn
Scale: 1:2	Drawing Number: 1 of 1



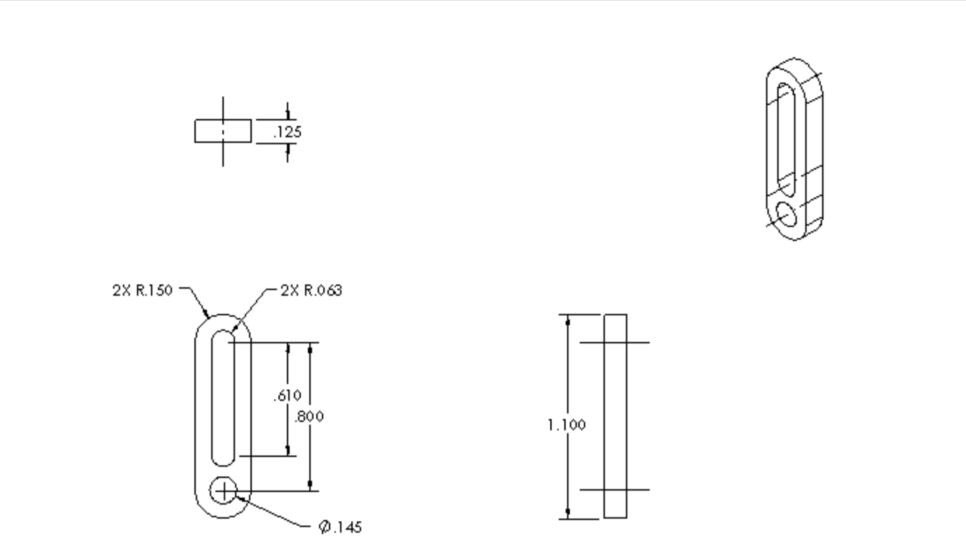
Project Name: Articulated Mounting For BLDS	
Date: 2/17/14	Part Name: T-Joint Foot V1
Units: Inches	Design Order: D.1.1
Volume: 0.247 Cubic Inches	Revision Number: 1
Material: 6061 Aluminum	Drawing Engineer: Mitch Conn
Scale: 1:2	Drawing Number: 1 of 4



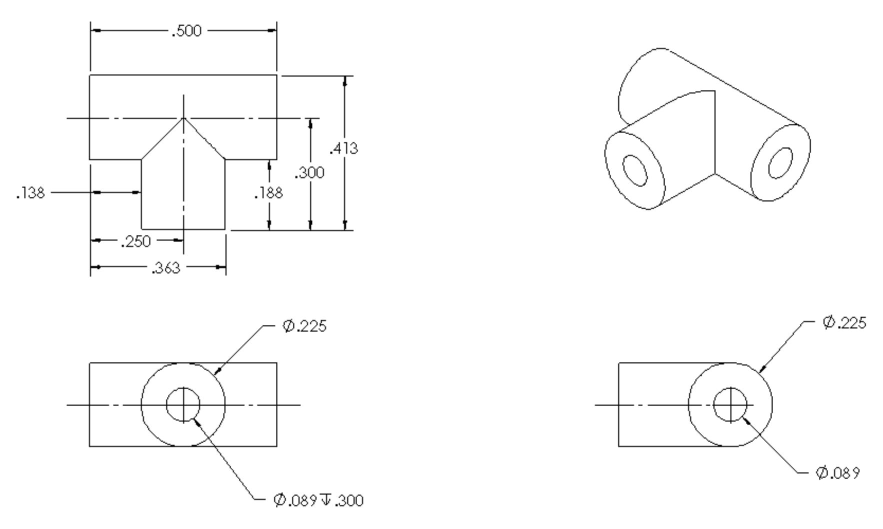
Project Name: Articulated Mounting For BLDS	
Date: 2/17/14	Part Name: T-Joint Foot V2
Units: Inches	Design Number: D.1.2
Volume: 0.247 Cubic Inches	Revision Number: 2
Material: 6061 Aluminum	Drawing Engineer: Chris Mazzucco
Scale: 1:2	Drawing Number: 1 of 1



Project Name: Articulated Mounting For BLDS	
Date: 2/17/14	Part Name: T-Joint Assembly
Units: Inches	Design Number: D
Volume: 0.298 Cubic Inches	Revision Number: 1
Material: 6061 Aluminum	Drawing Engineer: Mitch Conn
Scale: 1:2	Drawing Number: 4 of 4

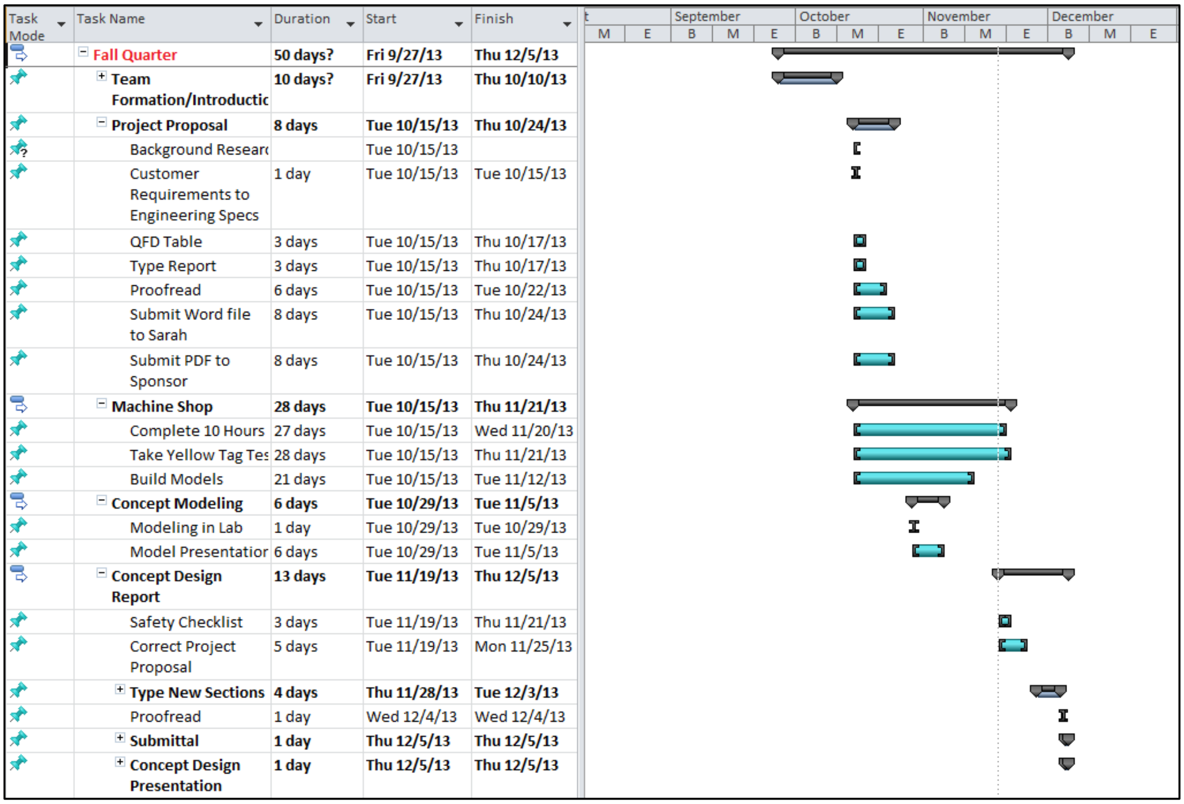


Project Name: Articulated Mounting For BLDS	
Date: 2/5/14	Part Name: T-Joint Slot Leg
Units: Inches	Design Number: D
Volume: 0.026 Cubic Inches	Revision Number: 0
Material: 6061 Aluminum	Drawing Engineer: Mitch Conn
Scale: 1:2	Drawing Number: 4 of 4

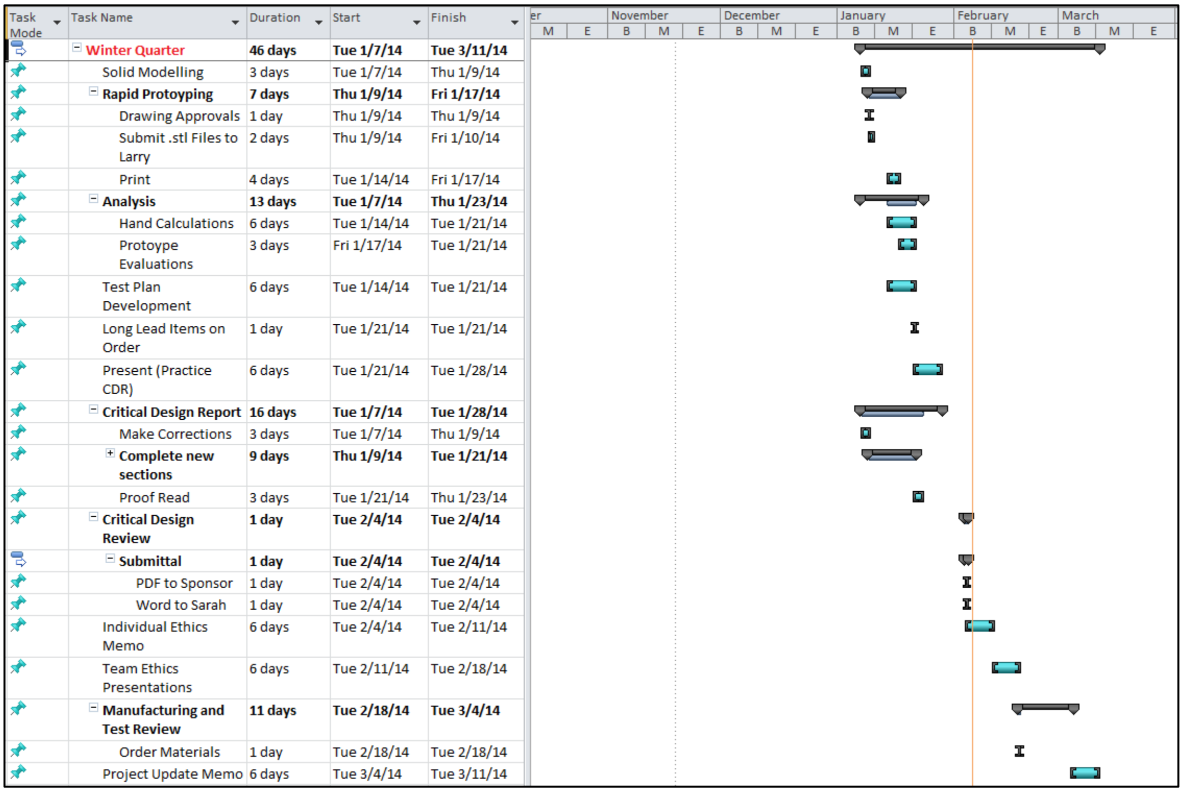


Project Name: Articulated Mounting For BLDS	
Date: 2/17/14	Part Name: T-Joint Hinge
Units: Inches	Design Number: D.2
Volume: 0.023 Cubic Inches	Revision Number: 0
Material: 6061 Aluminum	Drawing Engineer: Mitch Conn
Scale: 1:2	Drawing Number: 2 of 4

Appendix D: Gantt Chart



Task Mode	Task Name	Duration	Start	Finish
	Fall Quarter	**50 days?**	**Fri 9/27/13**	**Thu 12/5/13**
	Team Formation/Introductic	**10 days?**	**Fri 9/27/13**	**Thu 10/10/13**
	Project Proposal	**8 days**	**Tue 10/15/13**	**Thu 10/24/13**
	Background Researc		Tue 10/15/13	
	Customer Requirements to Engineering Specs	1 day	Tue 10/15/13	Tue 10/15/13
	QFD Table	3 days	Tue 10/15/13	Thu 10/17/13
	Type Report	3 days	Tue 10/15/13	Thu 10/17/13
	Proofread	6 days	Tue 10/15/13	Tue 10/22/13
	Submit Word file to Sarah	8 days	Tue 10/15/13	Thu 10/24/13
	Submit PDF to Sponsor	8 days	Tue 10/15/13	Thu 10/24/13
	Machine Shop	**28 days**	**Tue 10/15/13**	**Thu 11/21/13**
	Complete 10 Hours	27 days	Tue 10/15/13	Wed 11/20/13
	Take Yellow Tag Tes	28 days	Tue 10/15/13	Thu 11/21/13
	Build Models	21 days	Tue 10/15/13	Tue 11/12/13
	Concept Modeling	**6 days**	**Tue 10/29/13**	**Tue 11/5/13**
	Modeling in Lab	1 day	Tue 10/29/13	Tue 10/29/13
	Model Presentatior	6 days	Tue 10/29/13	Tue 11/5/13
	Concept Design Report	**13 days**	**Tue 11/19/13**	**Thu 12/5/13**
	Safety Checklist	3 days	Tue 11/19/13	Thu 11/21/13
	Correct Project Proposal	5 days	Tue 11/19/13	Mon 11/25/13
	Type New Sections	**4 days**	**Thu 11/28/13**	**Tue 12/3/13**
	Proofread	1 day	Wed 12/4/13	Wed 12/4/13
	Submittal	**1 day**	**Thu 12/5/13**	**Thu 12/5/13**
	Concept Design Presentation	**1 day**	**Thu 12/5/13**	**Thu 12/5/13**



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	Winter Quarter	**46 days**	**Tue 1/7/14**	**Tue 3/11/14**
	Solid Modelling	3 days	Tue 1/7/14	Thu 1/9/14
	Rapid Protoyping	**7 days**	**Thu 1/9/14**	**Fri 1/17/14**
	Drawing Approvals	1 day	Thu 1/9/14	Thu 1/9/14
	Submit .stl Files to Larry	2 days	Thu 1/9/14	Fri 1/10/14
	Print	4 days	Tue 1/14/14	Fri 1/17/14
	Analysis	**13 days**	**Tue 1/7/14**	**Thu 1/23/14**
	Hand Calculations	6 days	Tue 1/14/14	Tue 1/21/14
	Protoype Evaluations	3 days	Fri 1/17/14	Tue 1/21/14
	Test Plan Development	6 days	Tue 1/14/14	Tue 1/21/14
	Long Lead Items on Order	1 day	Tue 1/21/14	Tue 1/21/14
	Present (Practice CDR)	6 days	Tue 1/21/14	Tue 1/28/14
	Critical Design Report	**16 days**	**Tue 1/7/14**	**Tue 1/28/14**
	Make Corrections	3 days	Tue 1/7/14	Thu 1/9/14
	Complete new sections	**9 days**	**Thu 1/9/14**	**Tue 1/21/14**
	Proof Read	3 days	Tue 1/21/14	Thu 1/23/14
	Critical Design Review	**1 day**	**Tue 2/4/14**	**Tue 2/4/14**
	Submittal	**1 day**	**Tue 2/4/14**	**Tue 2/4/14**
	PDF to Sponsor	1 day	Tue 2/4/14	Tue 2/4/14
	Word to Sarah	1 day	Tue 2/4/14	Tue 2/4/14
	Individual Ethics Memo	6 days	Tue 2/4/14	Tue 2/11/14
	Team Ethics Presentations	6 days	Tue 2/11/14	Tue 2/18/14
	Manufacturing and Test Review	**11 days**	**Tue 2/18/14**	**Tue 3/4/14**
	Order Materials	1 day	Tue 2/18/14	Tue 2/18/14
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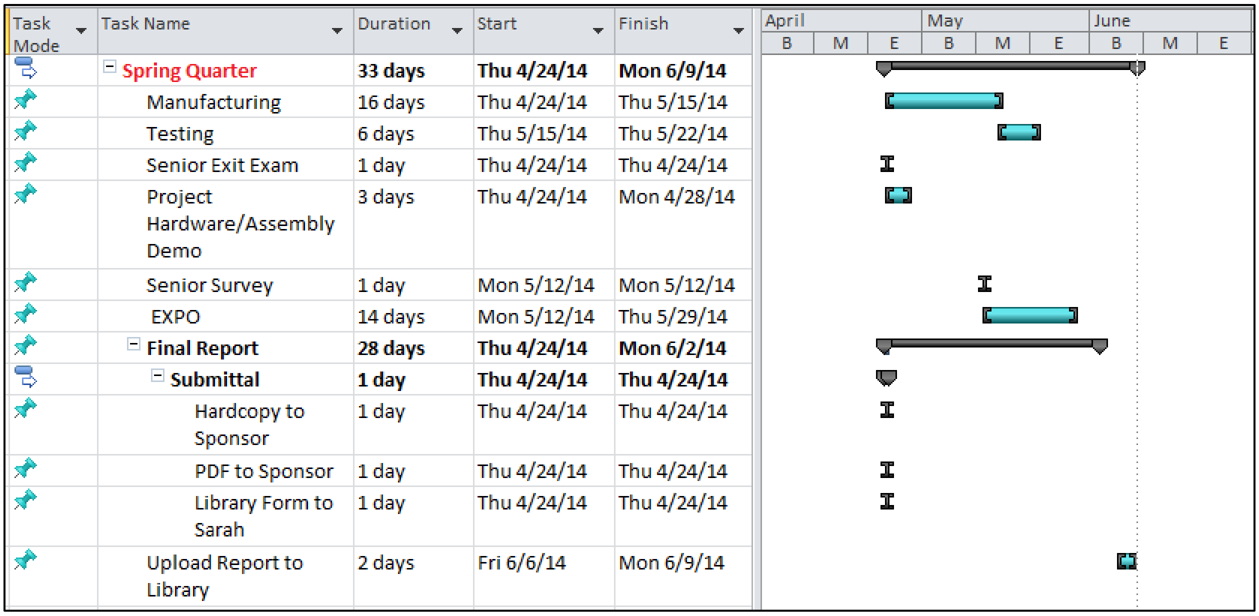

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	Manufacturing	16 days	Thu 4/24/14	Thu 5/15/14
	Testing	6 days	Thu 5/15/14	Thu 5/22/14
	Senior Exit Exam	1 day	Thu 4/24/14	Thu 4/24/14
	Project Hardware/Assembly Demo	3 days	Thu 4/24/14	Mon 4/28/14
	Senior Survey	1 day	Mon 5/12/14	Mon 5/12/14
	EXPO	14 days	Mon 5/12/14	Thu 5/29/14
	Final Report	**28 days**	**Thu 4/24/14**	**Mon 6/2/14**
	Submittal	**1 day**	**Thu 4/24/14**	**Thu 4/24/14**
	Hardcopy to Sponsor	1 day	Thu 4/24/14	Thu 4/24/14
	PDF to Sponsor	1 day	Thu 4/24/14	Thu 4/24/14
	Library Form to Sarah	1 day	Thu 4/24/14	Thu 4/24/14
	Upload Report to Library	2 days	Fri 6/6/14	Mon 6/9/14

Appendix E: Safety Hazard Checklist

SENIOR PROJECT CONCEPTUAL DESIGN REVIEW HAZARD IDENTIFICATION CHECKLIST

Y	N	
☐	■	Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
☐	■	Can any part of the design undergo high accelerations/decelerations?
☐	■	Will the system have any large moving masses or large forces?
☐	■	Will the system produce a projectile?
☐	■	Would it be possible for the system to fall under gravity creating injury?
☐	■	Will a user be exposed to overhanging weights as part of the design?
☐	■	Will the system have any sharp edges?
☐	■	Will all the electrical systems properly grounded?
☐	■	Will there be any large batteries or electrical voltage in the system above 40 V either AC or DC?
☐	■	Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
☐	■	Will there be any explosive or flammable liquids, gases, dust fuel part of the system?
☐	■	Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
☐	■	Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☐	■	Can the system generate high levels of noise?
☐	■	Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures ,etc…?
■	☐	Will the system easier to use safely than unsafely?
☐	■	Will there be any other potential hazards not listed above? If yes, please explain below?

Appendix F: Analysis

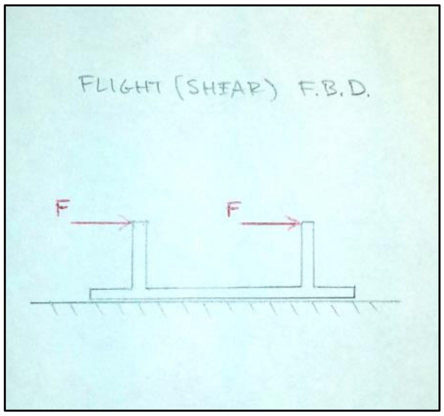
Design A and B: Pivoting Slotted Feet

- Material: 6061-T6 Aluminum
- Max Shear: 480 psi
- Max Bending: 3840 psi
- Buckling P_{cr}: 66825 psi
- Deflection: Negligible

1. ***Analysis as Beam in Bending***

$F = 10$ lb
$V = 10$ lb
$M = 7.5$ lb-in.
$A = 0.09375$ in^2
$I = 1.2207$ E-4 in^4
$c = 0.0625$ in.

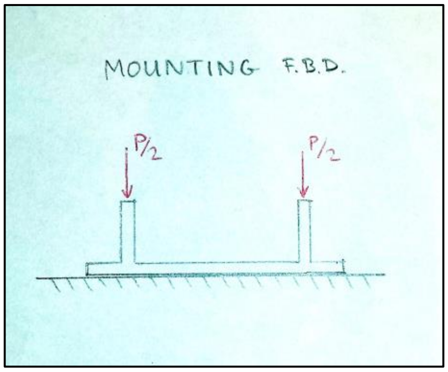
Equations Used: $\boldsymbol{\tau_{max} = \frac{3V}{2A}, \sigma = \frac{Mc}{I}}$



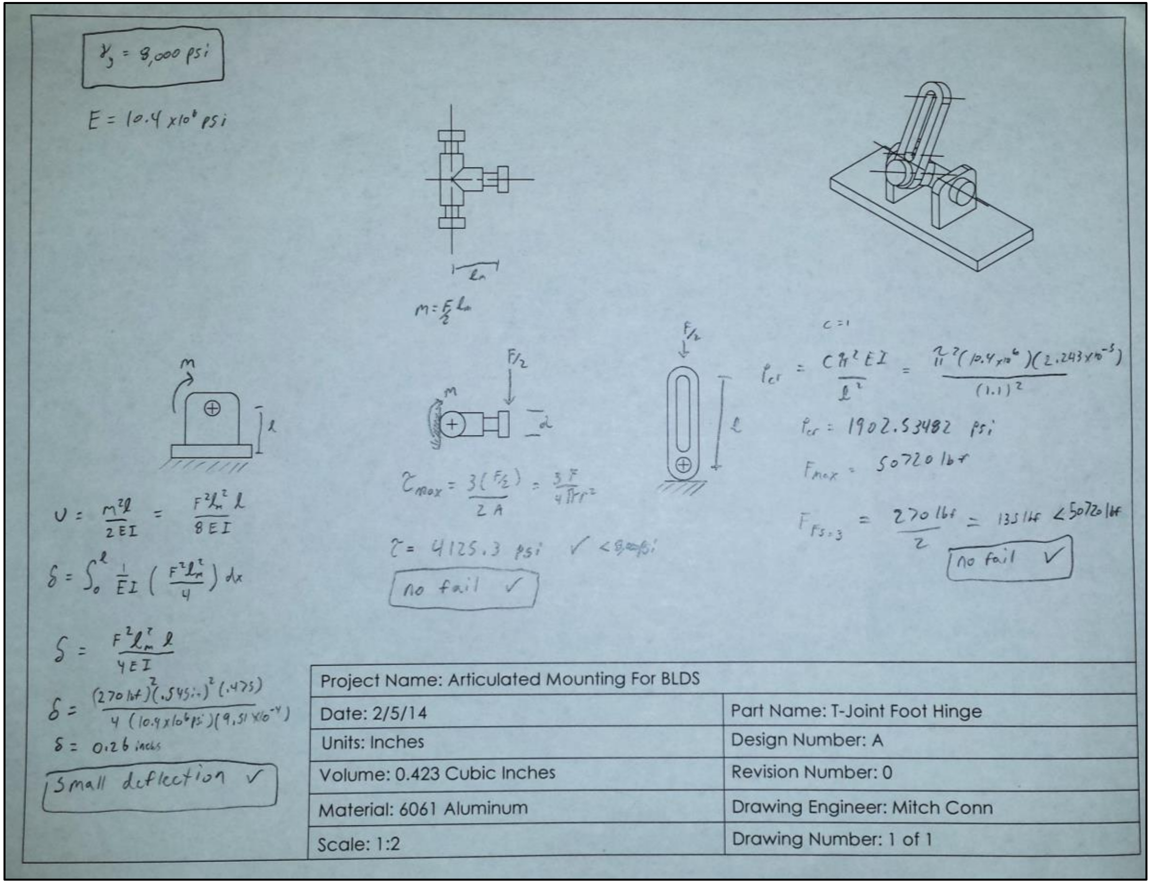
2. ***Analysis as Column with Central Loading***

$P = 90$ lbf
$l = 0.75$ in.
$I = 1.2207$ E-4 in^4
$A = 0.09375$ in^2
$E = 10.4$ Mpsi
$C = 4$ (fixed-fixed)

Equation Used: $\boldsymbol{P_{cr} = \frac{C\pi^2 EI}{l}}$



Design D: Locking T-Joint Foot Hand Calculations



$$\boxed{\tau_y = 8{,}000\ \text{psi}}$$

$E = 10.4\times10^{6}$ psi

$m = \frac{F}{2} l_m$

$$U = \frac{m^2 l}{2EI} = \frac{F^2 l_m^2 l}{8EI}$$

$$\delta = \int_0^l \frac{1}{EI}\left(\frac{F^2 l_m^2}{4}\right)dx$$

$$\delta = \frac{F^2 l_m^2 l}{4EI}$$

$$\delta = \frac{(270\ \text{lbf})^2(.545\ \text{in})^2(.475)}{4\,(10.4\times10^{6}\ \text{psi})(9.51\times10^{-4})}$$

$\delta = 0.26$ inches

$\boxed{\text{Small deflection ✓}}$

$$\tau_{max} = \frac{3(F/2)}{2A} = \frac{3F}{4\pi r^2}$$

$\tau = 4125.3$ psi ✓ $< 8{,}000$ psi

$\boxed{\text{no fail ✓}}$

$c = 1$

$$P_{cr} = \frac{C\pi^2 EI}{l^2} = \frac{\pi^2(10.4\times10^{6})(2.243\times10^{-5})}{(1.1)^2}$$

$P_{cr} = 1902.53482$ psi

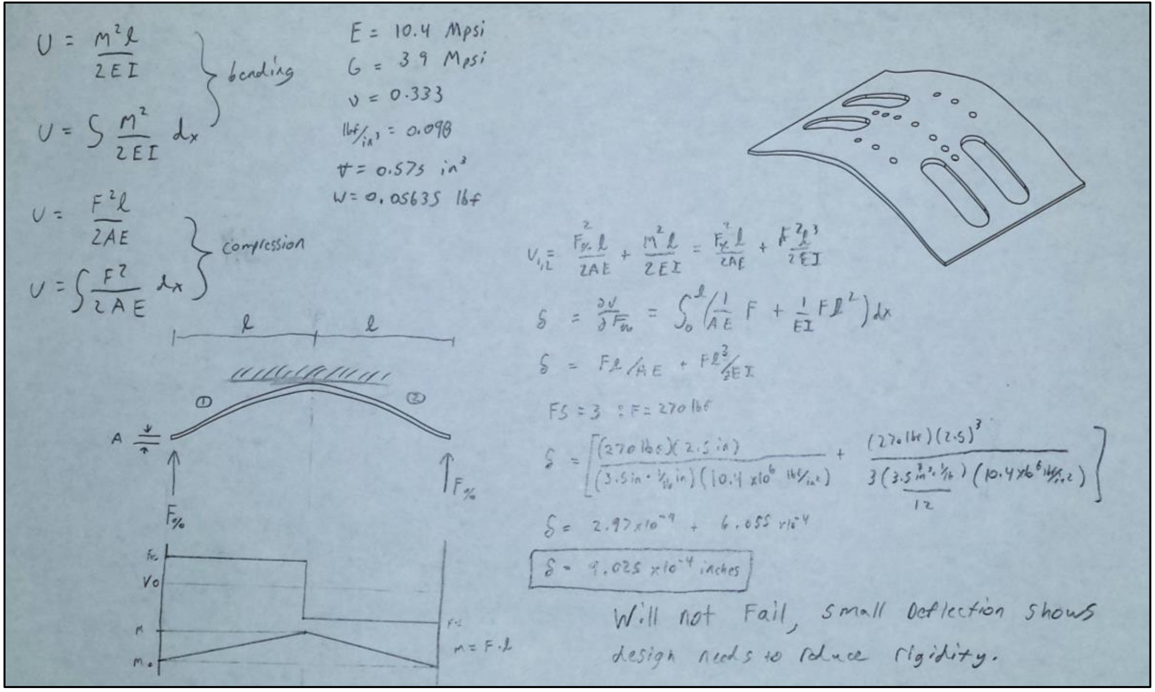
$F_{max} = 50720$ lbf

$$F_{FS=3} = \frac{270\ \text{lbf}}{2} = 135\ \text{lbf} < 50720\ \text{lbf}$$

$\boxed{\text{no fail ✓}}$

Project Name: Articulated Mounting For BLDS	
Date: 2/5/14	Part Name: T-Joint Foot Hinge
Units: Inches	Design Number: A
Volume: 0.423 Cubic Inches	Revision Number: 0
Material: 6061 Aluminum	Drawing Engineer: Mitch Conn
Scale: 1:2	Drawing Number: 1 of 1

Design E: Large Flex Foot Hand Calculations



$$\left.\begin{aligned} U &= \frac{M^2 l}{2EI} \\ U &= \int \frac{M^2}{2EI}\,dx \end{aligned}\right\}\ \text{bending}$$

$E = 10.4$ Mpsi

$G = 3.9$ Mpsi

$\nu = 0.333$

$\text{lbf}/\text{in}^3 = 0.098$

$V = 0.575\ \text{in}^3$

$W = 0.05635$ lbf

$$\left.\begin{aligned} U &= \frac{F^2 l}{2AE} \\ U &= \int \frac{F^2}{2AE}\,dx \end{aligned}\right\}\ \text{compression}$$

$$U_{1,2} = \frac{F_{\%}^2 l}{2AE} + \frac{M^2 l}{2EI} = \frac{F_{\%}^2 l}{2AE} + \frac{F^2 l^3}{2EI}$$

$$\delta = \frac{\partial U}{\partial F_{\%}} = \int_0^l \left(\frac{1}{AE}F + \frac{1}{EI}F l^2\right)dx$$

$$\delta = Fl/AE + Fl^3/3EI$$

$FS = 3 \therefore F = 270$ lbf

$$\delta = \left[\frac{(270\ \text{lbf})(2.5\ \text{in})}{(3.5\ \text{in}\cdot\frac{1}{16}\ \text{in})(10.4\times10^{6}\ \text{lbf}/\text{in}^2)} + \frac{(270\ \text{lbf})(2.5)^3}{3\left(\frac{3.5\ \text{in}^3\cdot\frac{1}{16}}{12}\right)(10.4\times10^{6}\ \text{lbf}/\text{in}^2)}\right]$$

$\delta = 2.97\times10^{-7} + 6.055\times10^{-4}$

$$\boxed{\delta = 9.025\times10^{-4}\ \text{inches}}$$

Will not Fail, small Deflection shows design needs to reduce rigidity.

Thread Strength Analysis: 4x40 6061 Aluminum Threads

Governing Equations:

Max Pullout Force

$$F = \pi D L \tau$$

Max Torque based on Force

T = cDF

F = (π)(0.112 in)(30000 psi)(0.125 in)

F = 1319.47 lb$_f$

T = (1.10 $_{\text{friction(dry)}}$)(0.112 in)(1319.47 lb$_f$)

T = 162.56 in-lb$_f$

Appendix G: Bill of Materials

BLDS Feet Bill of Materials

Item	Quantity	Source	Price
Type 316 Stainless Steel Button-Head Socket Cap Screw, 4-40 Thread, **1/4" Length**	1 (Pack of 50)	98164A061 (McMaster)	$2.77
Multipurpose 6061 Aluminum, 1/8" Thick, 3" Width, **2 ft. Length**	1	8975K83 (McMaster)	$6.99
Multipurpose 6061 Aluminum, Rectangular Bar, 1" x 1", **2 ft. Length**	3	9008K14 (McMaster)	$38.67
Rapid Prototyping Session #1	1	Cal Poly Stratasys	$134.36
Rapid Prototyping Session #2	1	Cal Poly Eden 250	$114.91
Zinc Lock Washers, #6, Ext. Tooth	1 (Pack of 20)	Home Depot	$1.98
		Total:	**$299.68**