F-35 Vane Box Handling Tool Design

Final Design Report

Magellan Aerospace Winnipeg

MECH 4860 Engineering Design

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Date of Submission: Dec.1/2014

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December 1, 2014

Dr. Paul Labossiere
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Dear Dr. Labossiere,

Enclosed within the final design report is the detailed design for the *F-35 Vane Box Handling Tool Design* in collaboration with Magellan Aerospace.

The team has designed a handling tool for supporting the F-35 vane box assembly process. Our handling tool supports the vane box with retractable plugs, while providing rotational freedom about the horizontal axis through a shaft bearing system. Furthermore, the handling tool provides pneumatic height adjustability, and rotational freedom about the vertical axis with a turntable.

This report has been submitted to our client, Magellan Aerospace and it marks the completion of the final design report. Magellan Aerospace will take the lead in the next phase for implementing the handling tool design into their current assembly process. If you have any questions or concerns regarding our project, please feel free to contact me at

Sincerely,

Eric Cheung
Team Lead

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Abstract

Magellan Aerospace manufactures a critical component in the F-35B Lightning II fighter jet known as the vane box. The vane box is essential for the F-35 fighter jet to achieve a short take off and vertical landing. The vane box is assembled from four aluminum forgings to very tight tolerances and is currently lifted and rotated by hand. To avoid damaging the vane box or injuring their technicians, Magellan Aerospace has requested a handling tool design that will allow the vane box orientation to be manipulated.

The final design of the F-35 vane box handling tool can be categorized into five sections. The first section is the base frame, which provides stability with a wide H-shape configuration and mobility with shock absorbing casters. The second section is the central axle assembly, which provides height adjustability through pneumatic cylinders. In addition, a turntable on the central axle assembly allows the vane box to be rotated about the vertical axis. Next, the main frame utilizes a shaft and spline mechanical system to offer the vane box 360° of rotational freedom about the horizontal axis. Also, the plug actuation mechanism interfaces with the vane box to secure it onto the handling tool. This is achieved using a combination of springs, pneumatic cylinders, and tapered Teflon® plugs. Lastly, the pneumatic control system incorporates dial gauges, valves, tubes, and switches to actuate the pneumatic cylinders for the central axle assembly and plug actuation mechanism.

With a projected cost of $13,820.60, Magellan Aerospace can implement our handling tool design to fulfill current and future orders of the F-35B vane box safely, ergonomically, and promptly.

1.0 Introduction

Magellan Aerospace is an aerospace manufacturing and design firm, with offices located internationally. They often perform contract work, manufacturing high-precision components for clients such as Lockheed-Martin and Boeing. One of the many parts manufactured by Magellan Aerospace is the vane box for the F-35 fighter jet, a vital component in providing the jet's Short Take-Off, Vertical Landing (STOVL) capability. The complex geometry of the vane box, coupled with a high weight and difficulty in accessing critical areas during assembly; indicates that a custom handling tool is required for this process.

1.1 Construction Process

The F-35 vane box consists of four aluminum forgings that need to be assembled together [1]. The aluminum forgings have very tight tolerances and assembly requires each forging to be located relative to the others for fastener installation. The current assembly method requires four operators to simultaneously lift the four corners from a workbench onto a handling tool. Once the vane box is on the handling tool, the wet assembly begins. Wet assembly refers to when the fasteners and mating surfaces are covered in a sealant to prevent moisture sitting in between parts. After the wet assembly, the vane box is removed from the handling tool and transported to a paint booth to be painted. The vane box is returned to the assembly area after being painted and the final assembly begins. The vane box is placed onto the handling tool again for the final assembly.

1.2 Problem Statement

The team must design a handling tool capable of supporting the vane box. This tool must allow the operator to safely manipulate the vane box to numerous positions, which will provide access to all parts of the vane box assembly. Therefore, the tool must provide the following:

- Be able to support the weight of the vane box
- Enable the vane box to rotate
- Be able to reduce the weight that the operator must support while transporting the vane box
- Prevent damage to the vane box, or injury to the operator through active and passive safety systems

1.3 Project Objectives and Needs

The objective of the design team is to provide a complete design document, ready for the engineers at Magellan Aerospace to review and implement. By the end of this project we will provide Magellan Aerospace with a full set of technical engineering drawings, from which their technicians can manufacture and assemble each part of the handling tool as required. Along with the drawings, a manufacturing guide will be supplied to aid the assembly technicians in the manufacture of the handling tool.

In addition to the objectives, a list of needs was generated with the client, Magellan Aerospace, and is presented in TABLE I [2]. These needs are organized into five categories: structural, health and safety, portability, and quality. The end goal is to fulfill all of these needs with an optimized handling tool design.

TABLE I: PROJECT NEEDS

Section		Need	Imp
1		**Structural Needs**	
1.1		Handling tool can support the vane box rigidly	5
	1.1.1	Handling tool can support the vane box securely	5
	1.1.2	Handling tool can support the vane box safely	5
1.2		Handling tool is stable	5
	1.2.1	Handling tool can restore itself from being tilted at high angles	3
	1.2.2	Handling tool remains balanced when loads are off centre	5
1.3		Handling tool is reliable	5
2		**Health and Safety Needs**	
2.1		Handling tool has minimal pinch points	3
	2.1.1	Handling tool prevents access to pinch points by the operator and bystanders.	4
	2.1.2	Handling tool indicates all pinch points	3
2.2		Handling tool follows Manitoba Workplace Health and Safety codes	5
	2.2.1	Handling tool incorporates factors of safety	5
	2.2.2	Handling tool uses materials allowable by Health and Safety Code	5
2.3		Handling tool is safe to operate	5
	2.3.1	Handling tool movement is easily controlled by the operator	3
	2.3.2	Handling tool motion can be lockable in any position	4
3		**Assembly Needs**	
3.1		Handling tool can be used during assembly of the vane box	5
	3.1.1	Handling tool can be used during wet assembly	5
	3.1.2	Handling tool can be used during final assembly	5
3.2		Handling tool contains room for all components to be installed	5
3.3		Handling tool makes assembly faster than the current method	3
3.4		Handling tool requires fewer people than the current method	3
3.5		Handling tool allows full access to the vane box	5
	3.5.1	Handling tool rotates the vane box	5
	3.5.2	Handling tool gives clearances for the assembler and their tools	5
	3.5.3	Handling tool allows repositioning of the vane box without adjusting the connection between the two	5
	3.5.4	Handling tool allows the operator to remain in a single position	4
3.6		Handling tool makes assembly easy for the technician	4
	3.6.1	Handling tool allows fastener installation on the box	5
	3.6.2	Handling tool allows for ergonomic assembly for the operator	4

Section	Need	Imp
3.6.3	Handling tool is easy to operate	3
3.7	Handling tool raises and lowers vane box from work bench	1
4	**Portability Needs**	
4.1	Handling tool can be moved around the factory	5
4.1.1	Handling tool can be moved on a concrete surface	5
4.1.2	Handling tool can support the vane box while moving over a crack in the floor	5
4.1.3	Handling tool is stable when moving	5
5	**Quality**	
5.1	Handling tool handles the vane box without introducing foreign object debris (FOD) into the environment	5
5.1.1	Handling tool is resistant to degradation and corrosion	5
5.1.2	Handling tool prevents components from being misplaced	2
5.2	Handling tool is aesthetically pleasing	2
5.3	Handling tool uses materials that are non-damaging to the vane box	5

1.4 Project Constraints and Limitations

Our team and our client identified the constraints and limitations for this project. Our constraints are grouped into three categories: time, finances, and codes and standards. Time is a major constraint because production of this design is scheduled to begin in early 2015 and the final design report is to be completed by December 1st, 2014. Although there are no financial constraints set by Magellan Aerospace, there is a $300 limit for printing reports and posters. The primary safety code and standard our team must abide by is the Manitoba Workplace Health and Safety M.R. 217/2006 [3].

In contrast to the constraints, the limitations for this project are determined as materials and foreign object debris (FOD). The material for the vane box handling tool must be non-corroding and strong enough to prevent degradation of performance over time. Additionally, FOD may not come into contact with the vane box assembly due to catastrophic consequences that arise from damaging the vane box assembly.

2.0 Final Design and Analysis

A detailed and concise concept development process was conducted to converge on an optimized design that satisfied the problem statement. Details of the concept generation and selection are located in Appendix A. This section will provide details of the final design, describe the critical components, explain the operating procedure, and an overview of cost considerations.

2.1 Features of Final Design

Our team's final F-35 Vane Box Handling Tool design is shown supporting the vane box in Figure 1.

Figure 1: F-35 vane box handling tool supporting vane box

Overall specifications of the handling tool design are tabulated in TABLE II. The main features of the final design include the base frame, central axle assembly, main frame, plug actuation mechanism, and pneumatic system.

TABLE II: F-35 HANDLING TOOL FINAL SPECIFICATIONS

Specification	Value
Height [in]	70.125
Width [in]	72.75
Length [in]	72.75
Weight [lb]	251.42
Degrees of Freedom	5

2.1.1 Base Frame

The base frame of the F-35 vane box handling tool design is the critical load-bearing assembly. The base frame contains three structural I-beams; the two lateral beams are bolted to the top of the central beam through a series of fasteners. Each of the four corners of the base frame is attached to a shock-absorbing caster where two of the casters swivel, and the other two are fixed. On the side with the swivelling casters there is a friction floor lock connected to the end I-beam via the fastener, the depth of which adjusts for the height of the casters. The base frame design can be seen in Figure 2. The base frame area measures approximately 2 [m^2] and with a large separation distance between the two lateral supports, there is substantial space for the operator to get close to the vane box assembly. 6061-T6 aluminum was used wherever possible, although the sourced casters, floor lock and bolts can vary in composition depending on the supplier used.

Figure 2: Base H-frame assembly

2.1.1.1 Structural Members

The load-bearing frame consists of 4 [in] x 4 [in], 6061-T6 aluminum American Standard I-beams. Each of the three I-beams is 72 3/4 [in] long, and the flanges and web are 0.290 [in] and 0.313 [in] thick, respectively. The 4 [in] base width is well suited to fit the casters, which have a baseplate length of 4 [in] in the direction of travel of the non-swivel casters. Since the dimension of the I-beam is constrained by this limit, it is not necessary to use a stiffer material than 6061-T6 aluminum, which will be validated by finite element analysis (FEA).

The I-beam shape was chosen because it allows for easy access to all bolt locations for the gussets and casters on the base frame. This means that the bolts can be easily replaced if needed, reducing the necessary downtime considerably over hollow tube structures, and being lighter than a solid aluminum block. Figure 3 shows the cross section of the American Standard I-beam shape.

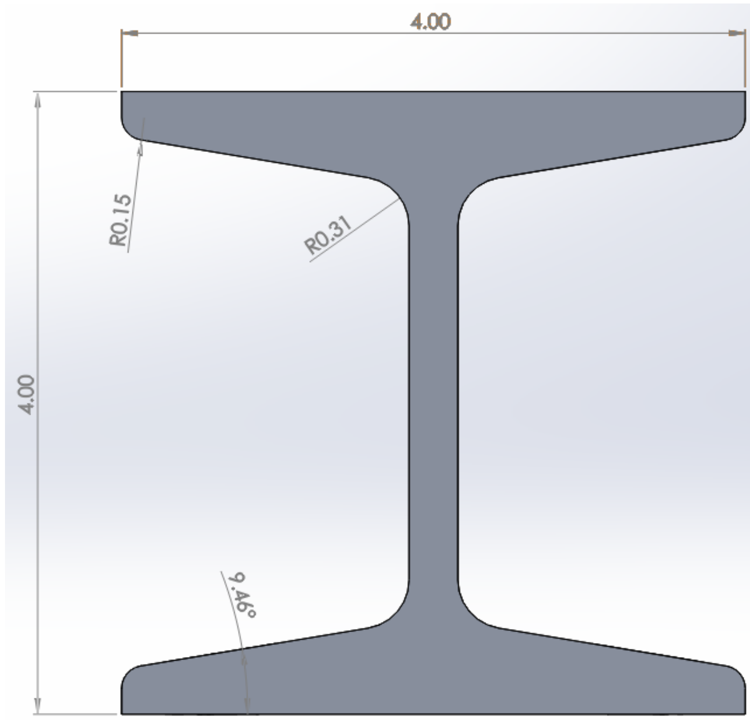

Figure 3: I-Beam cross section

The two lateral supports are identical with four 0.28 [in] holes on the bottom flanges at each end for the attachment of casters. Furthermore, twelve 0.28 [in] holes are located in the centre of the lateral I-beams on the bottom flange shown in Figure 4. The centre holes allow for the attachment of the gusset plate and friction floor lock. The central support has four 0.28 [in] holes in the top flange at both ends, for a total of eight holes, for attaching the lateral I-beams. In addition, on the top flange of the central I-beam, eight holes drilled with an H drill bit are located at the centre for attaching the central axle assembly.

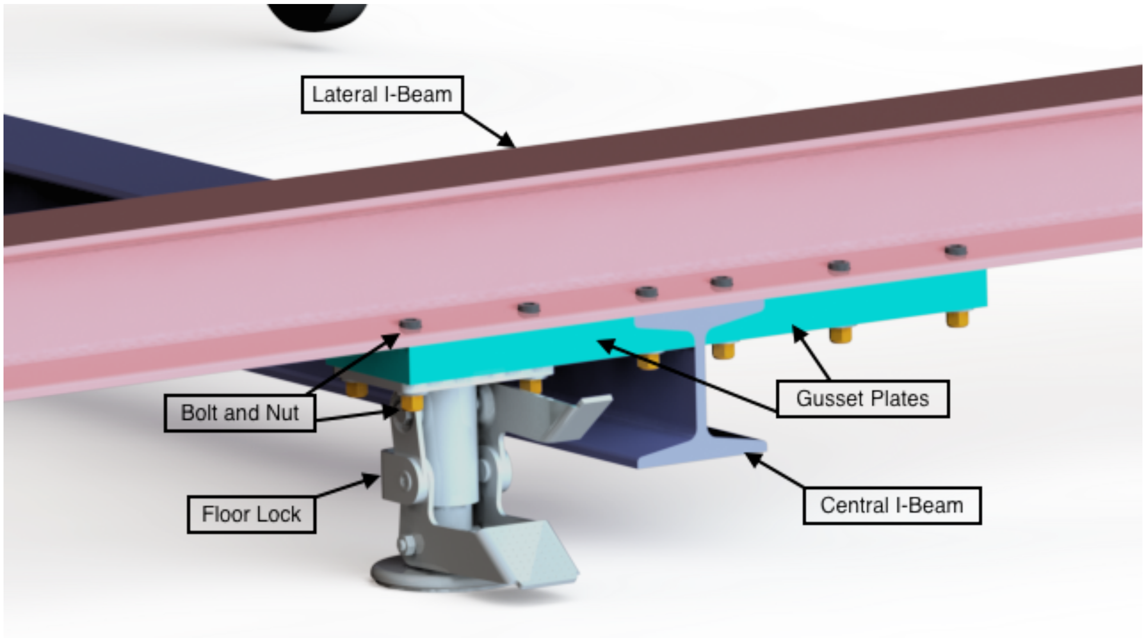

Figure 4: Base H-Frame with I-Beams highlighted

2.1.1.2 Attachment Methods

The entire base frame assembly is constructed through the use of gusset plates and is attached to the I-beams through standard 5/16 [in] bolts. This method was chosen because aluminum is more difficult to weld than either steel or titanium, and the height restrictions of the handling tool necessitate the use of an under-slung central I-beam. The gusset plate is fabricated from1/2 [in] thick 6061-T6 aluminum, with six 0.28 [in] holes for the I-beam attachment, and measuring 8.625 [in] x 4.000 [in]. To interface with the I-beam, the top gusset contour matches that of the I-beam. As a visual aid, Figure 5 displays a zoomed in view of the gusset plate to provide a better understanding.

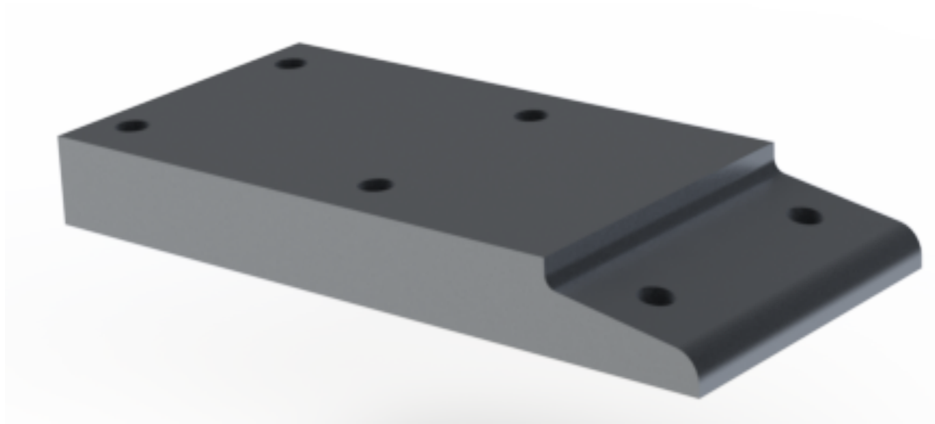

Figure 5: Custom gusset plate

18-8 steel was chosen as the material for the bolts, as aluminum bolts are more expensive and not as strong. 18-8 steel is appropriate because it exhibits high yield strength and is more ductile than other steels; reducing wear on the aluminum components. Inner-hex head bolts were chosen to provide consistency with the rest of the design. These bolts require counterbored holes due to the shape of the American Standard I-beam. Nylon locking nuts and washers are used to secure the end of the bolts in place.

2.1.1.3 Ground Interaction

The handling tool's only source of contact with the ground is through the base frame. The two ground contact points are the casters and the floor lock. The casters selected for this design contain a layer of plastic and flexible wheels, allowing the caster to absorb some of the shock of any impacts with inconsistencies in the floor surface or other structures. Therefore, the handling tool experiences a lower impact load from such events, reducing the chance of a sudden failure after an impact event. A caster mounting plate allows the caster to be fastened on to the I-beams. The wheels of the casters have a 5 [in] diameter, and are rated up to a load of 485 [lb] each.

The floor lock chosen by the group for this design uses a high-friction pad on the end of a spring-loaded lever. This allows the operator to easily lock the assembly tool in place when it is in position. As recommended by the supplier, McMaster-Carr [4], only one floor lock is used because it is not designed to carry any load from the handling tool.

2.1.1.4 FEA

A model of the central I-beam structure was generated for FEA. This structural member is the location at which the full load of the assembly tool is carried, and where the maximum stress will be located. The model was fixed at the hole locations where the central I-beam would be attached to the lateral I-beams. Figure 6 shows the mesh of the structural member. An h-adaptive process was utilized to provide accurate results at all points of the beam.

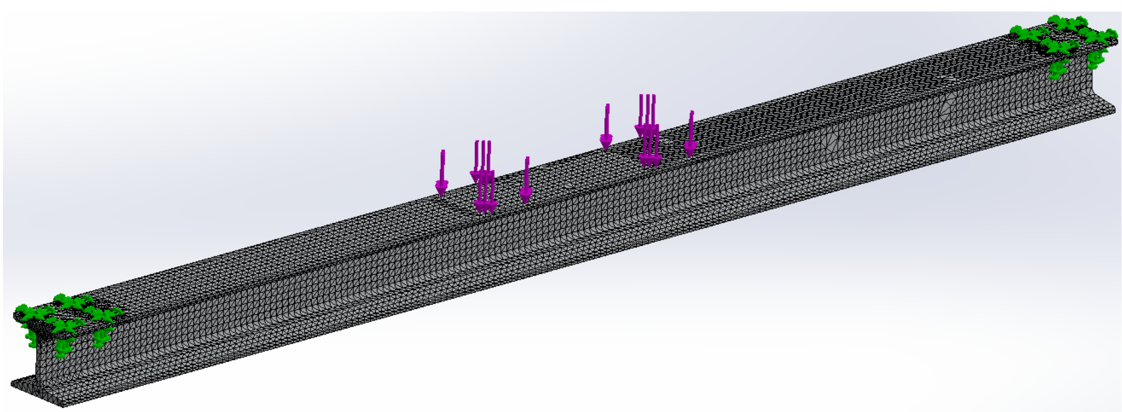

Figure 6: I-beam mesh detail

This mesh was then used to generate three sets of data: von Mises stress, displacement, and a convergence plot. As seen in Figure 7 the maximum stress is located at the fasteners as anticipated. This was expected because all the forces are transferred through the fasteners. The max stress experienced is 1.37 x 10^7 [N/m^2] located at the edge of the fasteners, which generates a yield and ultimate safety factor of approximately 20 and 22, respectively. The results prove that the central I-beam satisfies the yield stress safety factor requirement of 3, and ultimate stress safety factor requirement of 5.

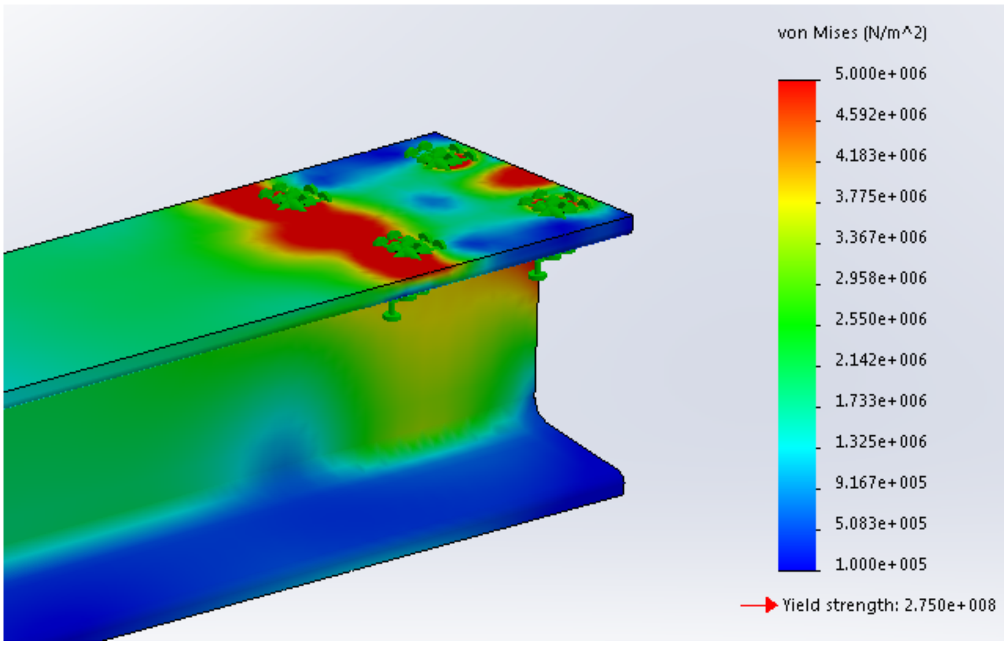

Figure 7: Centre I-beam von Mises stress distribution at high stress concentration area

Figure 8 verifies that the maximum deflection occurs at the very centre of the I-beam. The largest deflection experienced by the structure is 0.00839 [in], which is well within tolerable limits for this structural member.

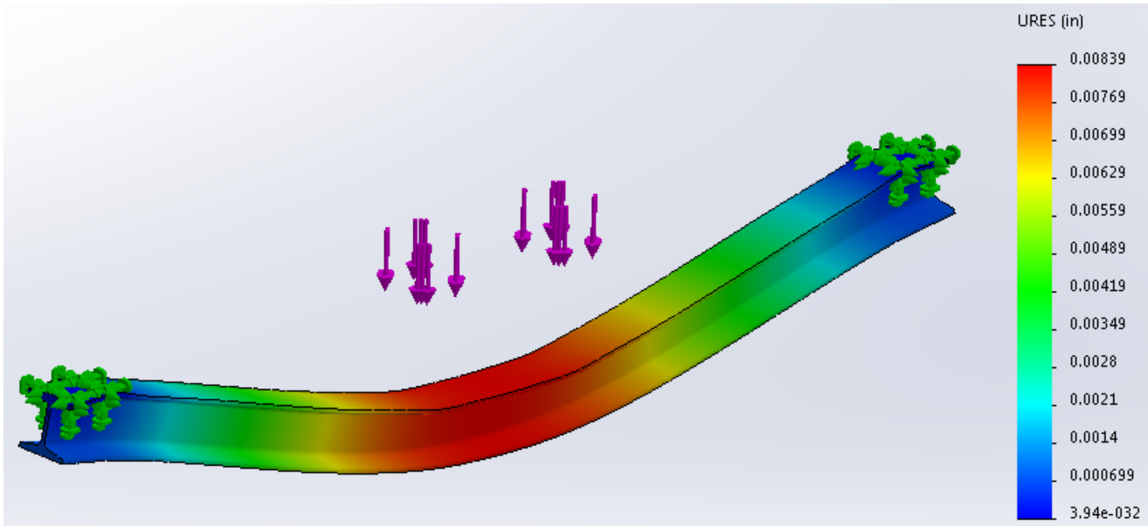

Figure 8: Centre I-beam max displacement distribution at a scale of 867:1

A convergence plot was generated from the h-adaptive analysis and is shown in Figure 9. From the convergence graph, the max von Mises stress converges to a normalized value of 1 as the mesh size decreases.

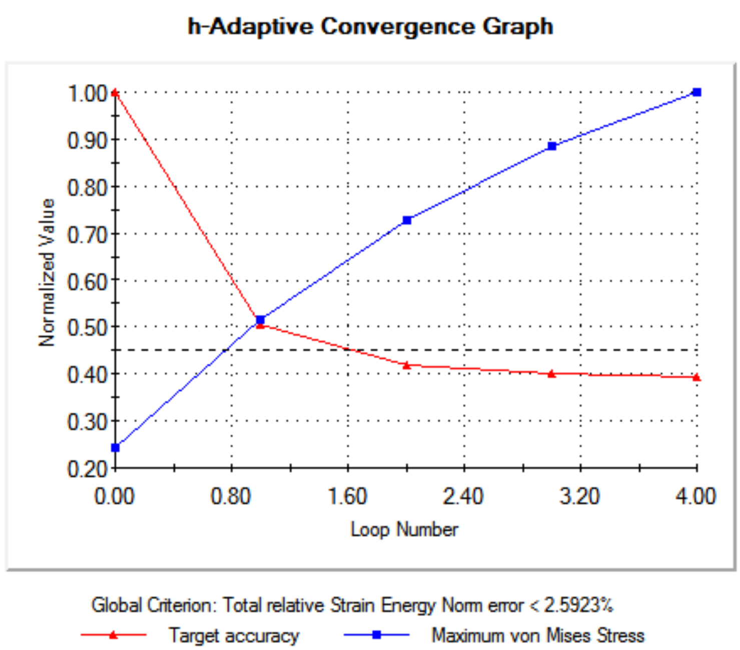

Figure 9: Central I-beam convergence plot

This design satisfies the clients most important needs with regards to the safety and usability of the vane box handling tool. The wide base frame must surpass a tipping angle of 45° before instability occurs, while the H-shaped design allows for easy operator access. The highest stress in the base frame has a much larger factor of safety than that required by the Government of Manitoba [3]. The shock-absorbing casters allow the operators to move the handling tool from station to station without having to be concerned about small deviations in the floor surface. Finally, the floor lock allows the handling tool to be left in position once the operator has moved it, preventing accidental forces from moving the tool with potentially negative safety concerns.

2.1.2 Central Axle Assembly

The central axle of the F-35 vane box handling tool design is the interface between the main frame and the base frame, and it provides rotational freedom about the vertical axis as well as translational freedom up and down. The main axle consists of four key components: the turntable, air cylinders, cross mounting plate, and base mounting plate. The turntable allows for rotation about the vertical axis, while the two pneumatic air cylinders allow for translational freedom up and down. The cross mounting plate securely connects the air cylinders to the turntable, and the base mounting plate connects and aligns the air cylinders while securing the assembly to the base frame. Figure 10 shows a render of the final central axle assembly design.

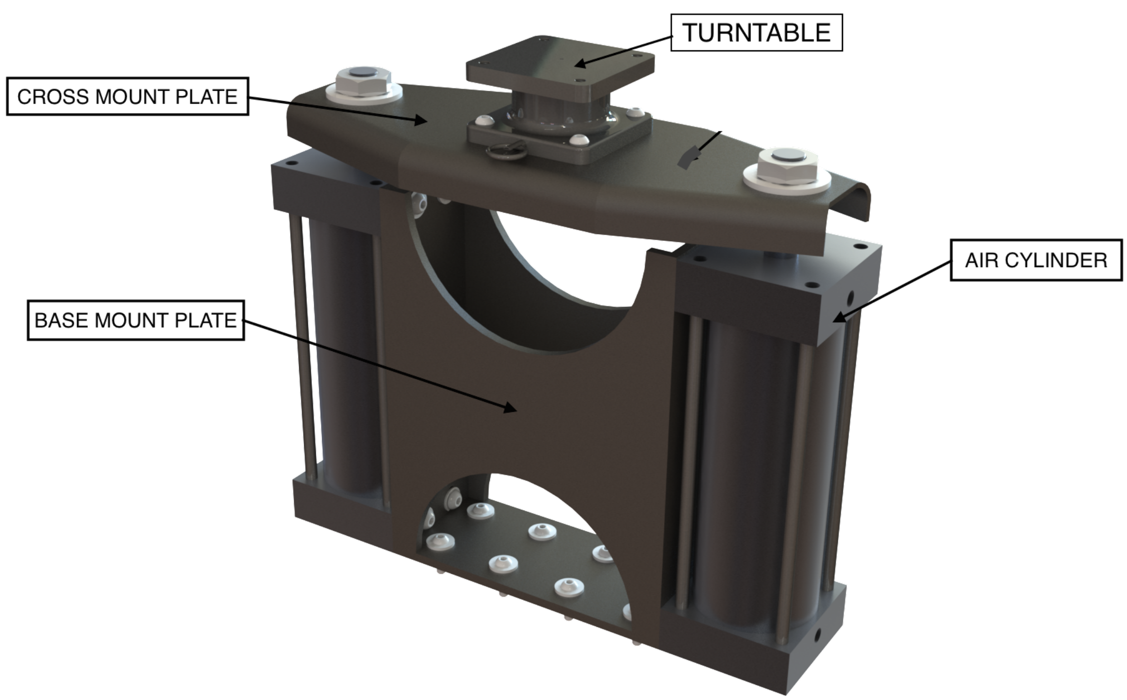

Figure 10: Central axle assembly

2.1.2.1 Turntable

The turntable is permanently lubricated, suited for industrial use, and is a readily available part supplied by McMaster-Carr [4]. The base of the turntable is cast iron, while the top plate has a milled-flat level surface made of steel. The turntable has fully sealed steel ball bearings that allow the handling tool to rotate a full 360° about the vertical axis. The turntable contains slotted grooves that allow it to be locked in place at 90° increments. Furthermore, a spring-loaded pin with a pull ring engages and disengages the lock on the turntable, allowing it to spin freely with ease. There are four 1/4 – 20 threaded mounting holes located on the top plate while 1/4 [in] through holes are located on the base plate for fastening. The turntable has a load capacity of 1000 [lb], and when assuming a vane box weight of 200[lb] and the main frame weight of 100 [lb], the turntable maintains a safety factor of no less than 3. The overall dimension of the turntable is 3.25[in] x 3.25[in] x 1.77[in]. Figure 11 shows a render of the turntable; note the fasteners are not included in the picture and will be discussed in a later section.

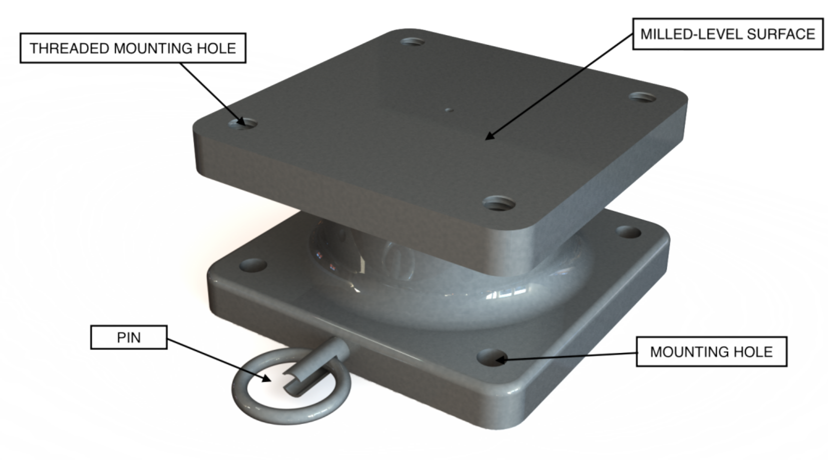

Figure 11: Turntable

Design options were considered to accommodate the vertical rotational freedom of the vane box handling tool, while providing structural integrity. Some of these design options included the integrated rotational capabilities of pneumatic air cylinders, shaft and bearings, shielded thrust bearings, and sleeve bushings. A turntable was ultimately selected as the final design for the central axle assembly.

Justification for the turntable design as opposed to any of the other design options is as follows. Turntables are readily available as complete assemblies, which result in a straightforward and convenient central axle assembly. As the turntable provides all requisite functions, there is no need for custom manufactured parts which would otherwise add additional time and cost to the manufacturing process. Turntables have listed load capacities that ensure the design performs and operates safely, with confidence. A single air cylinder that could allow for rotational as well as translational motion was considered, however eccentric loading on one shaft is unfavorable. In addition, there are mounting limitations with a single air cylinder. Various bearing designs were considered, however a turntable is essentially a bearing design suited perfectly for this application.

The turntable selected is permanently lubricated and has fully sealed ball bearings. This minimizes contaminants entering the ball bearing, which would otherwise reduce performance. Furthermore, this turntable eliminates the need for external lubrication, therefore reducing the maintenance needs of the central axle. The lockable option was selected as technicians will need a fixed handling tool to be able to operate safely and effectively on the vane box. A non-lockable version would need an external method to lock the turntable in place. The benefits for a non-lockable turntable with a custom external locking mechanism could allow for finer locking increments than 90°, which provides better access for the technicians to vane box fastener locations. However, the external locking mechanism will need to be custom made which adds an extra element of uncertainty with regards to safety and reliability. Furthermore, it requires additional custom manufactured parts, which increases assembly time and cost. The turntable design is simplistic, reliable, safe, and promotes easy assembly with no additional parts required.

2.1.2.2 Air Cylinder

Two aluminum tie rod air cylinders are used simultaneously to raise or lower the vane box assembly. The air cylinders are readily available parts supplied by McMaster-Carr [4]. External tie rods, made of steel, are used to support and protect the cylinder barrel during operation. The bore cylinder, as well as the piston is made of aluminum. Furthermore, the rod is chrome plated and threaded to allow for easy fastening to other components. The air cylinder has a push force of 662 [lb] @ 100 [psi] with a maximum allowable force of 250 [psi], and with both acting simultaneously, they achieve a minimum safety factor of 4. The cylinder has an overall stroke length of 5 [in]. The bore diameter is 3 [in], while the rod diameter, thread size, and length is 3/4 - 10 x 1 1/2 [in]. The cylinder is double acting, allowing pressurized airflow through two $3/8$ [in] NPT ports. There are four $5/16$ [in] $- 24$ threaded mounting holes located on the side of the cylinder. The cylinder features an air cushion that prevents unwanted slamming and decreases noise. The overall dimensions of the air cylinder are

3.375[in] x 3.375[in] x 7.047 [in] in its retracted state. Figure 12 shows the aluminum tie rod air cylinder.

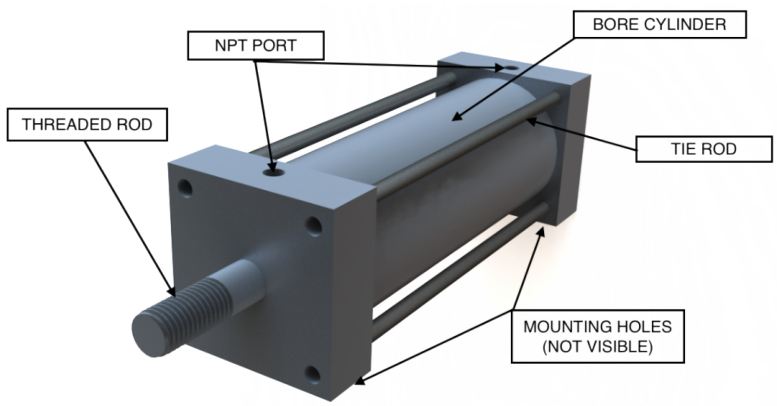

Figure 12: Aluminum tie rod air cylinder

Several design options were considered for providing translational motion up and down of the central axle assembly. One pneumatic air cylinder was considered, however due to the effects of eccentric loading as well as mounting complications, this design was not implemented. To combat the effects of eccentric loading, one pneumatic cylinder with two rods connected to a single piston was considered. Unfortunately the maximum load rating on these cylinder types were inadequate to provide a required safety factor of 3; therefore this design was not selected. A barber-shop foot pedal style lift was considered for this design, however due to insufficient detailed technical specifications of these lifts, as well as limited suppliers, this configuration was not chosen for the final design. A bottle jack pneumatic lift operated by a foot pedal was also considered for raising and lowering the vane box assembly. However, these types of lifts are tall which is unfavorable for our design. In addition, these lifts have few mounting locations and are not suited for eccentric loading; therefore this design was not selected. The two tie rod air cylinders configuration is rated to handle the expected loading scenarios, and provides a feasible mounting solution to connect the main frame to the base frame. The cylinder is readily available and is simple and easy to install onto the central axle assembly. With the aforementioned reasons, two tie rod air cylinders were selected to provide translational movement up and down.

2.1.2.3 Cross Mounting Plate

The cross mounting plate is responsible for connecting the turntable to the two air cylinders. The plate is made of 0.190 [in] thick AISI 4130 steel and supports the load of the vane box, main frame, and the plug actuation mechanism safely. The plate is symmetric in nature, with a 0.75[in]x 1.5 [in] slot on either end that allows the plate to fit onto the cylinder rods while accommodating potential tolerance build-up during assembly. Four 1/4 [in] through holes align with the turntable mounting holes to securely fasten the turntable to the centre of the plate. The sheet is stiffened by 90° bends which minimizes overall deflection and are welded for added structural integrity. The overall dimensions of the cross mounting plate are 14.0[in]x 5.5 [in]x 1.0 [in]. The approximate weight of the mounting plate is 3 [lb]. Figure 13 shows the final cross mounting plate design.

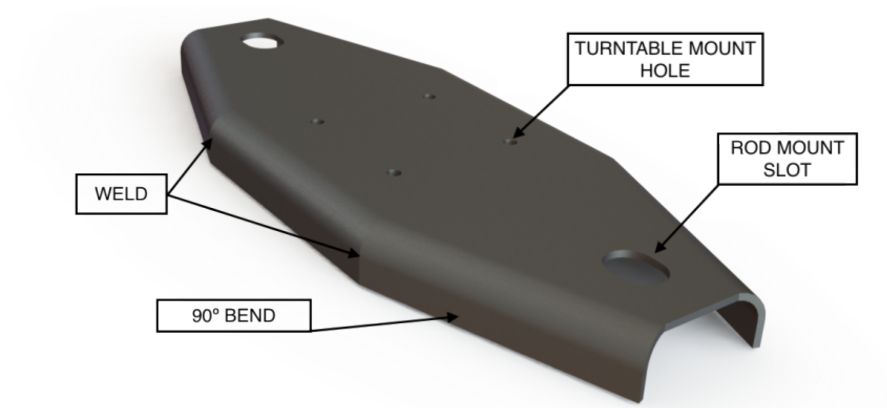

Figure 13: Cross mounting plate

FEA was conducted to validate that the appropriate safety factors have been achieved. An initial curvature based mesh was created from the solid model and can be seen in Figure 14. A fixed geometry was selected on the plate surface where the washers are tightened. A load of 300 [lb] was applied to the centre of the plate where the turntable would rest.

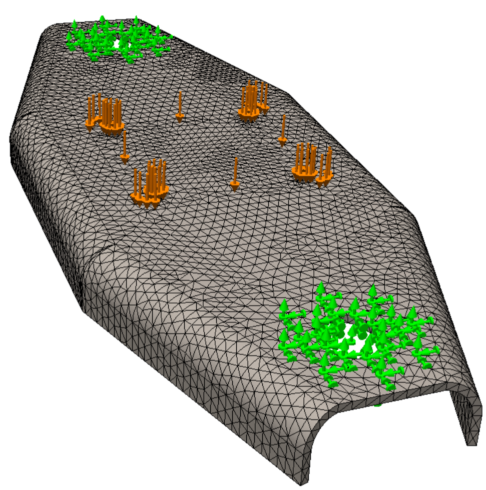

Figure 14: Cross mounting plate initial mesh

An h-adaptive iterative process was used in the analysis to ensure the determined stresses have converged, and that the results are accurate. A target accuracy of 98% was selected as well as mesh coarsening. Figure 15 and Figure 16 show the final mesh after the h-adaptive iterations.

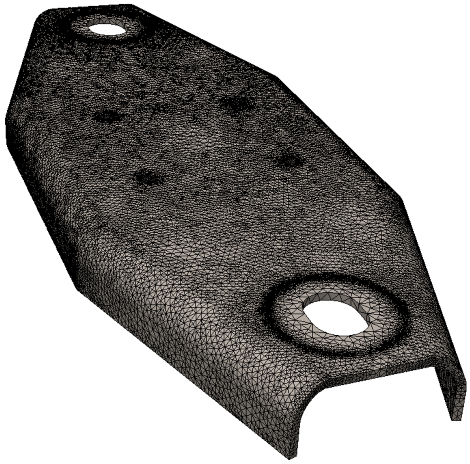

Figure 15: Cross mounting plate h-adapted mesh

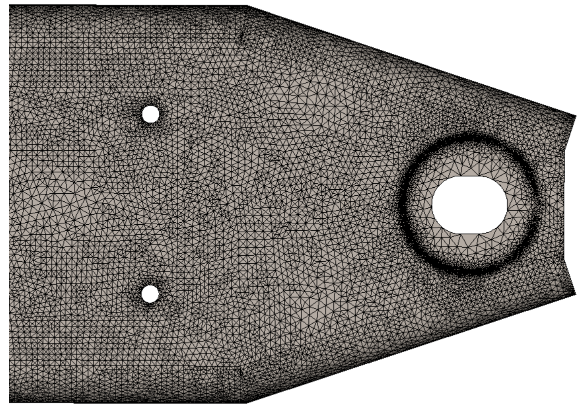

Figure 16: Cross mounting plate h-adapted mesh

A convergence plot, as seen in Figure 17, shows the target accuracy is achieved after six FEA iterations. This validates the results from FEA are accurate within 2%, and can be trusted. The mesh after six iterations became quite dense, where the tightest elements are present at the forefront of the fixed boundary condition. It is clear that at this location, very high stress concentrations will exist which does not depict the actual stresses present at that location.

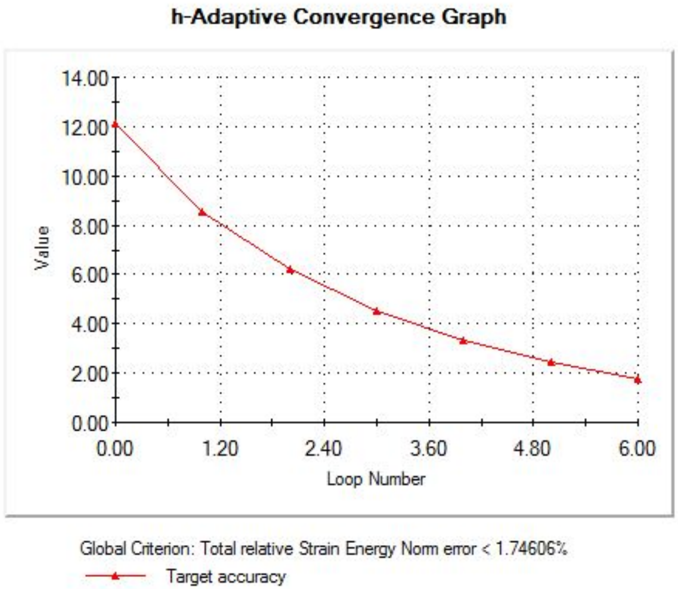

Figure 17: Cross mounting plate h-adaptive convergence plot

Figure 18 and Figure 19 show a distribution of stresses throughout the plate from the FEA results. Several conclusions can be drawn from these plots. It is apparent that there are high stress locations at the centre of the plate, edge of the plate, as well as the corners of the plate where there will be welds. There are high stress concentrations at the boundary condition, which is expected from the mesh distribution seen in Figure 16. This high stress concentration is to be ignored to a certain degree; it provides stress insight, however it is not the true effect.

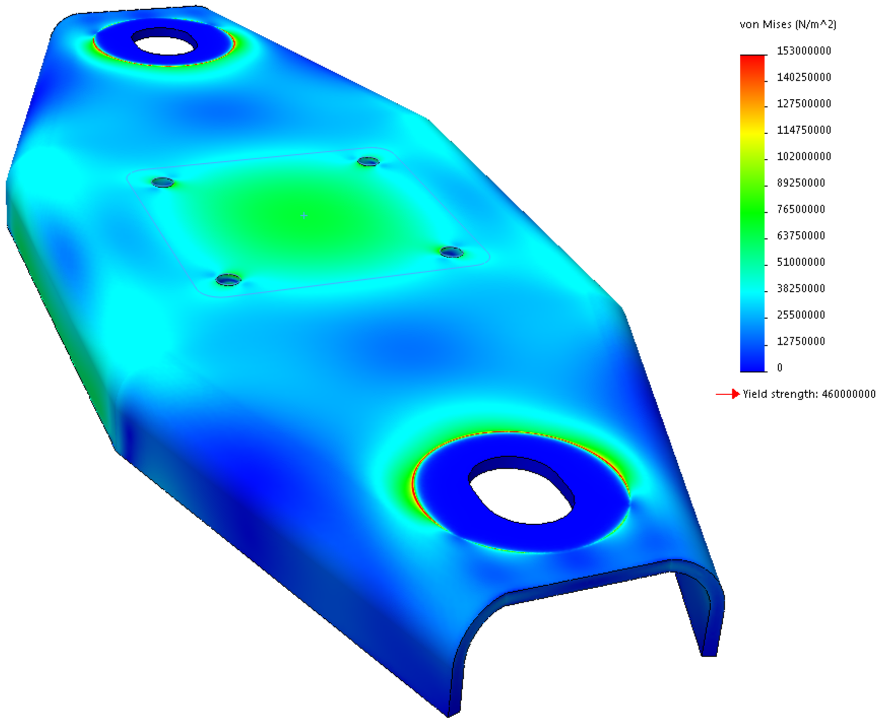

Figure 18: Cross mounting plate stress plot 1

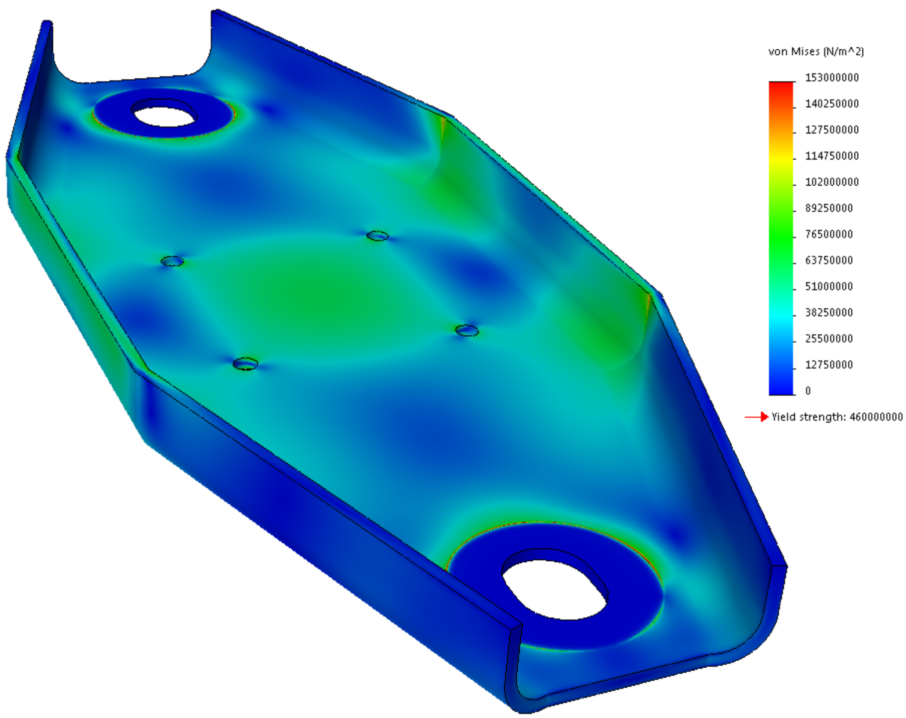

Figure 19: Cross mounting plate stress plot 2

Figure 20 through Figure 23 show safety factor plots for both yield and ultimate tensile stress. It can be seen that for both yield and ultimate stress, minimum safety factors of 3 and 5 have been achieved, respectively throughout the part. At the edge of the boundary condition, the results show that the part does not satisfy the safety factor requirement. However, this result is ignored due to false stress intensity readings.

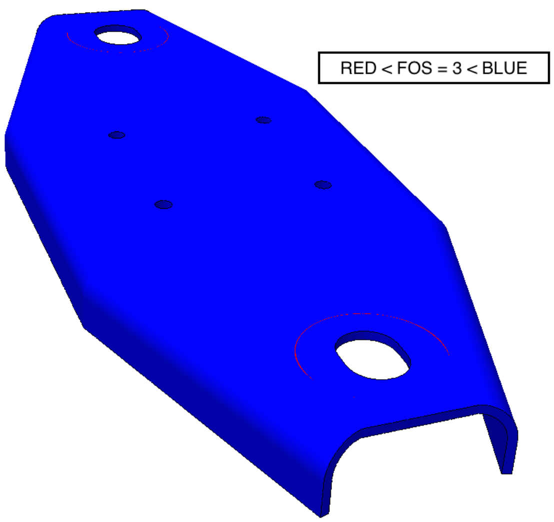

Figure 20: Cross mounting plate FOS plot YS 1

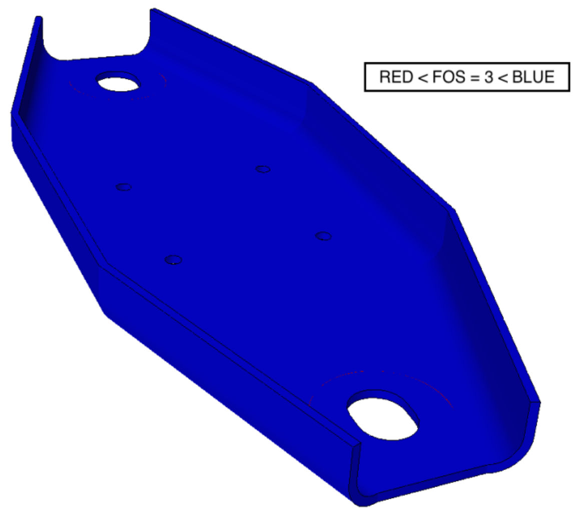

Figure 21: Cross mounting plate FOS plot YS 2

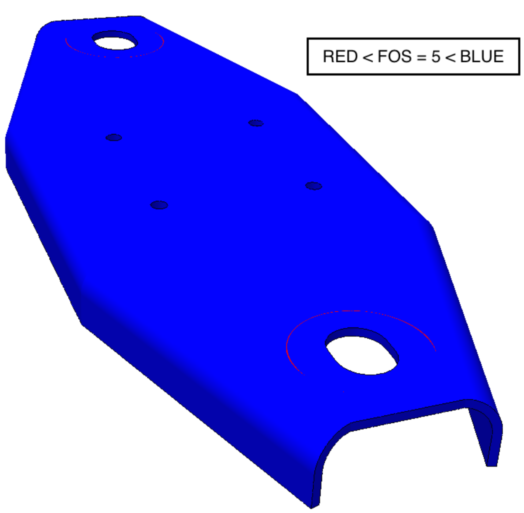

Figure 22: Cross mounting plate FOS plot UTS 1

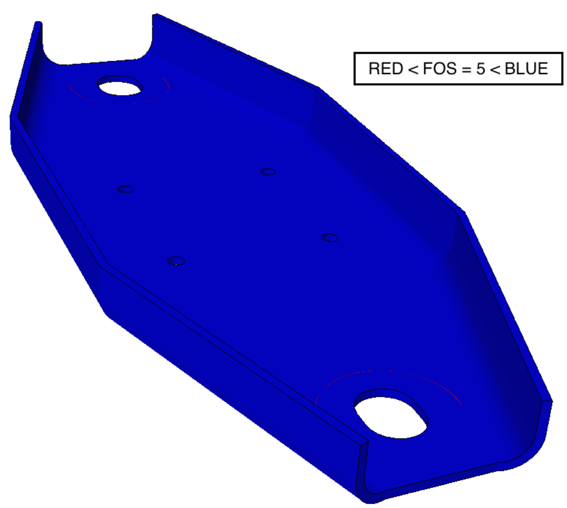

Figure 23: Cross mounting plate FOS plot UTS 2

The maximum displacement of the plate is located at the centre, with a value of 0.363 [mm]. Figure 24 shows the distribution of displacement throughout the part; note the deformation scale is true at 1:1. This minimal displacement value validates the part is rigid and can withstand the load of the vane box, main frame, and the plug actuation mechanism.

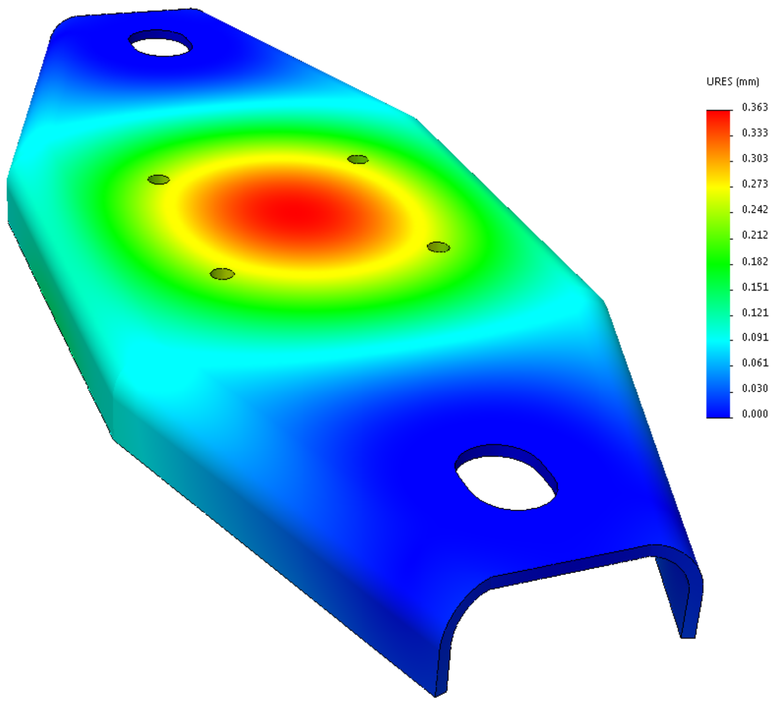

Figure 24: Cross mounting plate displacement plot at 1:1 scale

Through FEA, the cross mounting plate design has been confirmed to withstand the loads imparted by the vane box, main frame, and the plug actuation mechanism. The design maintains a minimum factor of safety of 3 for yield stress, and 5 for ultimate stress, throughout the entire part with minimal deflection. A detailed technical analysis of the cross mount plate from the initial design, iterating through to the final design, can be seen in Appendix B.

2.1.2.4 Base Mounting Plate

The base mounting plate connects air cylinders on each side, and then connects to the base frame. The plate is made entirely of 0.25 [in] thick AISI 4130 steel plate, which is designed to withstand large off-centre loads safely. The mounting plate consists of three major components that are welded together. These components are the two side plates, base plate, and the two bridge plates; together they form a box like structure. Four 5/16 [in] x 5/8 [in] slotted holes on the side plates align with the air cylinder mount locations. Eight 1/4 [in] through holes located on the base plate align with mounting holes on the base frame to form a secure connection. The bridge plates provide stiffness and rigidity to the box to mitigate effects of off-centre loading scenarios, such as the handling tool resting on an incline, or lateral impact loads. The bridge plate is design to allow room for technicians to access the fastener locations. The overall size of the base mounting plate is 3.375[in]x 8.000[in]x 10.000 [in] and the approximate weight of the part is 13 [lb]. Figure 25 shows the base mounting plate.

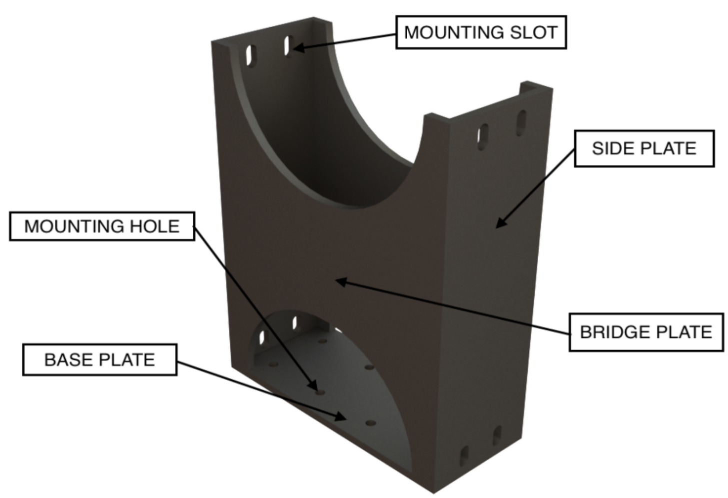

Figure 25: Base mounting plate

FEA was used to analyze the base mounting plate to ensure the design meets a safety factor of 3 for yield stress, and 5 for ultimate stress, for a worst case scenario loading situation. In a perfect state, the base mounting plate experiences zero forces as the air cylinders transfers the load straight to the base frame I-beam. The worst case loading scenario is assumed to be an impact load of 150 $[lb]$ acted laterally through the centre of gravity, which is over-approximated at 4 $[ft]$ above the base of the plate. In addition, the whole handling tool is assumed to tip $10°$ in the same direction as the impact load instantaneously. This creates a moment about the base mounting plate from the weight of the vane box and main frame, which is estimated to be 300 $[lb]$ acting through the centre of gravity location. The resulting equivalent moment experienced by the base mounting plate is a total of 7340 $[lb \cdot in]$. FEA was performed for this loading scenario. A curvature based mesh of the mounting plate was varied from coarse to fine, and a convergence plot of three probed locations was created and can be seen in Figure 26.

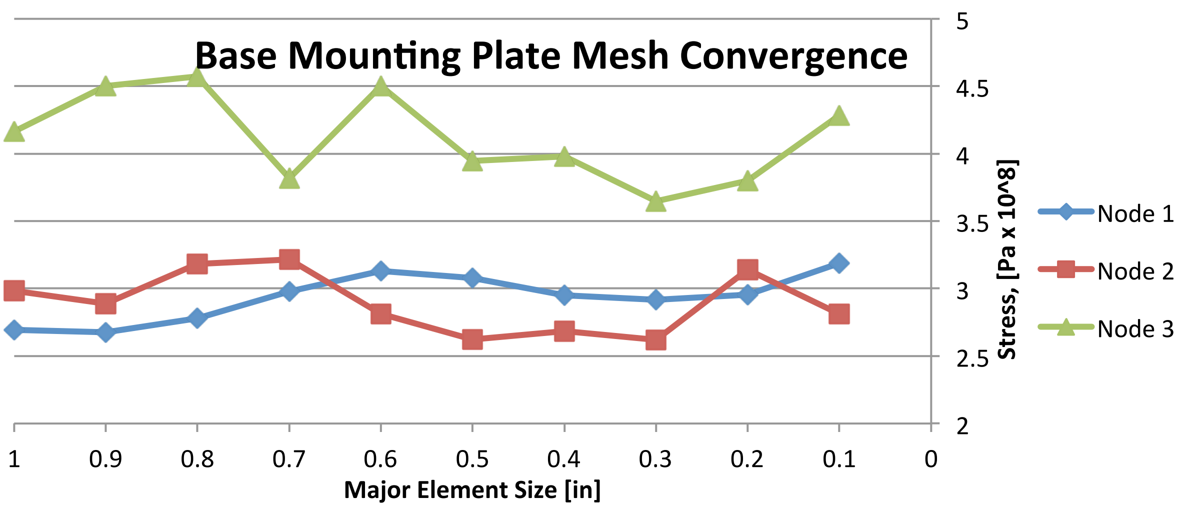

Figure 26: Base mounting plate convergence plot

From Figure 26 it is apparent that the mesh results become consistent and converge around the major element size of 0.3 $[in]$. Figure 27 and Figure 28 shows the final mesh of the base mounting plate, and the loading scenario on a simplified mesh. The pink arrows denote the applied force, and green arrows are where washers are located to secure the part to the base frame. The mesh generated was curvature based with a major element size of 0.10 $[in]$ and a minor element size of 0.02 $[in]$.

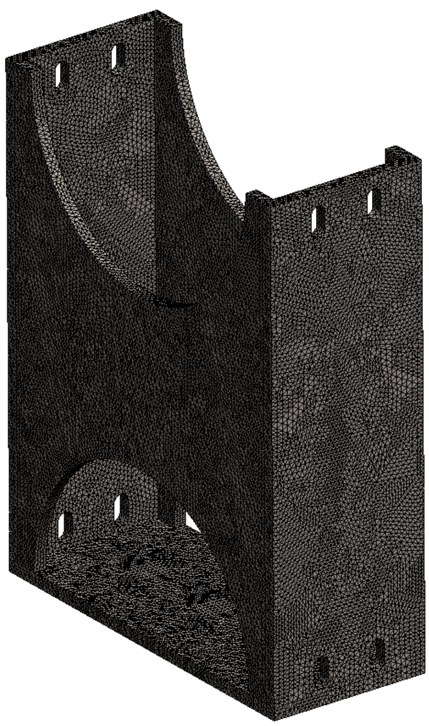

Figure 27: Base mounting plate mesh

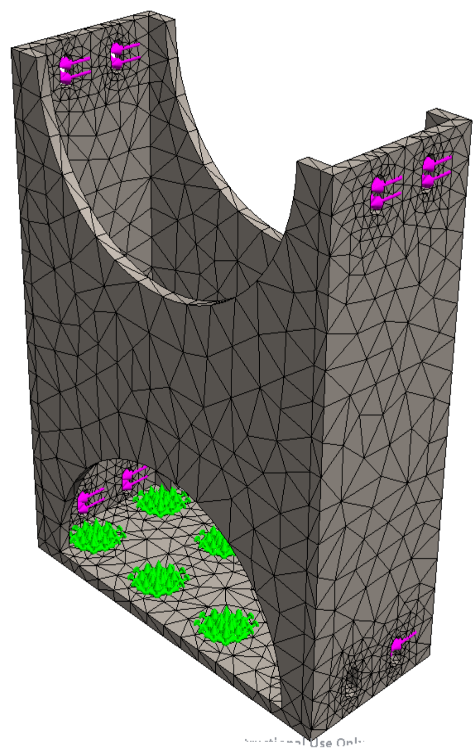

Figure 28: Base mounting plate loading scenario

Stress plots of the base mounting plate can be seen in Figure 29 through Figure 31. In the legend, dark blue represents areas of low stress, while areas of bold red represent stresses at or above the required safety factor of 3. The majority of the material above the base plate experiences little to no stress in this loading situation, which is anticipated. The highest stress locations are found in the bottom corner, at the edge of a boundary condition where a washer holds the base plate onto the I-beam base frame.

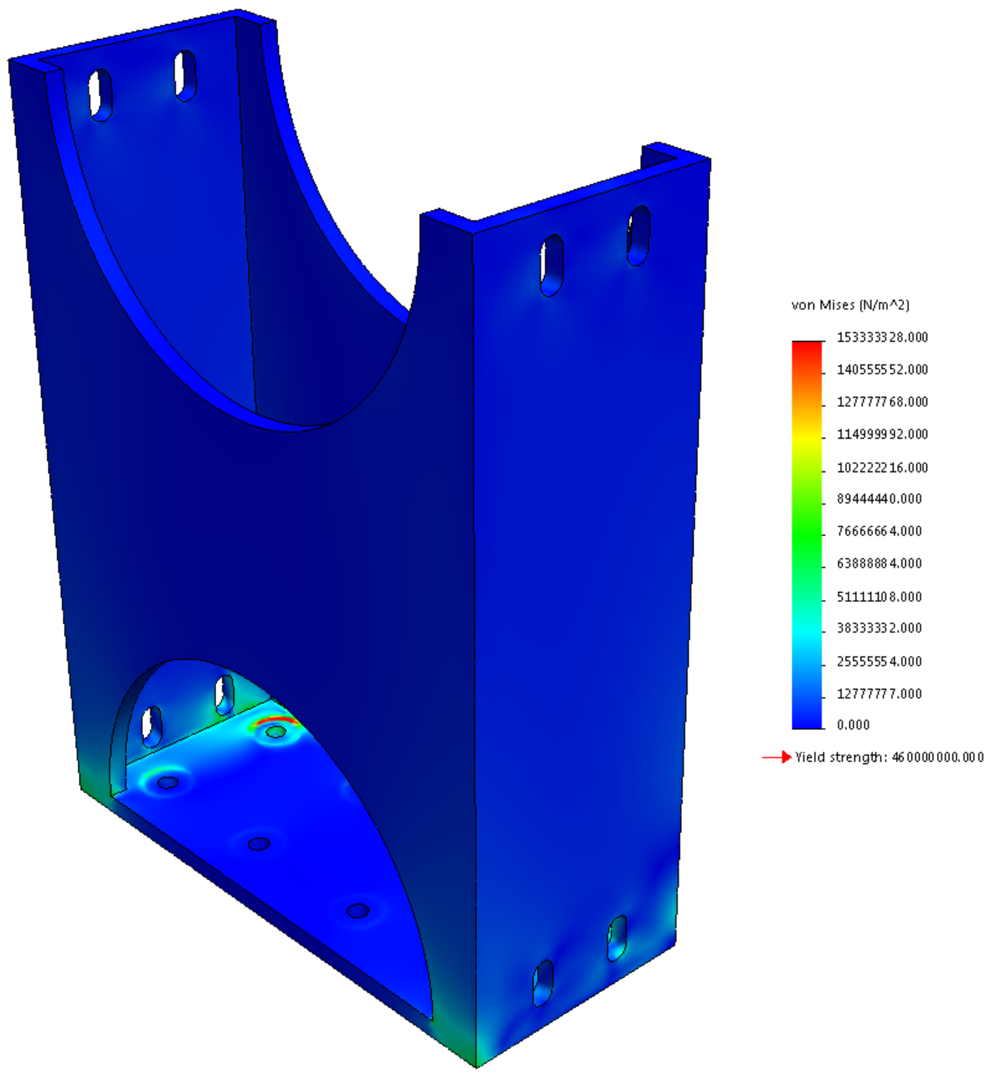

Figure 29: Base mounting plate stress plot 1

Taking a closer examination of the stresses in the bottom corner, Figure 30 displays an enlarged image of this location. The stresses seem reasonable throughout this location, except for the forefront of a boundary condition which is where a washer will be located, as well as an edge of the plate. These are stress concentrations that do not accurately reflect the true nature of stresses throughout the part, and will therefore be neglected. Figure 31 shows the bottom side of the base mounting plate, and the stresses appear to be reasonable and well above the required factor of safety.

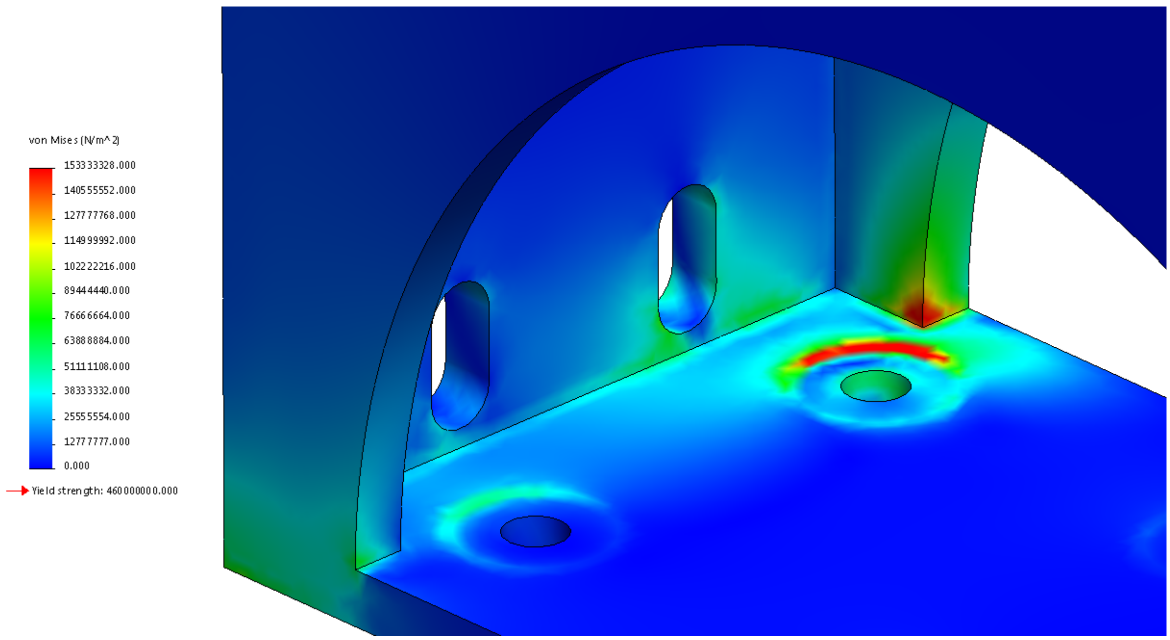

Figure 30: Base mounting plate stress plot 2

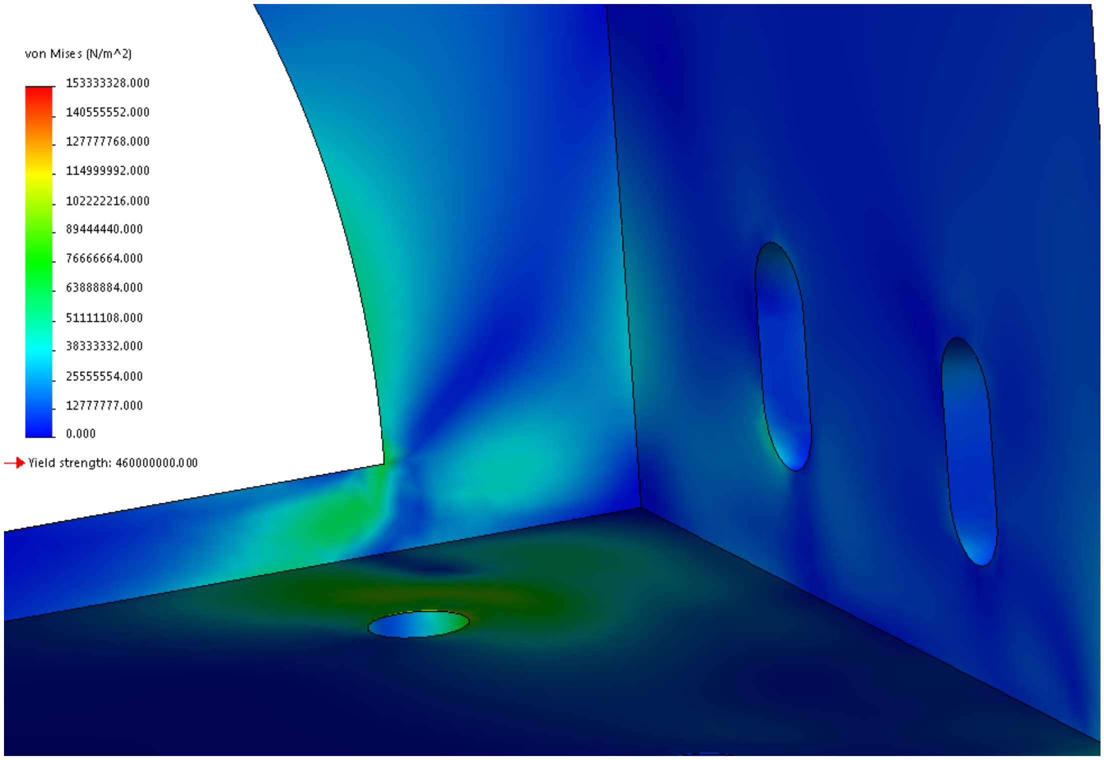

Figure 31: Base mounting plate stress plot 3

To further illustrate the safety of the design, Figure 32 and Figure 33 show safety factor plots of yield strength and ultimate strength, respectively. The only locations where the factor of safety is lower than the required is at the same locations where there are high stress concentrations. These stress concentrations have safety factors around 2, which is still above yield. However, as the stress concentrations are to be neglected, the design meets the safety factor requirements.

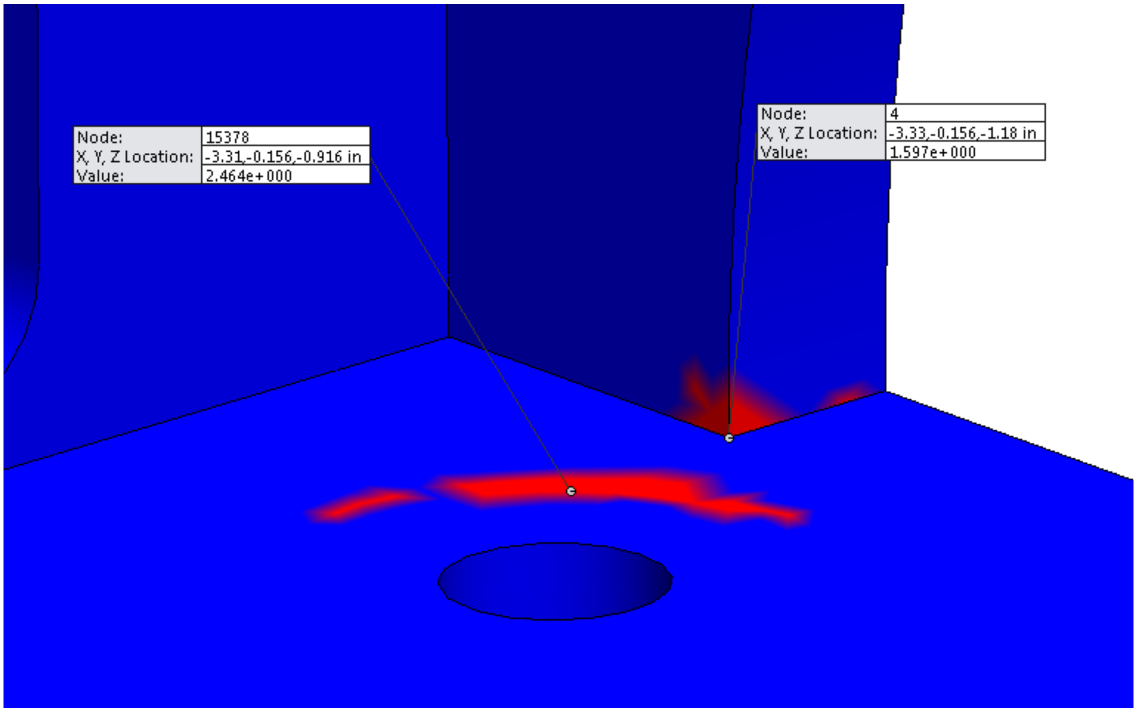

Figure 32: Base mounting plate FOS plot YS

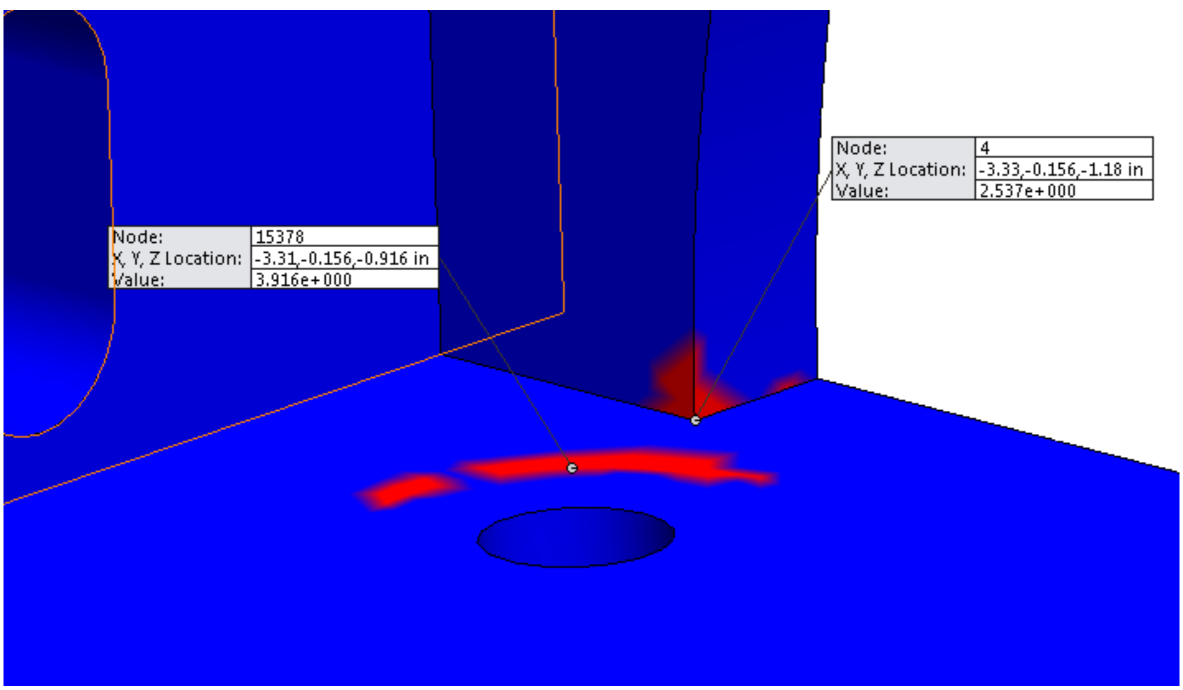

Figure 33: Base mounting plate FOS plot UTS

Finally, a displacement plot is shown in Figure 34 to reveal additional design insight. The maximum overall deflection is 0.1 [mm] located at the top of the part. This value is quite small, therefore is acceptable. The base of the part has significantly small deflections which is satisfactory.

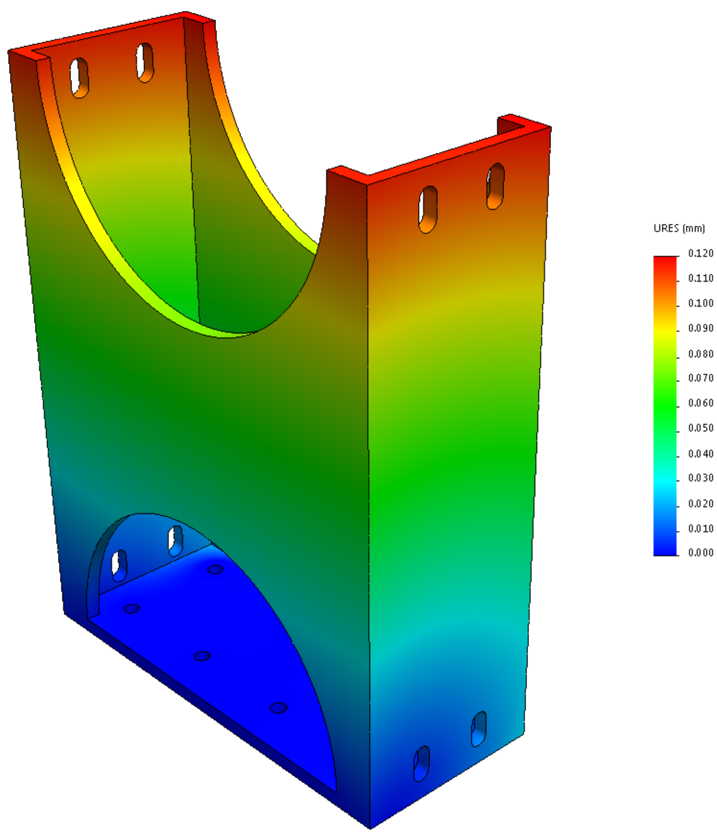

Figure 34: Base mounting plate displacement plot with a scale of 1:1

The base mounting plate meets safety design requirements, is simplistic, and easy to manufacture. It was designed with a worst case scenario loading situation in mind to ensure that the vane box handling tool maintains structural integrity throughout all aspects of its function.

2.1.2.5 Fasteners

Various fasteners were used to attach the major components together to form the central axle assembly. Additional fasteners were used to mount the assembly to the base frame as well as main frame. The base mounting plate is attached to the base frame through eight 1/4 - 20 x 1 [in] socket head button screws with 1/4 [in] stainless steel USS washers and 1/4 – 20 [in] plain hex nuts. The base mounting plate also connects the two air cylinders using eight 5/16 – 24 x 0.5 [in] socket head button screws with four 5/16 [in] aluminum washers, and four 5/16 [in] clipped aluminum washers. The two air cylinders have a 3/4 – 10 x 1.5 [in] threaded rod in which a 3/4-10 [in] plain hex nut and a 3/4 [in] oversized aluminum washer rest. The cross mounting plate rests on these washers, and is secured by another 3/4 [in] oversized aluminum washer and a 3/4 [in] thin wide hex nut. The turntable is mounted to the cross mounting plate using four 1/4-20 x 1 [in] socket head button screws with corresponding 1/4 [in] stainless steel washers and 1/4-20 [in] plain hex nuts. Finally, the turntable is mounted to the main frame assembly through four 1/4 – 20 x 5/8 [in] socket head button screws with 1/4 [in] aluminum washers and corresponding 1/4 -20 plain hex nuts.

2.1.3 Main Frame

The main frame of the F-35 vane box handling tool design is a critical section in the function of providing rotational freedom about the horizontal axis. The main frame contains three key components: the rotating fork, mechanical hub, and structural frame. All of the structural components are symmetrical laterally; but the mechanical components within the hub and rotating fork differ on both sides. The main frame design can be seen in Figure 35, where the structural frame, mechanical hub, and rotating fork are labeled A, B, and C, respectively.

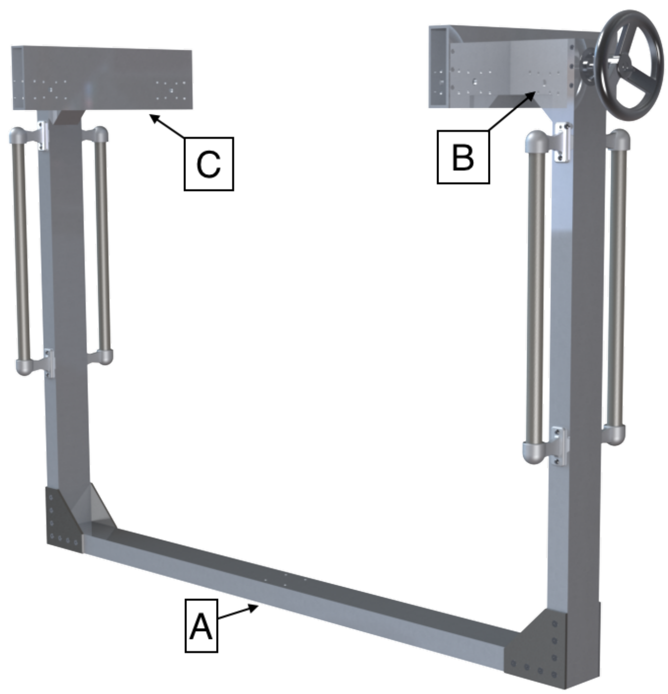

Figure 35: Main frame render

2.1.3.1 Structural Frame

The structural frame primarily comprise of 6061-T6 aluminum rectangular tube. The horizontal beam cross section is a 2 [in] x4 [in] x 1/4 [in] with a length of 62.385

[in]. The turntable from the central axle assembly is fastened to the bottom of the horizontal beam and the whole structural frame rotates about the turntable. Seen in Figure 36, a 6061-T6 aluminum upright tube is attached to the end of the horizontal tube, and is 45 [in] long with a cross-sectional area of 2 [in] x 4 [in] x 1/4 [in].

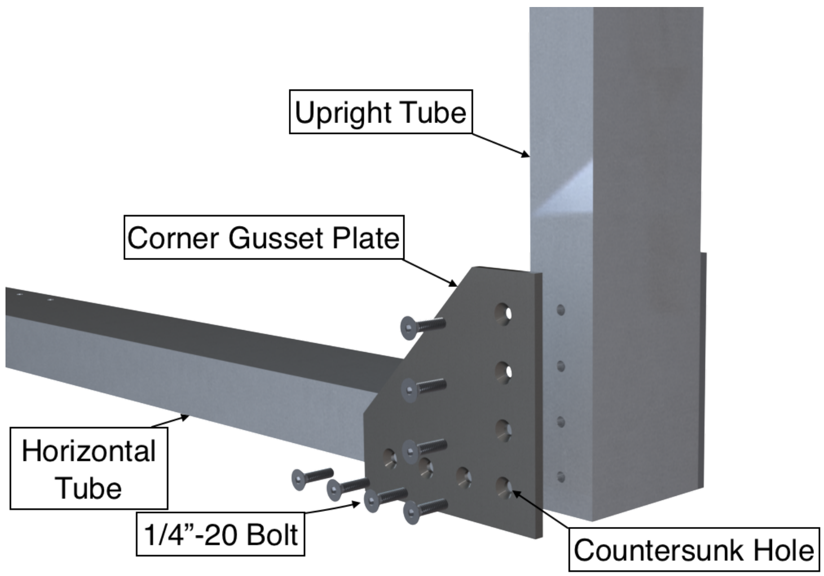

Figure 36: Exploded view of corner gusset plate

The length of the horizontal tube and upright tubes are the minimal length required to allow the vane box to rotate a full 360° about the horizontal axis without encountering any obstructions. The upright tubes are attached to the horizontal tube with gusset plates on the front and backside as pictured in Figure 36. 1/4 [in] diameter countersunk cap screws were chosen to provide the force required, as well as keeping an aesthetic appeal to the structure by sitting flush with the surface. In addition, countersunk fasteners automatically centre in a hole allowing for easier assembly. The gusset plates are a simple and easy method to attach the tubes together without being permanent. Welding the tubes together was considered but our team decided that our design would avoid welding as much as possible because the quality of weld depends on the skill of the welder. Welding aluminum is considered much more difficult in comparison to steel or cast iron, thus high quality welds are harder to achieve. For each upright tube, an aluminum handle is attached to both sides for the operator to grasp while transporting the handling tool, or to rotate the assembly about the vertical axis. The handles were chosen because the handles can be cut to the desired length, and can satisfy the different heights of operators at Magellan Aerospace. Lastly, the structural frame is attached to the mechanical hub with an aluminum stiffener welded on, as seen in Figure 37. In this particular situation, gusset plates could not be implemented because of the lack of fastener locations available; thus the design requires aluminum to be welded.

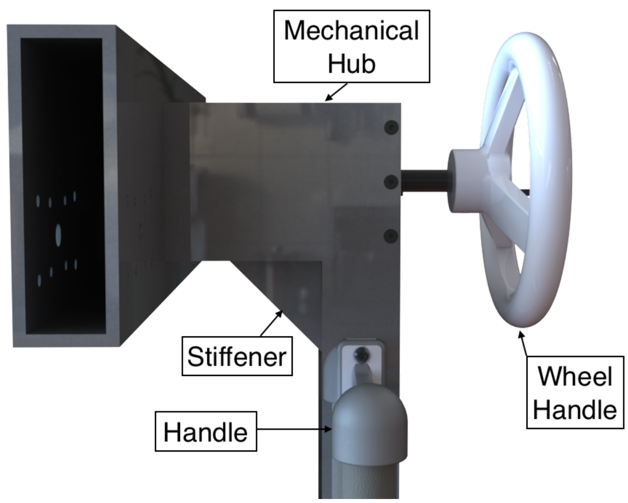

Figure 37: Upright tube and mechanical hub interface

To ensure that the structural frame is not going to displace an undesirable amount or fail due to yielding, a preliminary FEA was performed. FEA was conducted separately on the horizontal tube and upright tube. The horizontal tube is fixed at the centre on the bottom of the surface, with forces directed outwards at the bolt locations. The corresponding mesh generated is shown in Figure 38. It is important to note that the mesh decreases in size in areas where higher percentage of error may occur.

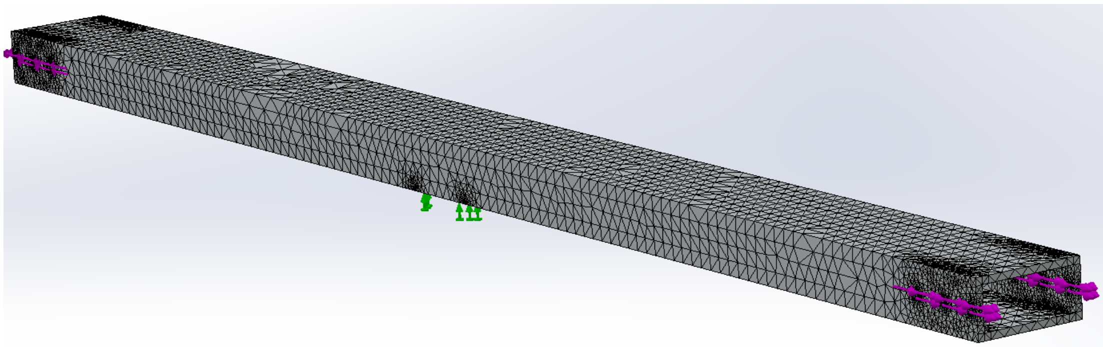

Figure 38: Horizontal beam mesh

The displacement of the horizontal beam from the calculated forces is shown in Figure 39. From Figure 39, it is determined that the deflection does not exceed 0.0008566 [in] in all locations, with the max deflection occurring at both ends of the tube. Since the displacement experienced is so minimal, displacement is not a concern for this component.

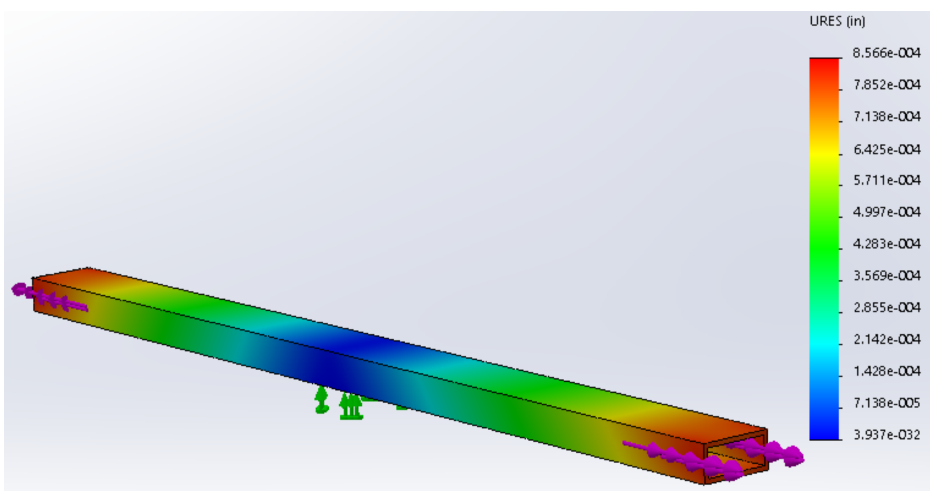

Figure 39: Horizontal beam displacement distribution

The max von Mises stress is shown in Figure 40 with a max stress value of 1.945 x 10^7 [Pa]. The max value occurs at the fixture location on the beam and is 14 times less than the yield stress. Therefore, the beam meets the safety factor requirement of 3 in yield.

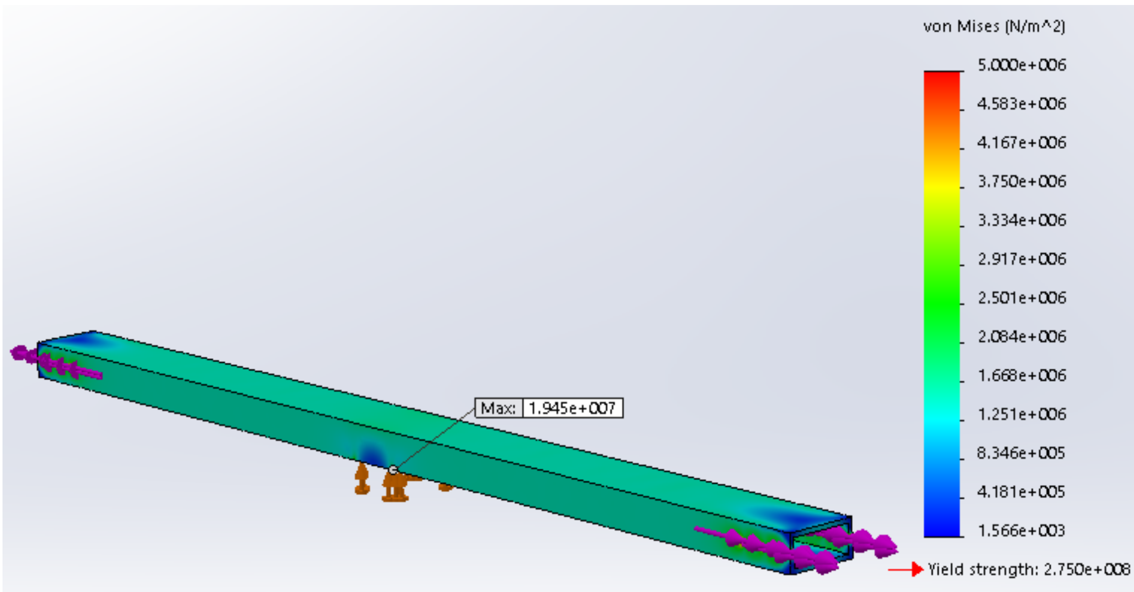

Figure 40: Horizontal beam von Mises stress distribution

To confirm that the correct approach of FEA was taken, an h-adaptive method of analysis was utilized. The software performs FEA with the generated mesh, gathers the results, and then determines areas with a higher percentage of error. From there, the program re-meshes the corresponding high error locations with a finer mesh and recalculates results. The program loops five times to provide an accurate result and the convergence plot of stresses for the size of mesh is displayed in Figure 41. As it can be seen, the stress values converge to the normalized value of 1.00 and confirms that the FEA results are useful.

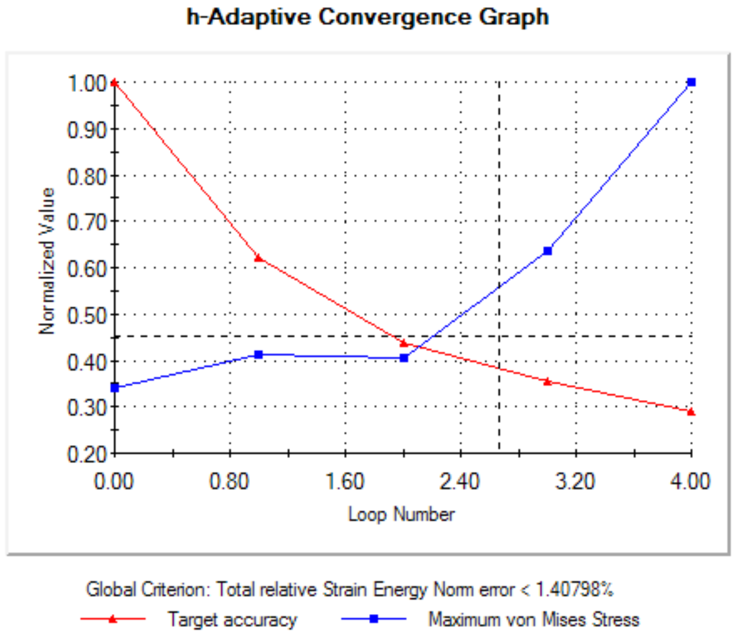

Figure 41: Horizontal beam convergence graph

Moving on from the horizontal tube to the upright tube, the upright tube is fixed as a slider on the top side face where the stiffener would be welded. Furthermore, it is fixed at the holes where the gusset plate would be attached to the horizontal plate. The applied load contains two separate components. The vertical downward component is acting on the top face of the tube and along face of the slider fixture. The horizontal component is acting normal to the slider fixture face. The generated mesh with the corresponding fixtures and applied loads for the upright tube can be seen in Figure 42. The displacement of the upright beam is seen in Figure 43, with 0.0001439 [in] being the max displacement experienced. The displacement can be considered negligible in comparison to the overall dimensions of the structure. In Figure 44, the max stress experienced occurs at the top gusset hole location, with a stress value of 2.178×10^6 [Pa]. The corresponding factor of safety is approximately 126, which exceeds the requirement needed. Figure 44 also displays the shape that the upright tube would experience under that load with a scale of 31272:1. The deformation shape reinforces the confidence of how the fixtures and loads are applied to the component.

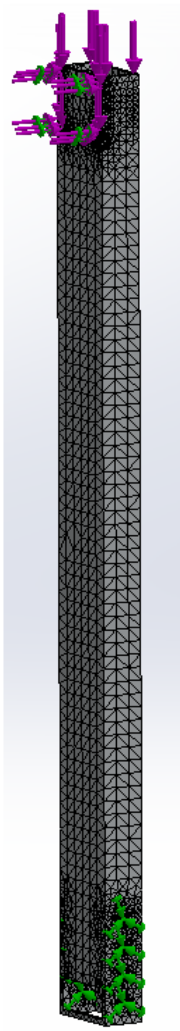

Figure 42: Upright tube mesh

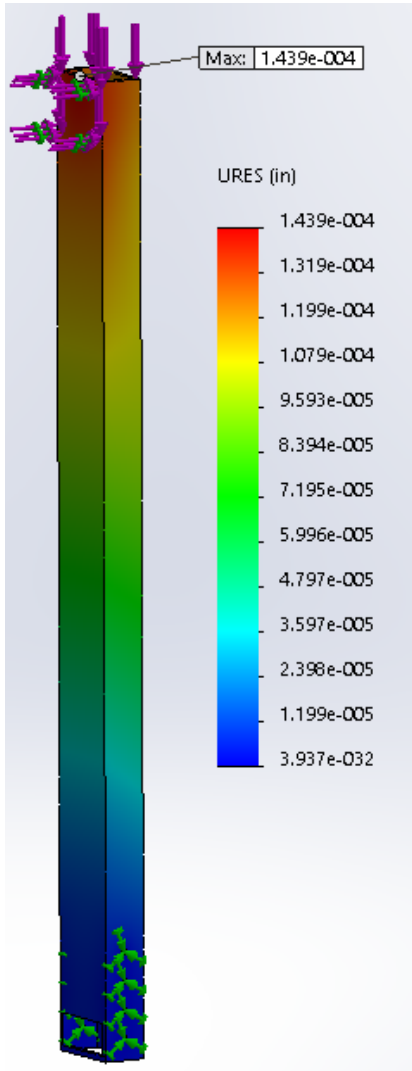

Figure 43: Upright tube displacement distribution

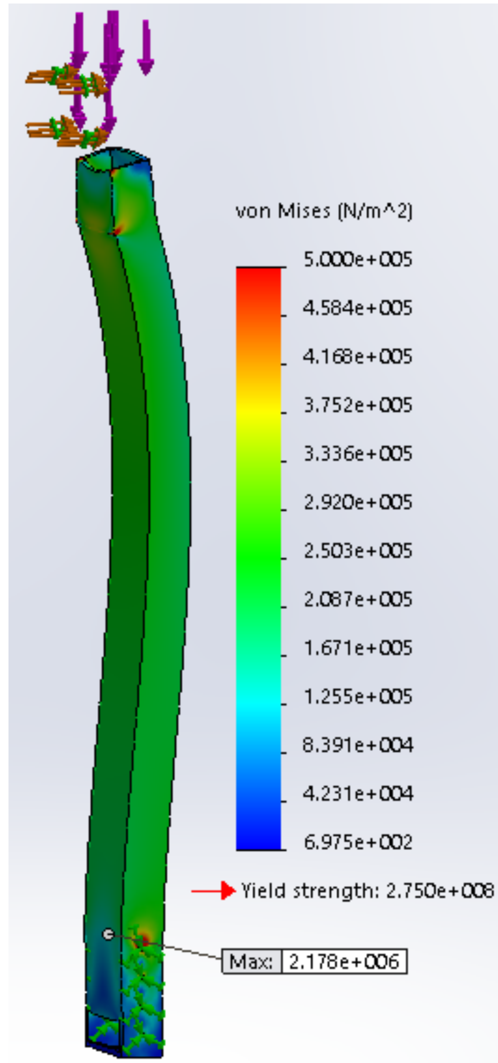

Figure 44: Upright tube von Mises stress distribution with a 31272:1 scale

With the same methodology as the horizontal beam, an h-adaptive method of FEA was utilized in analyzing the upright tube. The convergence graph of the max von Mises stress in the upright tube is shown in Figure 45. From the convergence graph, the max von Mises stress is shown to converge to a normalized value of 1.00, thus reassuring the analysis performed generated useful results.

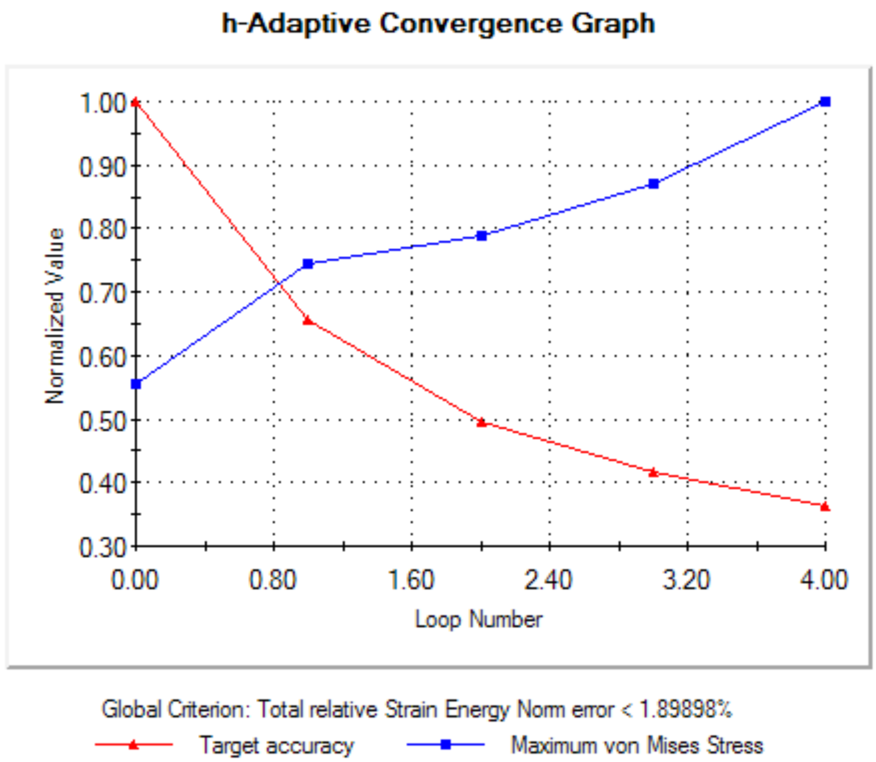

Figure 45: Upright tube convergence graph

After performing FEA on the horizontal and upright tube, our team was satisfied with the results and is confident that the structural frame will not fail.

2.1.3.2 Mechanical Hub

The mechanical hub contains many parts and components that are critical for the rotation of the vane box about the horizontal axis. The mechanical hub is mounted on the top of the upright tubes of the structural frame, shown in Figure 46. The hubs on both upright tubes are similar but one of the hubs house the driving parts, while the other hub houses idler parts. Both mechanical hubs are made from 6061-T6 aluminum with a cross-sectional dimension of 4 [in] x 4 [in]. The length of the hub is 6 [in] while the wall thickness is 1/4 [in].

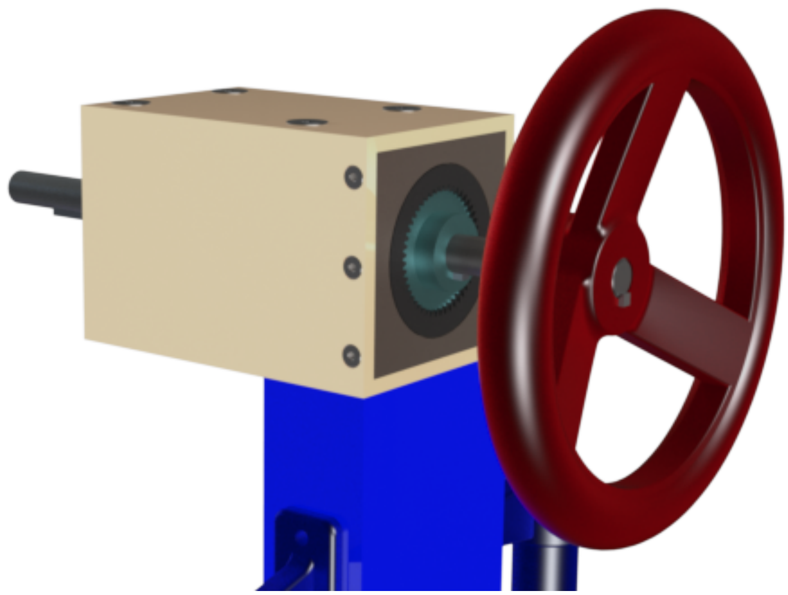

Figure 46: Mechanical hub render

The mechanical hub containing the driving components will be referred as hub A, while the hub with the idler components will be referred to as hub B. On the edge of hub A, a 6061-T6 aluminum mounting plate measuring 3.5 [in] x 3.5 [in] x 1/2 [in] is fastened at three locations on opposite sides, shown in Figure 47. The plate is responsible for holding a ring gear in place by weld. Another consideration made for holding the internal gear in place was through friction fitting, but considering the task required for the ring gear, it is undesirable to rely on friction as the method of securing. The mounting plate is fastened to hub A with 1/4 [in]-20 counterbore cap screws with a length of 0.375 [in]. Counterbore screws were selected because countersink heads are too wide at the edge of the hub and buttonheads are not as aesthetically appealing since they are not flush with the surface. On the front face of the mounting plate a 2.8 [in] diameter hole is cut out 1/4 [in] deep, while a 2.25 [in] diameter hole is cut out from 1/4 [in] depth to the back surface. Both of the hole cutouts are located at the centre of the mounting plate. The larger hole cutout allows the ring gear to be welding on the mounting plate while the smaller hole cutout allows the matching spur gear to slide in and out of the mounting plate.

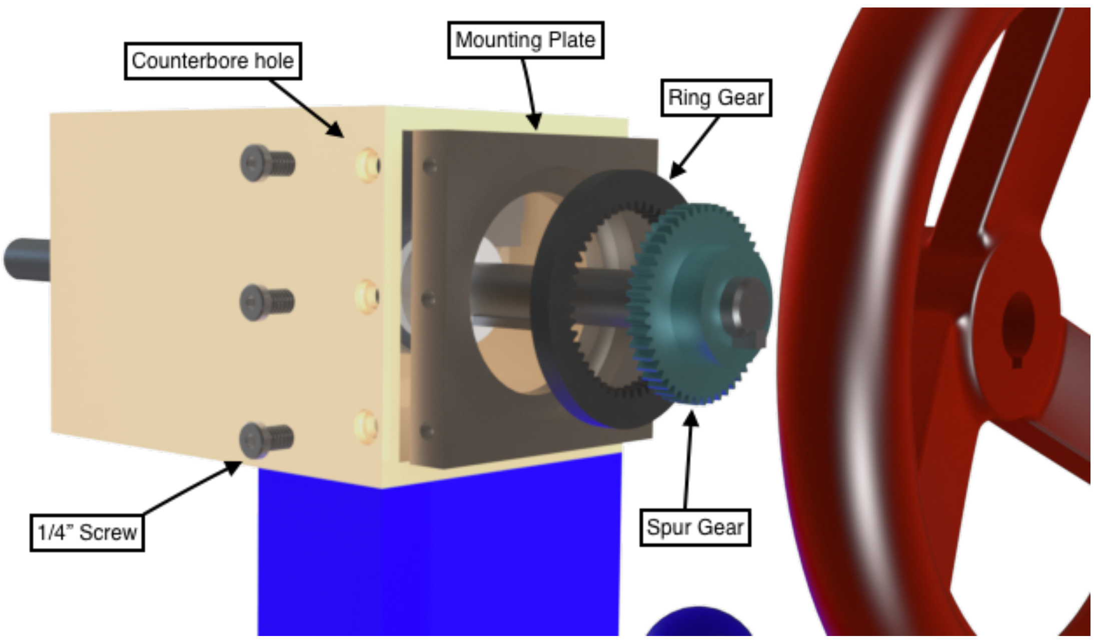

Figure 47: Exploded view of mechanical hub

The ring gear welded onto the mounting plate is made from 6061-T6 aluminum with an outer diameter of 2.75 [in]. The selected ring gear contains 48 teeth with a diametral pitch of 24. Furthermore, the pressure angle is 20°, pitch diameter is 2 [in] and the face width is 1/4 [in]. A matching aluminum spur gear containing 48 teeth with a diametral pitch of 24 interlocks with the ring gear. In addition, the pitch diameter is 2

[in], the bore diameter is 0.625 [in], the face width is 1/4 [in], and the pressure angle of 20°. The spur gear is attached to a 0.625 [in] diameter aluminum shaft. A key measuring 3/16 [in] x 3/16 [in] is slotted between the shaft and spur gear, where a setscrew from the spur gear secures the gear longitudinally along the shaft. The purpose of the gear system is to utilize it as an indexing method for rotation about the horizontal axis. The gear system allows the assembly technicians to manipulate the orientation of the vane box by 7.5° increments. Other design ideas were considered for indexing such as a spline connection, and custom plate and pin. The spline connection was not selected because further investigation identified a flaw that requires the spline to have constant force inwards toward the mating spline. The inward force is required because the saw tooth feature allows the assembly to rotate if a large enough force is applied even when the spline is engaged. The other design consideration was utilizing a circular plate with holes around the circumference and a pin to lock the assembly in place. The idea was not selected because to be able to index the rotation every 7.5°, the plate would have to be fairly large, making the process cumbersome.

The 2024-T4 aluminum shaft, as mentioned earlier, has the spur gear attached with assistance from a key and setscrew. In addition, the shaft for hub A has a hand wheel, two shaft collars, a steel spring, and a custom made 6061-T6 aluminum plate attached as seen in Figure 48. The shaft allows the whole vane box assembly to rotate and is the critical component that supports the entire load. It is important to note that the shaft is considered as part of the mechanical hub and the rotating fork. The hand wheel is attached to the external end of the shaft by a key and setscrew. The aluminum hand wheel has an 8 [in] outer diameter with a 0.625 [in] bore diameter. The hand wheel provides an easy method for the assembly technician to grasp the mechanical system to manipulate the vane box. Two shaft collars clamp onto the shaft at specific locations to prevent the range of motion the shaft can travel. Furthermore, a spring is situated on the shaft between the shaft collar and pillowblock bearing. The spring provides resistance on the shaft when the spur gear is to be disengaged, as well as assisting the spur gear in re-engaging into the ring gear. The range of travel for the shaft is limited as a safety feature because the shaft may experience an applied load large enough to overcome the spring force. This would result in the custom aluminum plate to go beyond the support and potentially cause heavy damage to the vane box assembly, handling tool, and operators. The custom aluminum plate is part of the rotating fork and will be discussed in section 2.1.3.3.

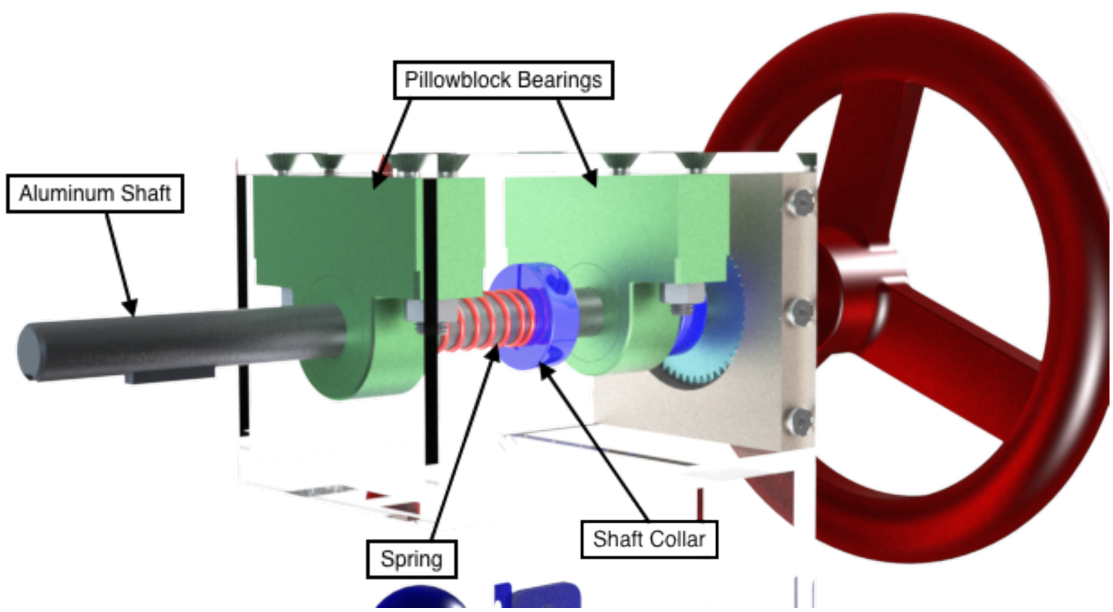

Figure 48: Transparent view of mechanical hub

Mounted inside on the top face of hub A are two self-lubricating pillowblock bearings, where bearing one is flush with the end face of the hub and the other bearing is spaced 3 [in] away from the first bearing. The pillowblock bearings are PTFE-filled bronze and contain an aluminum housing. According to the supplier [4], these pillowblock bearings are rated for loads up to 8000 [psi], and the max load experienced by any pillowblock bearings used for the main frame was calculated as 275 [psi]. The detailed steps for the aforementioned calculations can be found in Appendix B. Therefore, the selected bearings are functional for their application. The bearings have a 0.625 [in] bore diameter, and are mounted to aluminum blocks acting as spacers to make sure the bearings are centred within the hub. 5/16 [in]-18 countersunk bolts with a head angle of 82° are the fasteners chosen for mounting the bearings. The countersunk bolts are made from 316-stainless steel with a length of 2 [in]. Countersunk bolts are chosen for the same reasons mentioned in section 2.1.3.1. The bearings provide locations for the shaft to transfer the load onto the hub. On either side of bearing two, the shaft collars are clamped onto the shaft. In between the shaft collar and bearing one is a spring, as seen in Figure 48, that provides 20 [lb/in] of resistance.

As previously mentioned, hub A and B are slightly different. Hub B contains a shaft with only two shaft collars attached to the shaft. The same two pillowblock bearings are mounted at the same locations on hub B with the shaft collars on either side of bearing two to restrict travel of the shaft. This is because it acts as an idler shaft and will rotate along with the rest of the vane box assembly when the driveshaft is rotated.

To ensure that the mechanical hub does not fail due to bending loads, a preliminary FEA was performed on the aluminum hub and shaft separately. The shaft is the main component withstanding the bending load for the vane box; thus the primary part to perform FEA on. The shaft is fixed at the two pillowblock bearings located in the mechanical hub and the forces are applied at the locations of the shaft interfacing with the pillowblock bearing and aluminum plate. The computed mesh for the corresponding fixtures and external loads is shown in Figure 49.

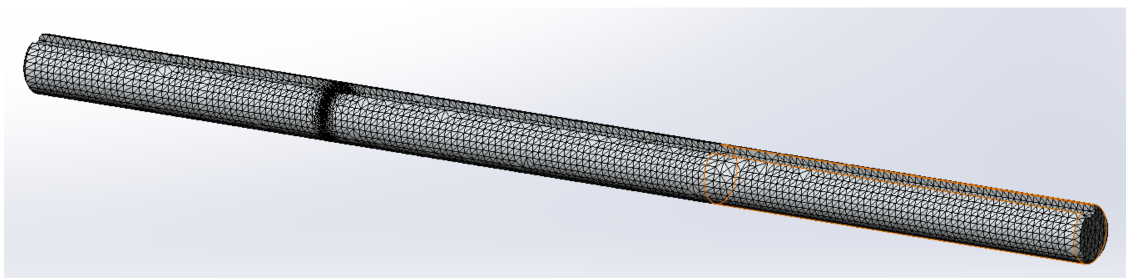

Figure 49: Keyed shaft mesh

The von Mises stress is pictured in Figure 50 with the max stress located at the edge of the first pillowblock bearing. This is expected because the majority of the load will be supported through the first bearing. The max stress is determined as 7.68×10^7 [Pa], which is less than the yield stress of the 2024-T4 aluminum shaft. The corresponding safety factor for the keyed shaft is 4.23 and thus satisfies the safety requirement.

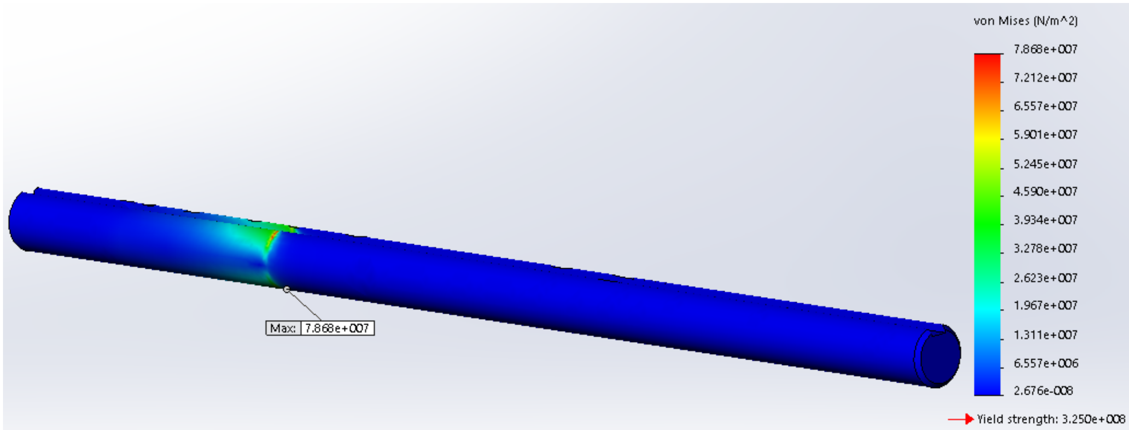

Figure 50: Keyed shaft max von Mises stress distribution

Shown in Figure 51 is the max deformation of the shaft scaled by 8769:1, which is 0.004947 [in] and is located at the shaft end in the rotating fork. Since the deformation is so minimal, there is no concern whether the shaft will bind in the bearings or not.

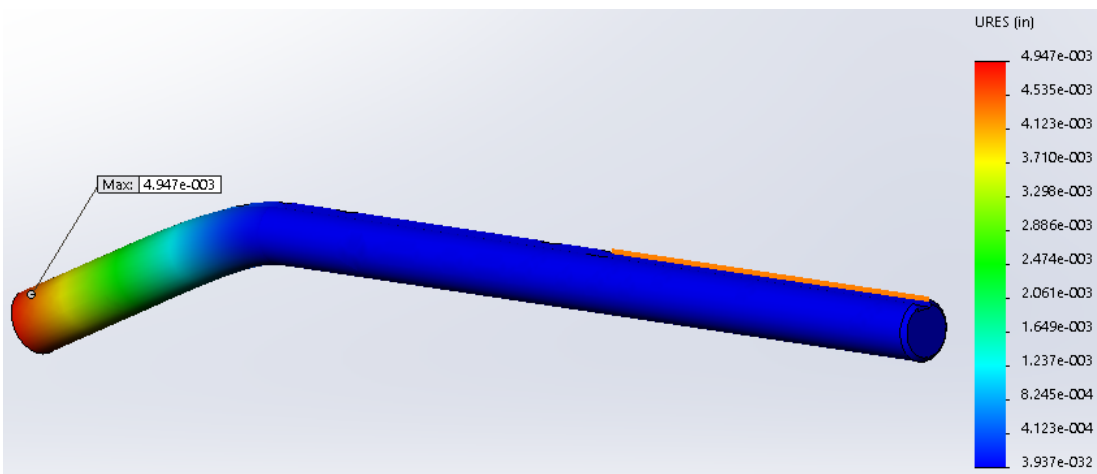

Figure 51: Keyed shaft displacement distribution with a scale of 8769:1

A stress convergence plot is shown in Figure 52 and the convergence plot is generated using the h-adaptive methodology to confirm that the FEA was applied correctly. From Figure 52, the max von Mises stress converges to a normalized value of 1.00 and confirming the FEA results are applicable.

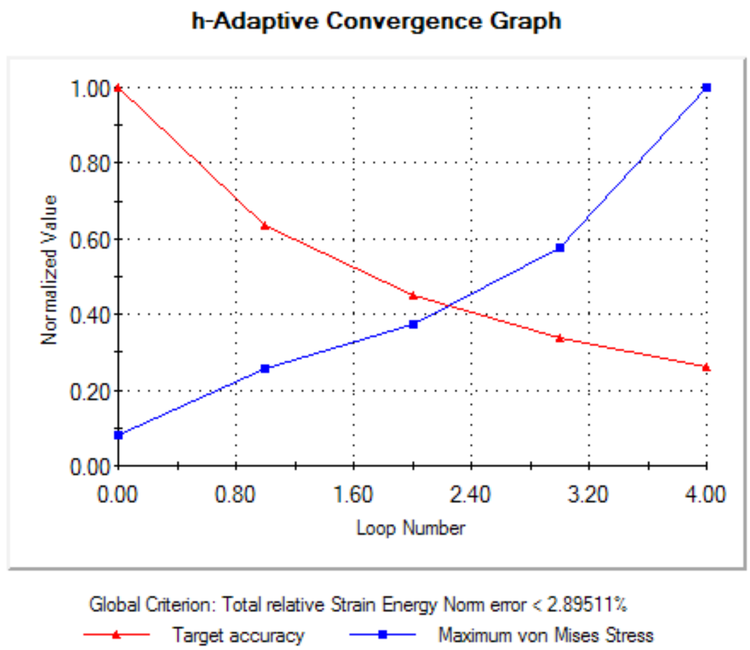

Figure 52: Keyed shaft convergence graph

The next component analyzed with FEA is the mechanical hub. The hub is fixed at the surface welded to the stiffener and the applied forces are located on the countersunk holes where the pillowblock bearings are mounted. The generated mesh with the applicable fixtures and forces applied are shown in Figure 53.

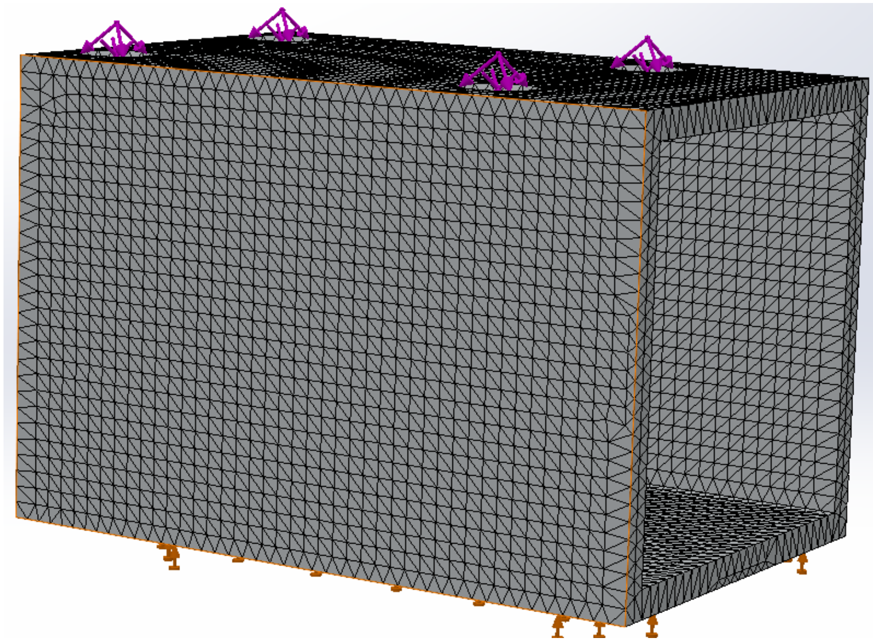

Figure 53: Mechanical hub mesh

Computing the FEA, the max displacement experienced by the hub is 0.0004015 [in]. The location of max displacement occurs on the top surface of the end interfacing with the rotating fork as seen in Figure 54. The result is expected because the front pillowblock bearing is supporting most of the load and transferring the load onto the mechanical hub. Since the max displacement is small, there is no concern of the structure deforming.

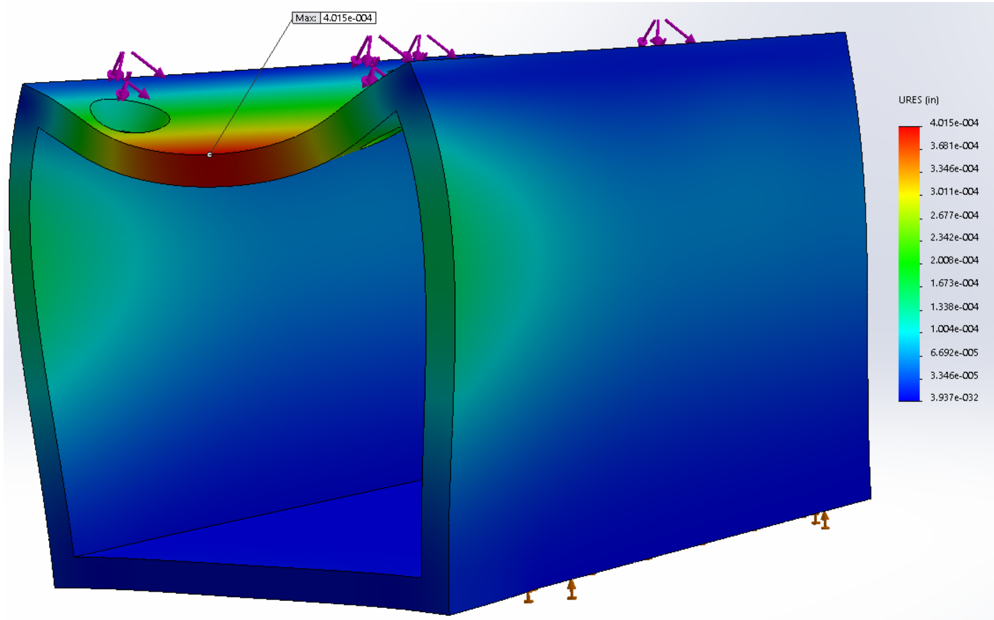

Figure 54: Mechanical hub displacement distribution with a scale of 12409:1

The max von Mises stress results are shown in Figure 55, where the max stress experienced by the mechanical hub is 1.586 x 10^7 [Pa]. The corresponding safety factor is approximately 17, which is above the safety factor requirement [3].

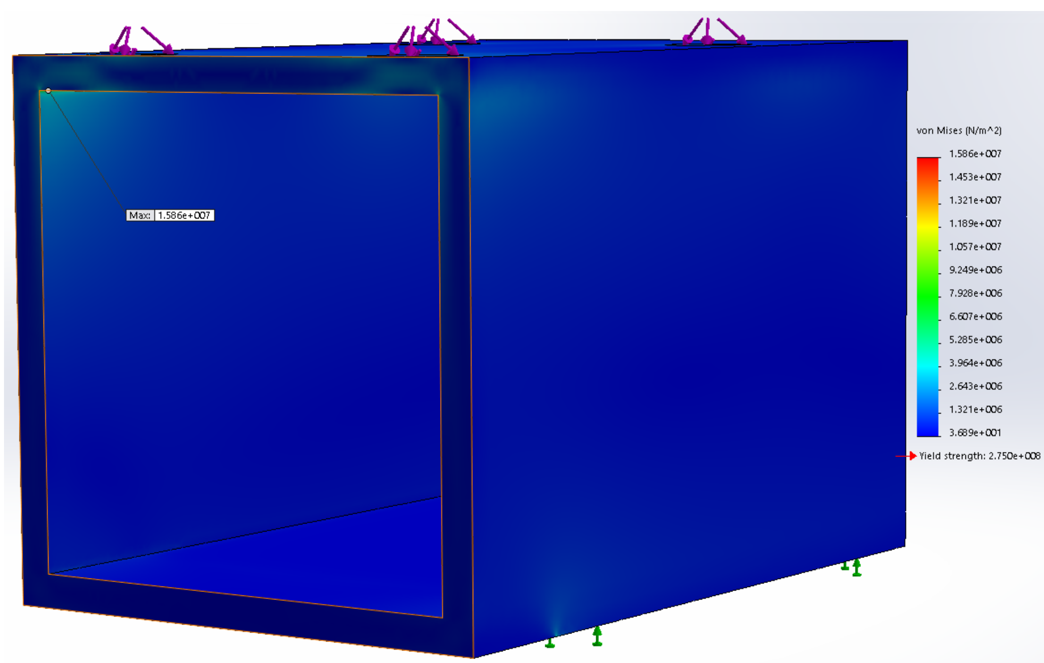

Figure 55: Mechanical hub max von Mises stress distribution

Using the h-adaptive methodology for conducting FEA, the convergence plot for the max von Mises stress is shown in Figure 56. It is observed from Figure 56 that the max von Mises stress converges to a normalized value of 1.00 and ensures that the FEA results are usable.

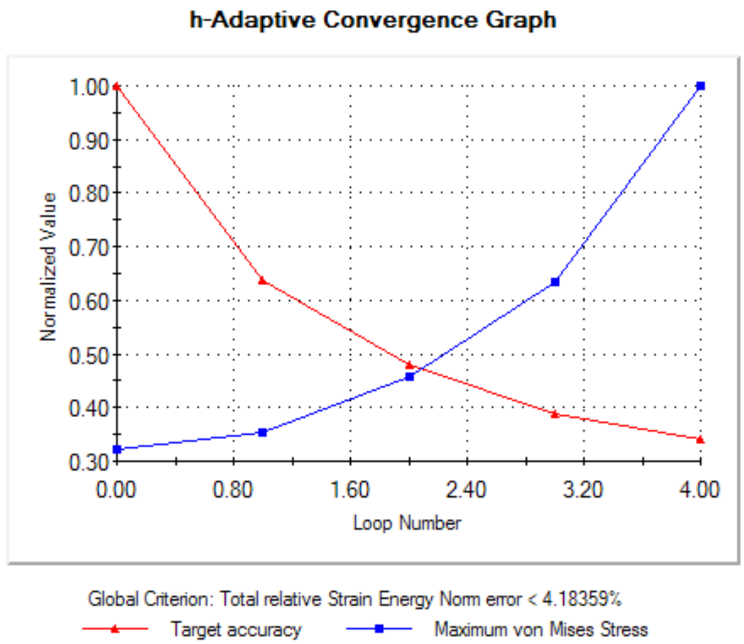

Figure 56: Mechanical hub convergence graph

From the results of the FEA performed on the shaft and mechanical hub, our team is confident that the component will not fail due to yielding and satisfies the safety requirement of 3 times yield stress.

2.1.3.3 Rotating Fork

The rotating fork is aligned horizontally with the mechanical hubs and similar to the mechanical hub, the rotating fork is different for the driveshaft and the idler shaft. Both rotating fork structures consist of a single 2 [in] x 6 [in] x 1/4 [in] 6061-T6 aluminum rectangular tube with a length of 20.48 [in], shown in Figure 57. Centred inside both tubes, a self-lubricating aluminum pillow block PTFE-filled bronze bearing is mounted to the top surface. This pillow block bearing is supporting the shaft from the mechanical hub and is responsible for transferring half of the load from the vane box. Many design proposals include but are not limited to, flange mount bearings, sleeve bushings, linear bearings and friction fit bearings, were considered in transferring the load onto the shaft. But ultimately, the team decided a pillowblock bearing best satisfies the function required because it can be mechanically attached, is readily available, and occupies minimal space. The bearing is self-lubricating to allow the shaft to rotate smoothly and is sealed to prevent debris from entering the bearing. In addition to the bearings, both rotating forks interface with the tapered plug design. The pneumatic cylinders and bushing from the plug design are strategically mounted to the rotating fork at specific distances to ensure that the centre of gravity of the whole vane box assembly is always in-line with the aluminum shaft. This reduces instability concerns when the vane box is not directly horizontal and positioned in different orientations.

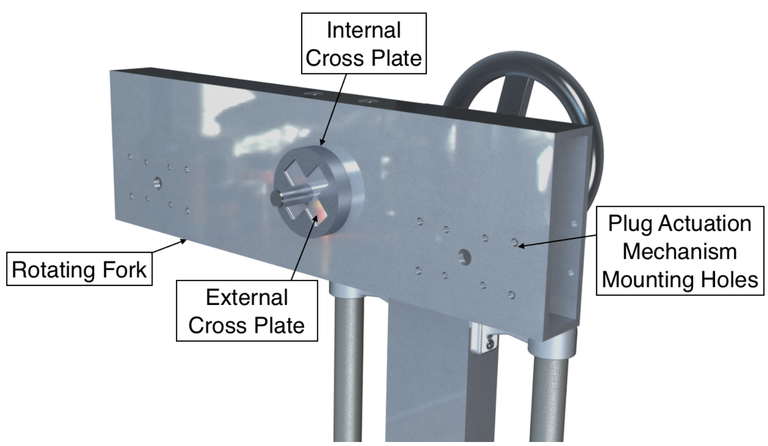

Figure 57: Rotating fork render

The driving rotating fork, A, pictured in Figure 57 has a 1 [in] diameter cutout on both 6 [in] faces in order for the shaft to penetrate the rotating fork. As mentioned in section 2.1.3.2, the shaft is a component in the mechanical hub and the rotating fork. The section of the shaft that is within the rotating fork contains a custom made 6061-T6 aluminum plate attached to the end. Seen in Figure 58, the aluminum plate is 1/4 [in] thick and is manufactured into the shape of a cross. A key and setscrew secures the plate, laterally and longitudinally, to the shaft. The custom aluminum cross plate is bounded by a larger aluminum plate. The larger aluminum plate is 3 [in] in outer diameter with a thickness of 3/4 [in], and is shown in Figure 58. The centre of the plate has the cross shape from the aluminum cross plate removed so that the two plates can interlock together. The larger aluminum plate is welded onto the outer face of the tube, with the centre of the plate concentric to the shaft. The purpose of the two plates is to support the rotating fork structure while allowing the shaft to disengage and engage with the gear from the mechanical hub.

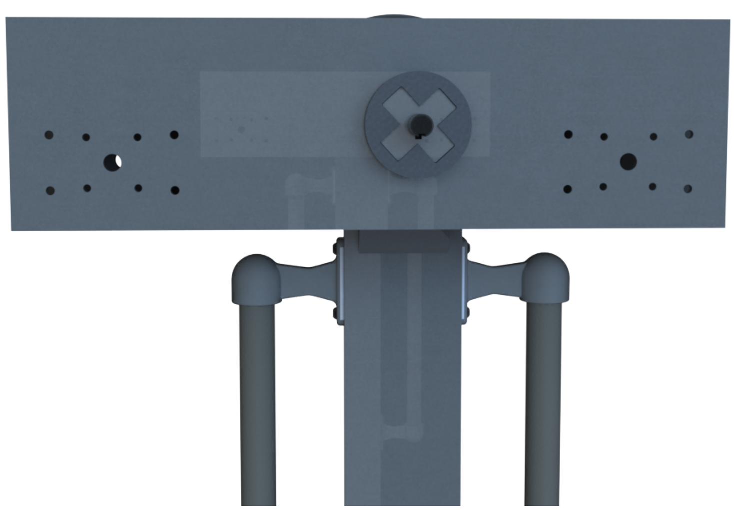

Figure 58: Aluminum cross render

Other design considerations for supporting the rotating fork were contemplated. One design consideration incorporated the same gear system on the mechanical hub to support the rotating fork. The gears would remain engaged permanently but the amount of teeth engagement would not be required. Therefore, the gears weren't selected because of high cost, as well as increased complexity in comparison to custom-made aluminum plates. Another design considered was a flange mounted bushing that was mounted to the aluminum tube. The bushing would allow the shaft to function similarly as it would with the custom aluminum plates. The disadvantages of the bushing are that the sizes required are not readily available and the amount of force it could handle was not sufficient for our purposes; thus the mounted bushing was not selected to be in the design.

The driven rotating fork, B, consists of fewer parts and is much simpler to manufacture and implement. The aluminum tube has the same 1 [in] diameter cut out on the wall closest to the mechanical hub but on the opposite face, there is no hole cutout. The reasoning this difference is because there is no need for the custom aluminum plates on the driven rotating fork. The shaft rests on the pillowblock bearing and rotates as the driveshaft from the other mechanical hub turns the vane box assembly.

To confirm that the rotating forks are structurally strong enough for the design application, FEA was performed on the structure. The aluminum tube experiences forces at the fastener holes that are attached to the plugs. Weight of the vane box and plug actuation mechanism generates a downward force on the fastener holes while the spring reaction force applies a load outwards. The front face of the aluminum tube is fixed as a slider while the interface between the mechanical hub and rotating fork is fixed. The generated mesh for the boundary conditions applied is seen in Figure 59.

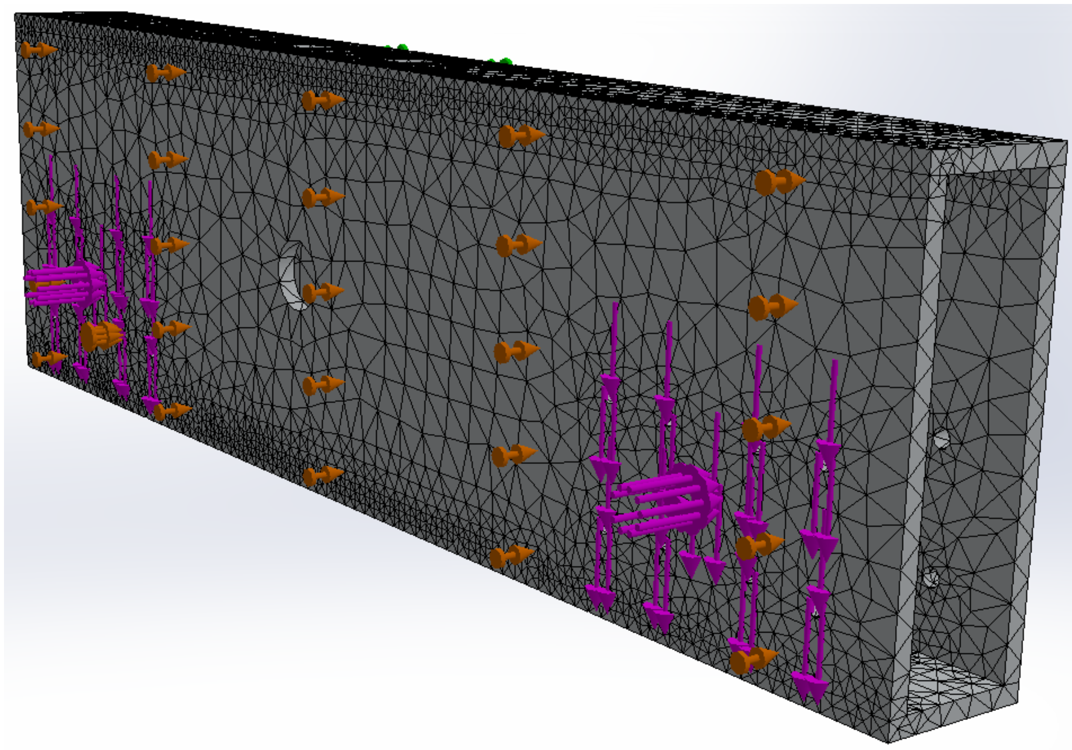

Figure 59: Rotating fork mesh

The von Mises stress analysis is pictured in Figure 60 and the max stress location is at the top edge of the interface between the mechanical hub and the rotating fork. The corresponding max stress value is 1.076×10^{7} [Pa] which is less than the 2.75×10^{8} [Pa] yield stress of 6061-T6 aluminum. The safety factor for yield stress is approximately 25 and satisfies the safety requirement [3].

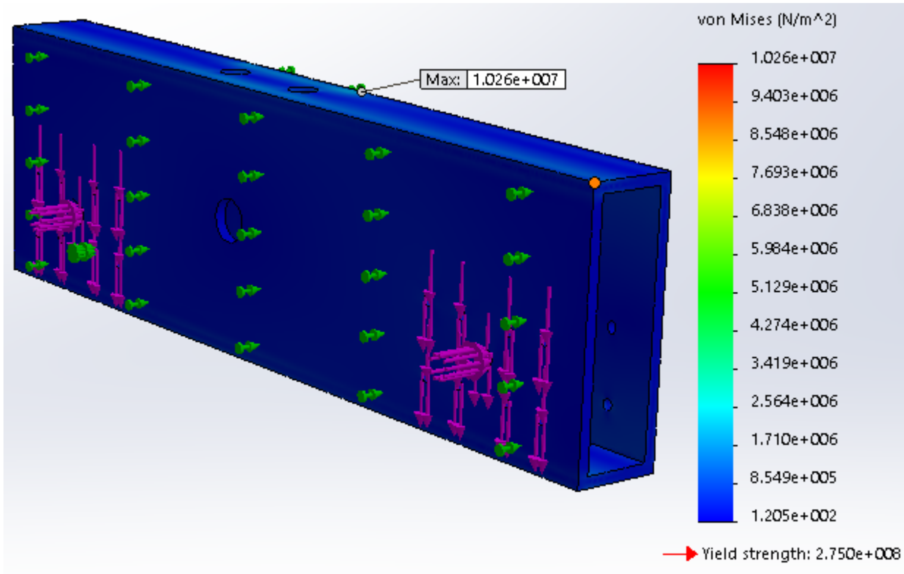

Figure 60: Rotating fork max von Mises stress distribution

Shown in Figure 61 is the 27835:1 scaled deformation of the rotating fork with the applied load. The max displacement of 0.000259 [in] is located at end of the tube. Since the deformation is infinitesimal, it can be neglected.

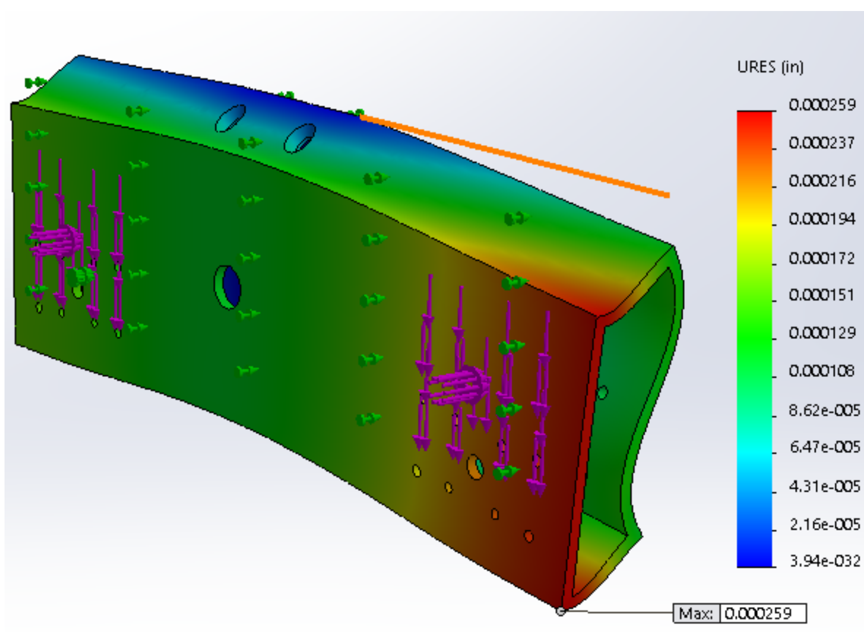

Figure 61: Rotating fork displacement distribution with a scale of 27835:1

A convergence plot of max von Mises stress as the mesh size decrease converges to a normalized value of 1.00, which is shown in Figure 62. From the convergence plot, our team determined that the FEA results are usable.

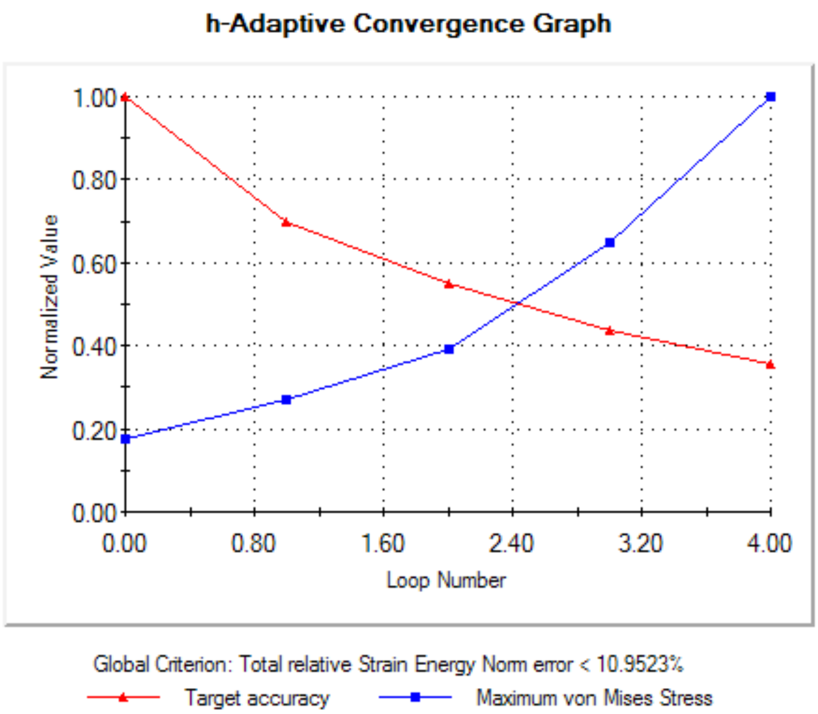

Figure 62: Rotating fork convergence graph

To operate the main frame as a full section, the assembly technician pushes in the hand wheel to disengage the gear system and rotate the vane box assembly. Moreover, when the desired orientation is achieved, the shaft will spring back and then the gear will be engaged; thus prohibiting further rotation.

2.1.4 Plug Actuation Mechanism

The handling tool contains four Teflon® plugs to grasp the vane box which, using a combination of springs and pneumatic cylinders, moves in and out of bores located on the vane box. Two plugs are held on each of the rotating forks, with each plug using one compression spring and two pneumatic cylinders for actuation. Each plug mechanism has a 2 [in] travel length for a 4 [in] overall clearance during loading and unloading. The compression springs provide a constant force to the plugs; pushing the plugs forward into the vane box. When the cylinders need to be retracted the pneumatic cylinders are pressurized, counteracting the spring and pulling the plugs to their retracted position. This actuation system provides passive holding of the part so that the vane box will not be released in the event of a loss of pressure, and allows the loaded tool to be moved around the factory without pneumatic hoses or electrical cables.

2.1.4.1 Plug Actuation Mechanism Components

Between the shaft shoulder and plug is a 1/2 [in] thick circular aluminum slider plate, in which the pneumatic cylinders are mounted and spring pushes onto. This shaft assembly is held by a 4 [in] long flange-mount linear ball bearing, which is mounted to the rotating fork. Also attached to the rotating fork is a 3/16 [in] spacer plate that provides the necessary spacing for the two 1 [in] bore double acting air cylinders, which bolt into the rotating fork through the spacer plate. The compression spring is concentric to the shaft and presses against the flange of the bearing and the slider plate. Two safety guards, made of acrylic tubing, cover the assembly to cover pinch points and are attached to the slider plate and spacer plate. Figure 63 shows the plug actuation mechanism.

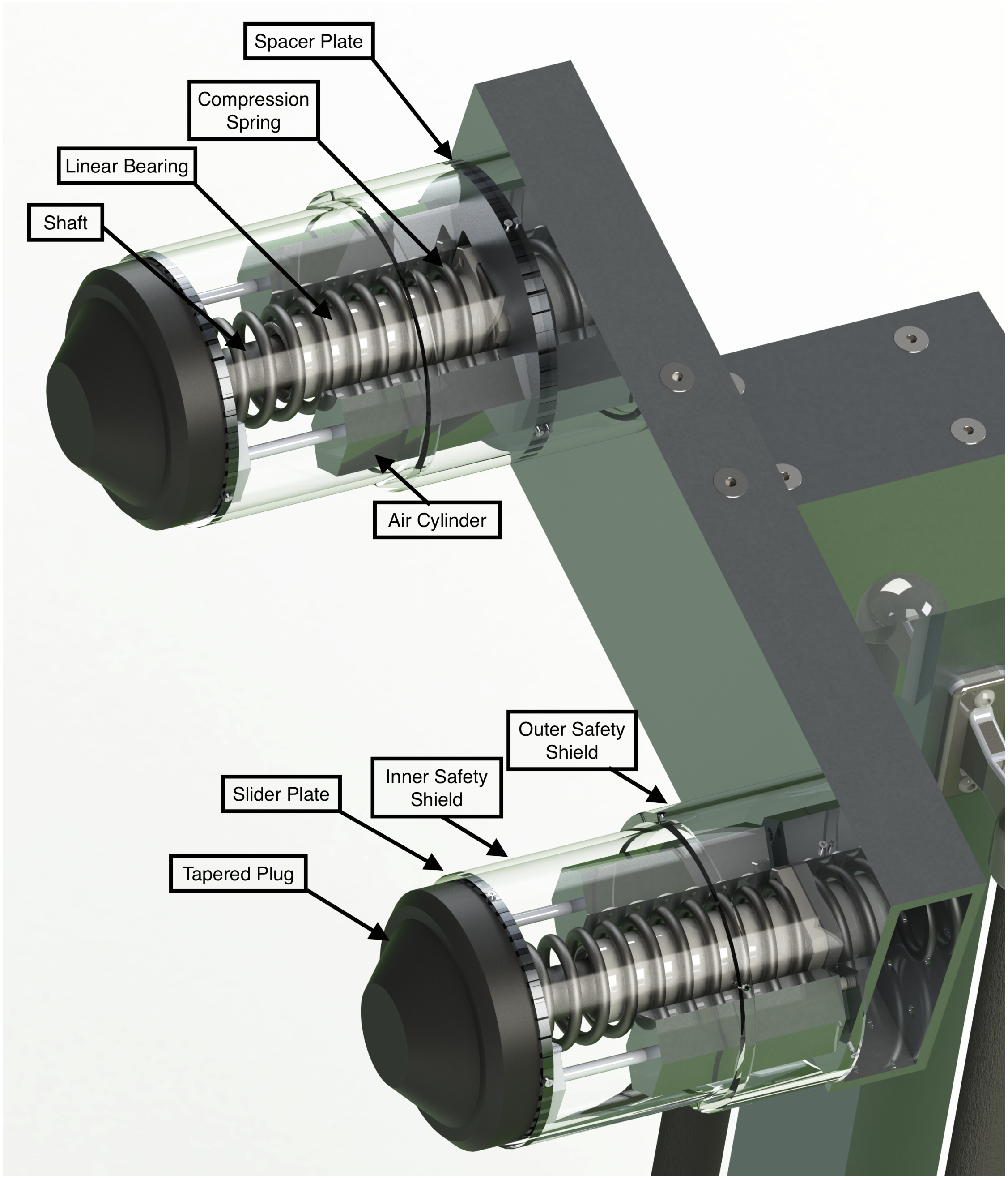

Figure 63: Plug actuation assembly

Each of the four plug assemblies in the plug actuation mechanism consists of a Teflon® plug, which is threaded onto to a 1 [in] diameter steel shaft. The plugs are made out of Teflon® as this material is much softer than aluminum and has a low friction coefficient. Softness is important to ensure that the plugs do not scratch or otherwise damage the aluminum vane box and friction must be kept to a minimum to ensure that the plugs move easily into and out of the part. The plugs are tapered, so that they self-centre when sliding into the vane box, and have a flattened section after the taper to ensure the vane box is protected against the actuation mechanism behind the plug. These plugs must be custom made, and as such, the major diameter was chosen to be a standard stock size of 5 [in].

The shafts are 1 [in] in diameter with a 5/8 [in]-11 thread and a 7 1/4 [in] overall length and made of 52100 steel. The diameter and material were chosen to ensure the shafts would support the weight of the vane box while the length provides enough travel for the plugs to be actuated in and out 2 [in]. The shaft is threaded, as this method of attaching the plugs does not require fasteners, which may protrude from the plugs and damage the vane box.

The slider plates are made of 1/2 [in] thick 6061-T6 aluminum and have an outer diameter of 5 [in]. These plates connect the shaft and pneumatic cylinders, provide a surface for the spring to push on, and provide a mounting location for the outer safety shield. Each cylinder attaches to the slider plate using four 8 - 32 flat-head socket cap screws while the safety shield is attached using four 2 - 56 countersink socket cap screws. The plate thickness of 1/2 [in] was chosen to ensure the plates do not deform under the imparted forces of the air cylinders and spring while the 5 [in] outer diameter gives sufficient room behind the plugs for the rest of the assembly. We chose 6061-T6 aluminum as a material because it is readily available, has adequate strength, and is easily machinable. These traits are important, as these parts will have to be custom made for the handling tool.

The bearings chosen are steel flange-mounted linear ball bearings with a 4 [in] length and a 1 [in] inner diameter. The bearings are attached to the rotating fork using four 10-24 socket-head cap screws. These bearings were chosen because their long length prevents the shaft from binding as it actuates and because they can tolerate a large load.

The spacer plates provide enough space between the air cylinders and bearings to allow the cylinders to be fully retracted. Additionally, the plates provide a mounting location for the outer safety shield, which attaches to the spacer plate using four 2-56 flat-head socket cap screws. These plates are made of 6061-T6 aluminum for ease of manufacture, as they must be custom made.

The air cylinders that we have sourced for this tool are compact non-rotating double acting cylinders with aluminum bodies, 1 [in] bores, and 2 [in] of travel. These cylinders were chosen because they are compact and their double acting nature allows them to be used to 'pull' from an extended position without a vacuum. These pneumatic cylinders can operate up to 145 [psi] which is well above our 100 [psi] air source. The 1 [in] bore size was determined to provide an adequate draw force of 114 [lb] to counteract the spring when using Magellan Aerospace's shop air system. Each cylinder attaches to a slider plate using four 8-32 flat-head socket cap screws and to the rotating fork using two 1/4 [in]-20 socket head cap screws.

For information regarding the pneumatic connections and controls for the air cylinders please see section 2.1.5.

The springs selected by our team are tempered steel, 2.187 [in] outer diameter, 1/4 [in] wire diameter compression springs with a spring coefficient of 61.8 [lb/in]. The springs were chosen to provide as much holding power onto the vane box as possible while still allowing the plugs to be retracted using small air cylinders. Each spring provides 100 [lb] of force onto the vane box in the extended position and 224 [lb] when the plug assembly is retracted. While a supplier was found for these springs, it should be noted that they must be cut to 7 5/8 [in] from their original 8 [in] lengths in order to provide the correct amount of force onto the vane box.

The safety shields are made of medium strength acrylic and have outer diameters of 5 1/4 [in] and 5 3/4 [in] respectively. These shields prevent access to the inner plug actuation mechanism, which mitigates potential injuries caused by the numerous pinch points inside. The inner safety shield attaches to the slider plate using four 2-56 flat-head socket head cap screws while the outer safety shield attaches to the spacer plate using the same four screw arrangement.

2.1.4.2 Plug Actuation Mechanism Stress Analysis

The vane box load propagates through the plugs to the shaft then through the bearings and onto the rotating fork. Descriptions of the analysis used on these various components are discussed in this section.

FEA was used to analyze the plugs because of their complex geometry. We chose a curvature based mesh and held the plug using fixed geometry in the central threaded hole. Forces were applied to the plug using a bearing load to simulate the loading of the plug by the vane box, and a pressure load to simulate the force applied to the back of the plug by the compression spring. As the load on the plug is symmetric, the model was simplified using symmetry. The fixtures used in this model, along with the force applied to the back of the plug, can be seen in Figure 64, while Figure 65 illustrates the bearing load applied to the plug.

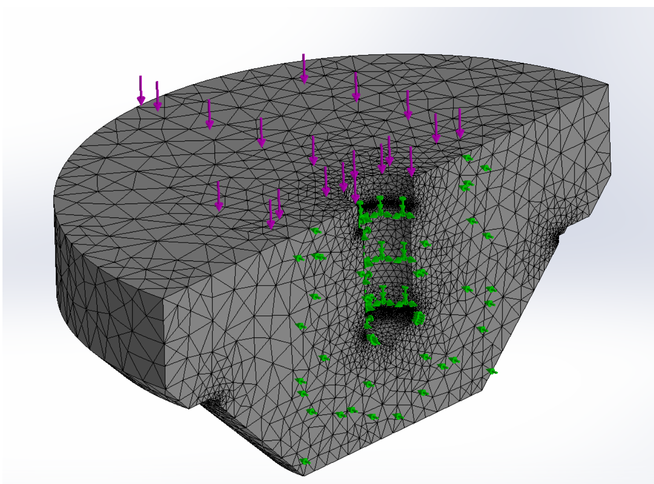

Figure 64: Tapered plug initial mesh, fixtures, and forces applied

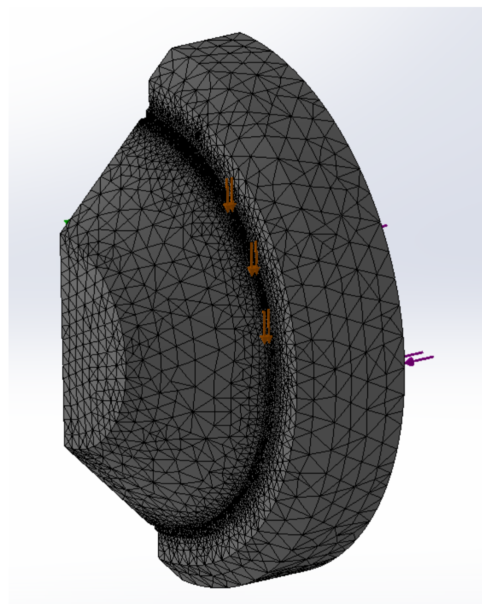

Figure 65: Tapered plug initial mesh and bearing load

An iterative h-adaptive method was used with a target accuracy of 98% and mesh coarsening. After six iterations the FEA was able to converge to within 2%, as seen in Figure 66, and can be considered reliable.

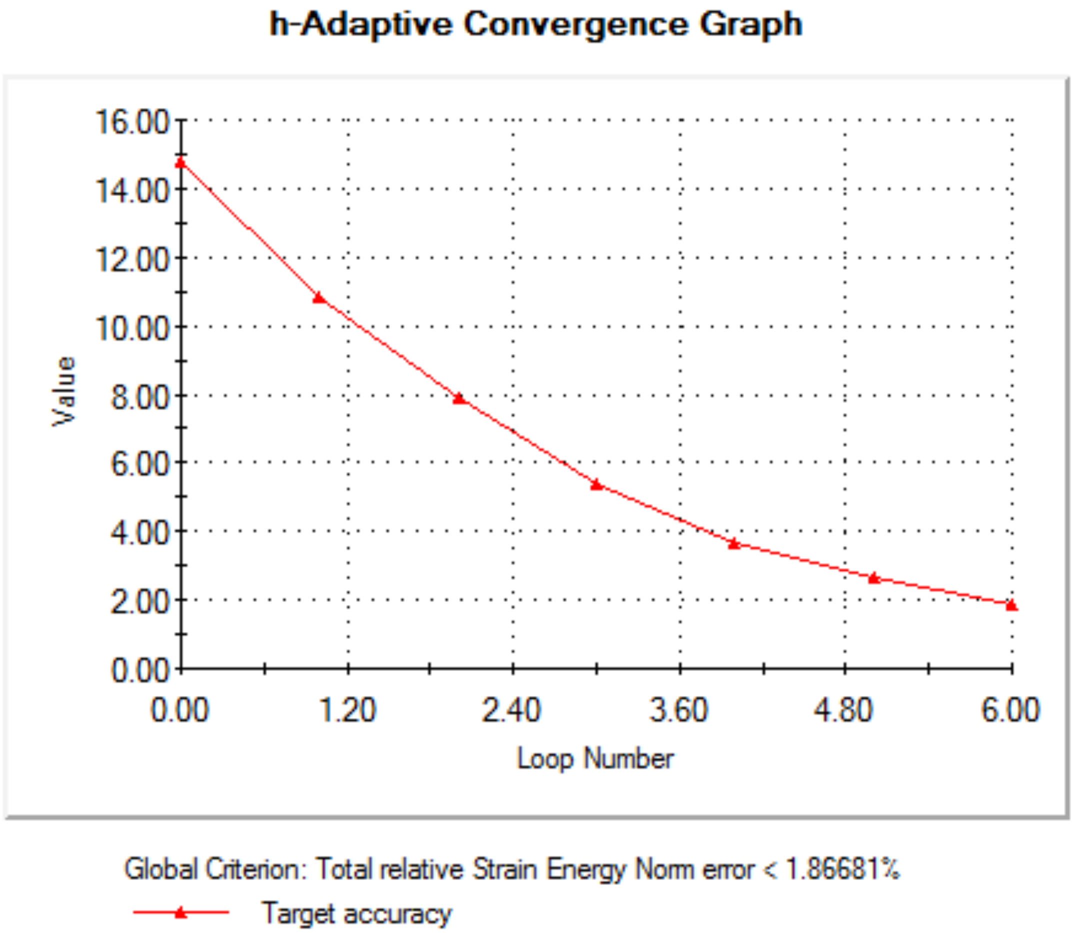

Figure 66: Plug h-adaptive convergence plot

From this analysis we determined that the areas of highest deformation are the upper portion of the plug where the vane box sits, and the inner edge of the central mounting hole where the shaft is fixed. As seen in Figure 67, there is little stress in the rest of the tapered plug.

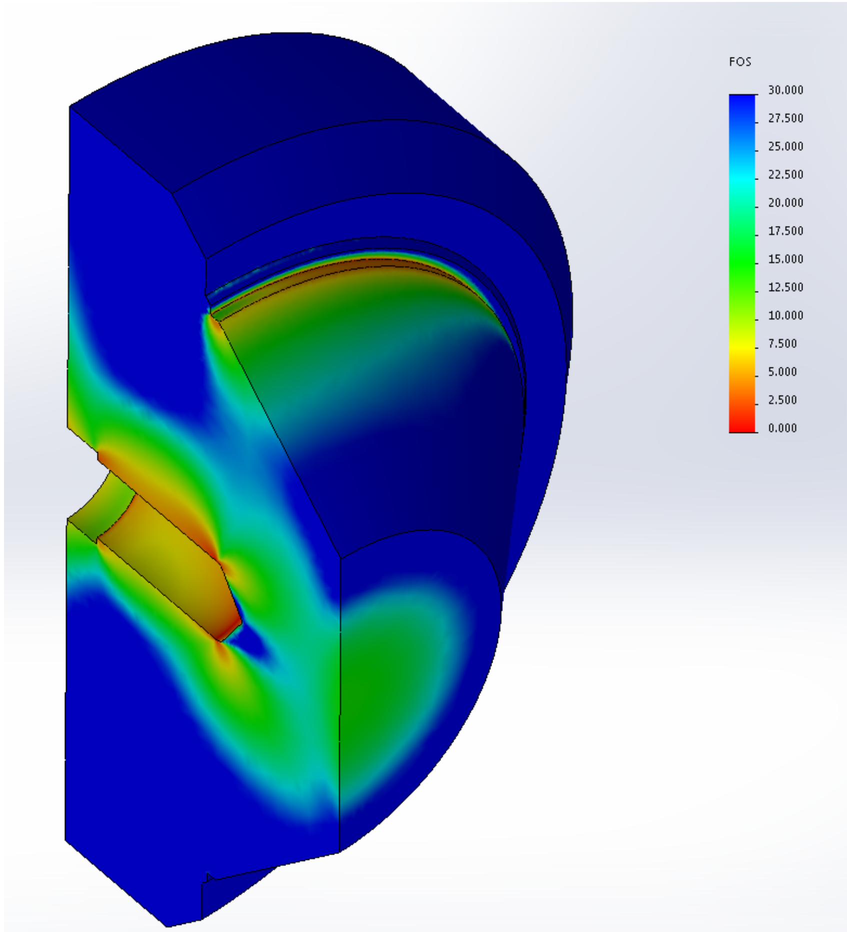

Figure 67: Plug factor of safety plot

While most of the plug experiences very low amounts of stress, the boundaries of the fixed geometry in the mounting hole experiences stress concentrations that are much greater. These concentrations are likely due to the boundary conditions themselves, as the stresses at these boundaries can be seen to approach infinity, but should be treated with caution. As seen in Figure 68 below, the edges of the fixed geometry have factors of safety approaching zero. Further FEA testing should be performed to ensure that the plugs are structurally sound.

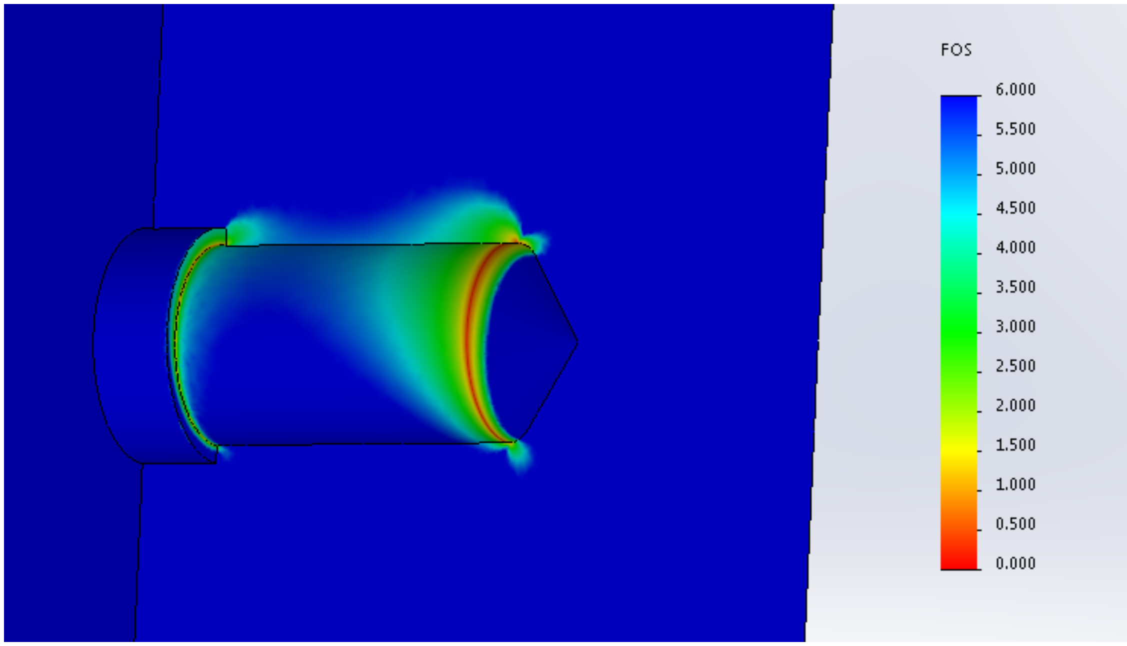

Figure 68: Plug mounting hole factors of safety plot

In addition to the stress concentrations surrounding the boundary conditions, there is a thin section of high stress directly on the contact between the plug and vane box, as seen in Figure 69. This stress is once again concentrated on areas where different geometries meet and is minutely below our required factor of safety of 5 for ultimate stress. Given the large quantity of material surrounding these areas, the stresses experienced are considered acceptable, but should be monitored to ensure they do not compromise the part.

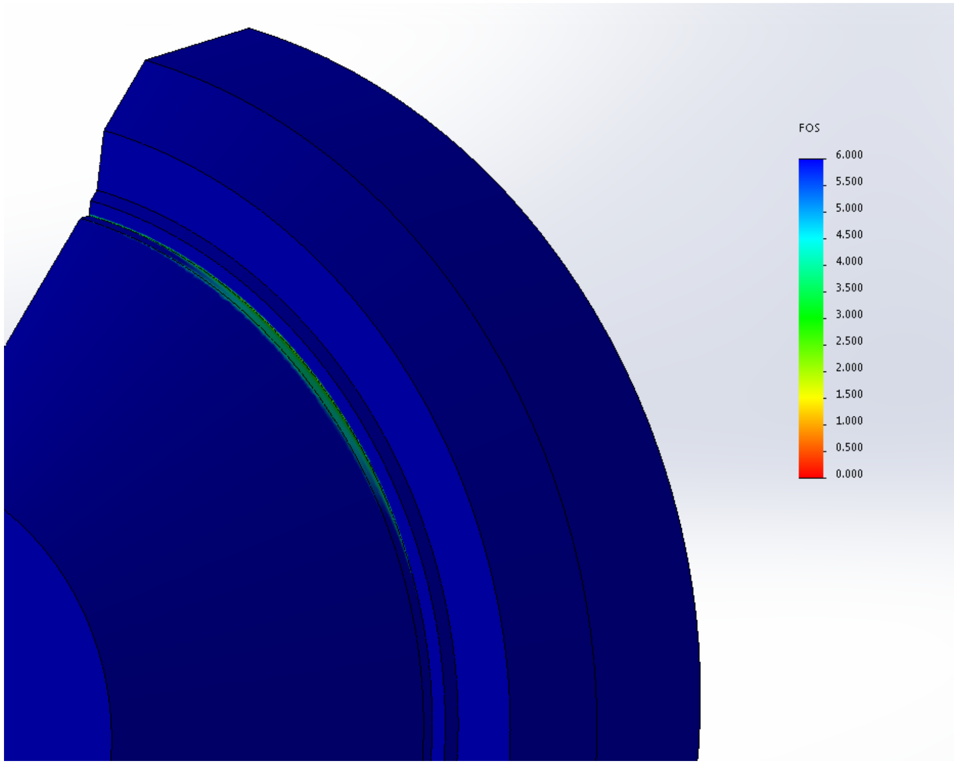

Figure 69: Plug factors of safety at loading point

The shaft has simple geometry and the forces acting upon it are known, and so the stresses were calculated by hand. This analysis was performed at the maximum extension of the shaft as this scenario has the largest applied moment. The calculations assume that the load from the plug is a point load and the shaft is supported by the vane box as a fixed support. From this analysis we determined that the shaft would be able to safely bear the applied load, experiencing a stress of 18420 [psi] with a factor of safety of 39. The detailed calculations of how the results were determined are found in Appendix B. While this factor of safety is extreme, the dimensions of the shaft were not reduced as shaft weight is not a concern, and a larger diameter allows for higher quality bearings to be used.

The force exerted onto the bearing from the shaft is 185 [lb] including a factor of safety of 5, and is still well under 353 [lb] maximum carrying capacity of the bearing as specified by the supplier [4]. As such, this bearing is adequate for our application.

The force from the bearing onto the 10-24 bolts, which connect the bearing to the rotating fork, was determined as 127 [lb] per bolt. This stress was much less than the bolt's maximum load capacity of 1982 [lb] and is considered as an acceptable load for the bolts.

2.1.5 Pneumatic Control System

The pneumatic system is composed of two parts, plug retraction and height adjustment. The system counteracts the spring force on the plugs and pulls them to their retracted position using four pairs of air cylinders located behind the plugs. The system also controls the overall height of the handling tool using two air cylinders located between the main frame and base frame. Both portions of the pneumatic system are controlled using a single control box located below the hand wheel on the side of the main frame.

Pneumatics were chosen over hydraulic and electric methods to control the retraction of the plugs and to adjust the overall height of the handling tool because Magellan Aerospace already has a shop air system in place and pneumatic controls are simpler and less expensive than the other options. Furthermore, pneumatics were chosen over manual mechanisms because the force required to control the plugs, and raise the handling tool with the vane box are beyond the allowable limit one person can apply according to the Manitoba Workplace Health and Safety Act [3].

The pneumatic system operates using five 3-position, 2-way manual switch operated valves, one pressure relief valve, and three pairs of tuning valves. Two pressure gauges are included as well to indicate when the system is pressurized. A rendering of this system can be seen in Figure 70 as a visual aid.

Figure 70: Pneumatic control box

The five switches seen in Figure 70 control from left to right: the loaded/unloaded tuning system, air into the plug adjustment and height adjustment subsystems, air into the system, plug extension/retraction, and height extension/retraction. To ensure that the system cannot be pressurized when disconnected from the air source, the last three switches are attached using a threaded rod such that they must be in the same position at all times. The three combined switches are referred to as the extend/retract switch and causes the system to vent all pressure when it is turned off. Also, when a subsystem is set to retract, the combined switches prevent pressure from remaining inside the system when it is disconnected from power. If the system is pressurized while disconnected from power then an operator who is unaware of the current system state may accidentally cause the system to discharge and cause damage to equipment or injury to a person. The control box is mounted to the upright tube of the main frame and connects to the tool's air system using quick-attach couplings. The quick-attach couplings allow it to be removed and attached easily during assembly and maintenance.

The pneumatic control diagram for this system can be seen in Figure 71. The symbols used in the pneumatic control schematic diagram are defined in Figure 72. Please note that a detailed pneumatic diagram, including all fittings used, can be found in Appendix C.

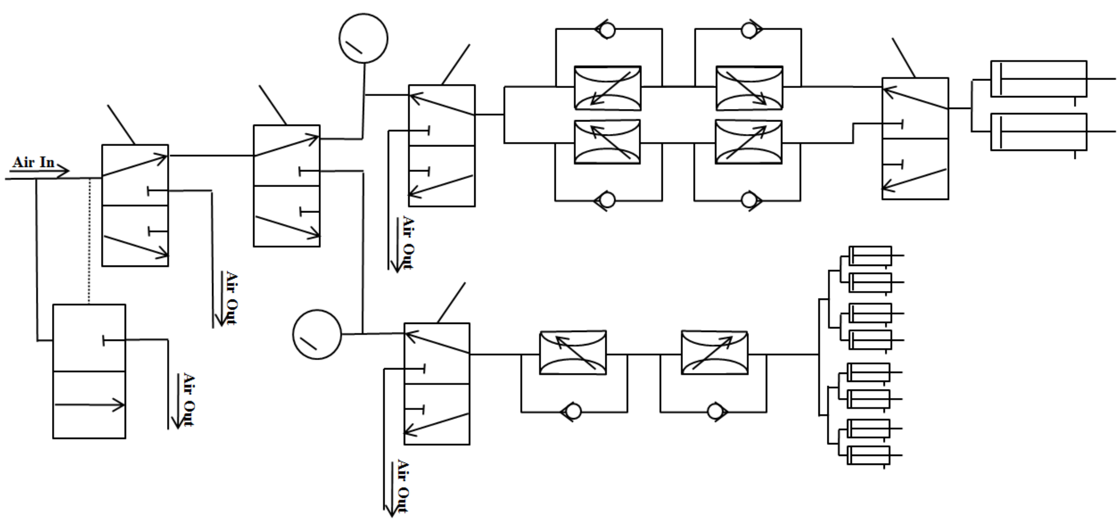

Figure 71: Pneumatic control schematic diagram

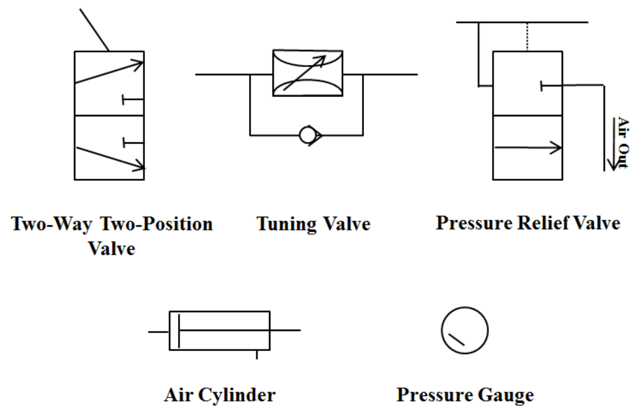

Figure 72: Pneumatic diagram symbols

As seen in the Figure 71, when the system is set to allow the plugs to be retracted the air in/out switch is activated. This brings air into the system and to the plug/height switch, which must be set to the plug position. Next, the air passes through the tuner valves that allow the rate at which air flows into and out of the system to be adjusted, and into the cylinders which causes them to retract. When extending the cylinders, the air in/out switch is set to out, which causes the air in the system to escape back through the in/out switch to the atmosphere. Another approach to extend the cylinders can be done by setting the plug extension/retraction switch to retraction, which also vents the air in the cylinders into the atmosphere. The compression springs acting on the cylinders ensure that the cylinders retract fully.

Similarly, when raising the height of the handling tool the air in/out switch must be set to in and the plug/height switch must be set to height. Air flows into the system, through the in/out and plug/height switches, and into the two pairs of tuning valves for height adjustment. Air may only flow through one of the tuning valve pairs depending on the state of the loaded/unloaded valve. The tuning valves and control valve allow the system to be tuned separately for when the vane box is loaded and when the tool is operating without a load, allowing the system to be optimized for both states. Once air passes through the loaded/unloaded valve the air fills the two pneumatic cylinders and causes the tool to rise. When the handling tool is to be lowered, the in/out valve is set to out, which vents air into the atmosphere. This can also be done by setting the height extension/retraction switch to retraction, which vents the air in the cylinders into the atmosphere. The weight of the handling tool ensures the cylinders retract fully.

As mentioned previously, it is possible for the system to be pressurized but unpowered. This occurs if the plug or height cylinders have been fully or partially pressurized, and then the plug/height switch has been changed to the non-powered system. Afterwards, the in/out switch can be set to out without venting the previously selected system. This has been prevented in our design by attaching the in/out switch to the two extension/retraction switches so that whenever the system is turned off, the cylinders must also be set to retract; venting all latent air from the system.

In the event that the inlet pressure exceeds the safe operating limit of our pneumatic system, 115 [psi], a pressure relief valve located between the air inlet and in/out valve opens and vents the air into the surroundings. This relief valve prevents any damage which may occur in our system. Additionally, a pressure gauge is connected to both plug and height subsystems to warn the operator if the system has become over pressurized or has latent air after the system has been turned off.

The manual 3-way, 2-position pneumatic valves control the airflow in our system. The valve is 3-way and 2-position, meaning that there are three inlets into the valve of which two can be connected to each in two different states, with the third valve isolated.

We chose to have manually operated valves so that the system does not require electrical power. The valves sourced are the highest flow rate 3-way, 2-position manual valves that were found, 25 [scfm], and have 1/8 [in] female NPT threaded inlets.

The pressure relief valve ensures that if the air system becomes over pressurized it will vent air before any components fail. The valve we have selected releases air at 115 [psi] and has a 1/8 [in] male NPT threaded inlet.

The tuning valves control the flow rate of air in one direction while allowing air to flow freely the other way. When two valves are placed inlet to inlet they can be used to tune the airflow rate in both directions of a pipe. The tuning valves were selected because they have a high flow rate, 58 [scfm], and use NPT threading. The inlet and outlet of these valves are 3/8 [in] male and female NPT thread respectively.

With this pneumatic system, our handling tool can safely load/unload the vane box assembly, and provide height adjustability. For a full list of fittings used in this system, please see Appendix D.

2.2 Operation of the Vane Box Handling Tool

Our handling tool is designed to successfully hold and manipulate the vane box from a single standing position. The complete operating process of the handling tool is detailed in this section.

2.2.1 Loading and Unloading the Vane Box

The process to load the vane box onto the handling tool includes six steps from beginning to end. The steps are outlined in detail below.

Step 1: Locate and transport handling tool to vane box

One operator disengages the floor lock on the handling tool and with another operator, use the transport handles to move the handling tool to the vane box assembly workbench. Then engage the floor lock to prevent handling tool movement.

Step 2: Attach pneumatic system and adjust height

The operator attaches the requisite hoses from the shop air supply onto the handling tool to power the air cylinders. The operator then adjusts the handling tool accordingly to the desired height via the switches at the control panel. The high-load/low-load switch, the second switch from the left, must be set to the appropriate position depending if the tool is loaded or unloaded. After this the operator must set the system to height adjustment, using the first switch from the left. Next the system can be turned on and the handling tool can be raised using the three connected extend/retract switches. Figure 73 and Figure 74, show the range of height that the vane box can travel when the cylinders are extended and retracted, respectively.

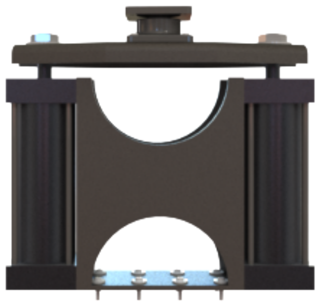

Figure 73: Central axle retracted

Figure 74: Central axle extended

Step 3: Retract tapered plugs

With the pneumatic system already attached from the previous step, adjusting the switches on the control panel can retract the tapered plugs. The system must be set to plug adjustment using the first switch from the left. Next to the three connected switches, the extend/retract control, on the right side of the control box are thrown. This allows air to move into the plug air cylinders and retract the plugs. The retracted and extended tapered plugs are shown in Figure 75 and Figure 76, respectively.

Figure 75: Tapered plug retracted

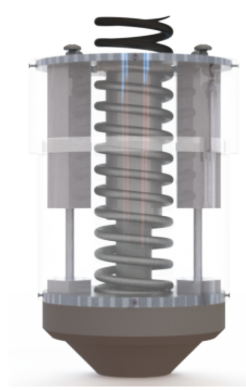

Figure 76: Tapered plugs extended

Step 4: Lift vane box into position and extend tapered plugs to secure

With two operators, lift vane box into the designated position. Slowly release the pressure from the air cylinders by turning the three connected switches to the off position, which allows air to vent from the cylinders. The tapered plugs will extend and secure the vane box without damaging the assembly. Shown in Figure 77 is the vane box secured in place by the tapered plugs.

Figure 77: Vane box secured by tapered plugs

Step 5: Detach pneumatic system

Once the vane box is secured in place, and the system is ready to be lowered the extend/retract switches must be set to the retract position, venting the air from the air cylinders. After operations are complete the shop air should be disconnected from the system and all hoses returned to their storage locations. Since the handling tool is designed to use the pneumatic system to retract the tapered plugs but not extend, the vane box will remain secured when the pneumatic system is detached.

Step 6: Unloading the vane box

To unload the vane box, the operator uses the same steps. First the operator attaches the pneumatic system, and then retracts the tapered plugs while other operators are holding the vane box assembly. Once the tapered plugs are retracted, the vane box assembly can be placed onto the workbench.

2.2.2 Manipulating the Vane Box Orientation

The vane box assembly can be manipulated in two ways: rotating about the vertical axis, and rotating about the horizontal axis. To rotate the vane box about the vertical axis it requires the following two steps.

Step 1: Remove the pin from turntable

To rotate the vane box assembly about the vertical axis, the operator first pulls the pin from the turntable. Once the pin is pulled, the top portion of the handling tool is free to rotate.

Step 2: Rotate to desired orientation and insert pin

The operator rotates the vane box along with the handling tool in 90° increments to the desired orientation. Once the vane box is in the desired orientation, the pin for the turntable is inserted in to prevent further rotation. Figure 78 and Figure 79 demonstrates two orientations that the vane box can be rotated.

Figure 78: Handling tool rotated at 0°

Figure 79: Handling tool rotated at 90°

A different approach is required to rotate the vane box about the horizontal axis. The following steps are performed when rotating the vane box about the horizontal axis.

Step 1: Disengage gear system

The operator grasps the hand wheel and pushes the shaft in. When the shaft is pushed in, it disengages from the gear system and allows the vane box assembly to rotate. Figure 80 displays the disengaged gear system. When the gear system is disengaged, the operator must keep a firm grip on the hand wheel to prevent the vane box from free spinning.

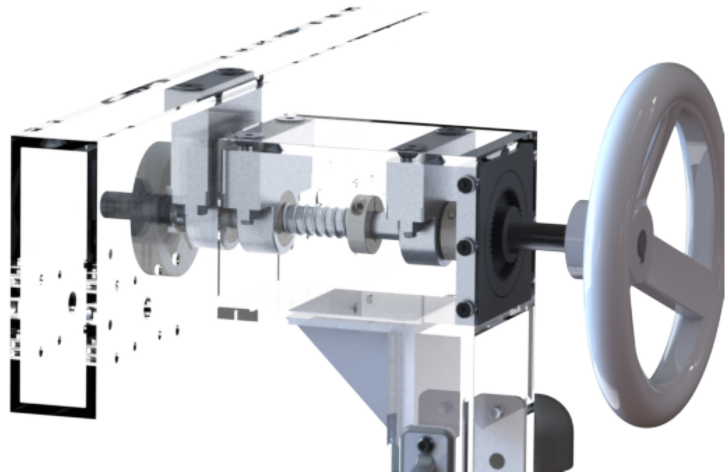

Figure 80: Pushing in hand wheel to disengage gear

Step 2: Rotate vane box and engage gear system

The vane box can be rotated in 7.5° increments to the desired orientation. When the orientation of the vane box has been satisfied, the operator can relieve the push force on the hand wheel. The spring-loaded shaft will re-engage with the gear system automatically once the operator stops pushing in on the hand wheel. With the gear system engaged, the vane box assembly is fixed in the orientation that the operator wants.

2.3 Overall Cost

The cost of parts and components for the design of the handling tool was considered when finalizing the design. Our team tried to balance the cost with the convenience of commercially available components and in-house manufacturing as best possible to generate the least amount of expenses. A detailed cost breakdown and bill of materials are located in Appendix D. The manufacturing and assembly costs associated with the design were not analyzed due to our team's inexperience with machining processes and assembly; therefore the cost estimate may not be accurate to reflect the actual manufacturing and assembly costs. The total estimated cost for implementing our F-35 vane box handling tool design is $13,820.60 and a summary of the cost for commercially available parts, raw material, and manufacturing costs is presented in TABLE III. It is important to note that taxes and shipping expenses are not taken into account, and vary depending on the warehouse location and shipping address.

TABLE III: SUMMARY OF FINAL COSTS

Category	Cost
Raw Material	$2537.58
Fasteners	$209.99
Commercially Available Parts	$6490.91
Machining and Manufacturing	$4,582.50
Total	$13,820.60

3.0 Conclusion

Through the process this report documents, our team was able to define the F-35 Vane Box Handling Tool Design project in detail, and finalize the handling tool design. The final design described throughout the report sufficiently satisfies the problem statement defined for the project. Magellan Aerospace, Lockheed Martin, and the JSF project will greatly benefit from the implementation of the F-35 Vane Box Handling Tool.

The handling tool allows the vane box to be easily transported, oriented in numerous positions, and is height adjustable. The handling tool function provides a simple, quick, and safe vane box assembly process. The handling tool comprises of five primary sections: base frame, central axle assembly, main frame, plug actuation mechanism, and pneumatic control system.

The base frame is designed to enable the handling tool to be transported and manoeuvred around the factory space effortlessly. Shock absorbing swivel casters on one end along with shock absorbing fixed casters on the other allow the assembly technicians to control and steer the handling tool easily. Additionally, the casters can absorb impact loads of up to 485 [lb] each. The structural members are American Standard I-Beams, where the length of the I-beams provides superior stability and requires the handling tool to be at an angle of 45° before tipping over. Although the base is large in size, the H-frame design allows the assembly technicians adequate area to work with.

The central axle assembly provides height adjustability of the handling tool design. In addition, the central axle assembly also allows rotational freedom about the handling tool's vertical axis. Two aluminum pneumatic cylinders achieve the height adjustment functionality with an operating range of 5 [in]. The turntable provides the rotational freedom of the handling tool and can be locked at every 90° increment through a spring-loaded pin. A custom designed cross mounting plate securely fastens the turntable to the air cylinders. The pneumatic air cylinders attach to a custom designed base mounting plate, and the plate safely mounts to the base frame I-beam. The base mounting plate is designed for a worst case loading scenario involving a lateral impact load as well as eccentricity from tipping. The central axle assembly is a simple to operate and compact design providing rotational and translational freedom of the vane box.

The main frame enables the vane box to rotate about the horizontal axis. The section was designed to allow the vane box to fully rotate 360° about the horizontal axis without encountering any obstructions. The design incorporates a spring-loaded shaft attached to a hand wheel, and also a gear system to allow for 7.5° of rotational increments. The spring-loaded shaft reduces the chance of accidental disengagement, which reduces the risk of damaging the assembly or injuring a person. The main frame design allows the assembly technicians to access and reach all of the required locations on the vane box in an ergonomical manner.

The plug actuation mechanism holds the vane box and retracts to allow for loading and unloading. This mechanism uses compression springs to passively hold the vane box, preventing disruptions in power from affecting the tool's capabilities. Additionally, Teflon® plugs prevent damage to the vane box due to their much lower hardness.

The pneumatic control system allows for both the plug actuation mechanism and central axle assembly to be automatically extended and retracted using the shop air supply, and has been optimized to prevent latent power in the air cylinders after the system has been deactivated. This control system prevents operator injuries, is simple to operate, and is easily tuned to provide consistent and controlled motion.

With our design, the operator can unload or load the vane box off and onto the handling tool safely, effortlessly, and in a timely manner with six simple steps. To rotate the vane box about the vertical axis, only two steps need to be performed by the operator. Likewise, two steps are required to rotate the vane box about the horizontal axis. By investing $13,820.60 into the manufacturing of the handling tool, Magellan Aerospace will be able to improve their vane box assembly process. Our team's handling tool design fully satisfies all needs by the client, as well as fulfilling all the deliverables requested.

4.0 References

[1] Rick Howard and Kevin Higgs, "U of M IDEA Program Application Form," Winnipeg, 2014.

[2] Rick Howard, Kevin Higgs, and Brian Harik, F-35B Vane Box Handling Tool, September 16, 2014.

[3] Government of Manitoba. (2014, April) Workplace Safety and Health Regulation. [Online]. http://web2.gov.mb.ca/laws/regs/current/217.06.pdf [Accessed Oct.14, 2014]

[4] McMaster-Carr. [Online]. www.mcmaster.com [Accessed Nov.9, 2014]

Appendix A

Conceptual Designs Considered

Table of Contents

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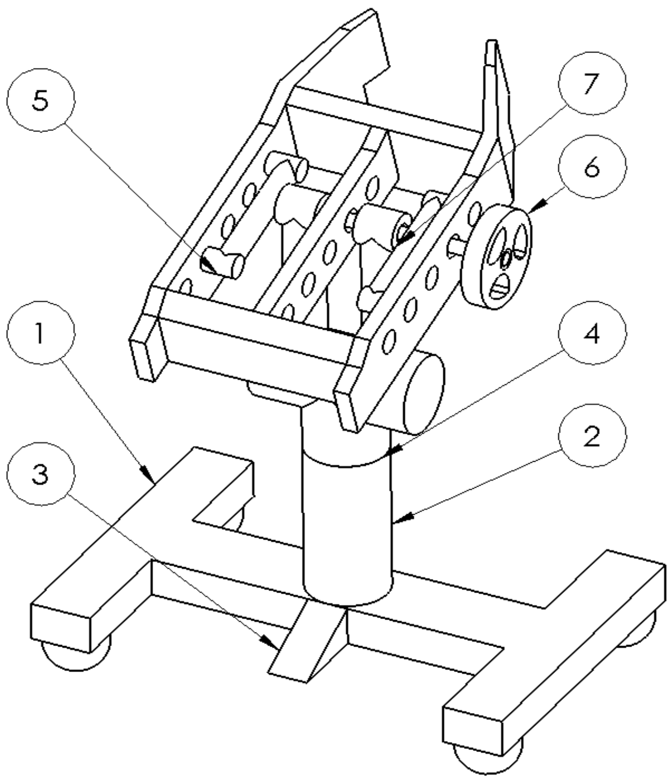
A.1 Concept Development

To arrive at our final design our group completed a detailed and thorough concept development stage. During concept development we brainstormed initial designs, screened these designs using several criteria, created improved designs from our initial screening, ranked our criteria, and finally scored our designs using the ranked criteria. Once we selected a concept we continued on with our system development by entering into the engineering design phase of the project.

A.1.1 Initial Designs

During the course of our concept development we utilized 3P to assist in our design. First we determined key functions that our design must fulfill and then brainstormed concepts to meet these functional needs. Next, we screened our function concepts and then combined them to create full design concepts. These design concepts can be seen in the figures below.

Name	CONCEPTUAL DESIGN 1	Key Features	
		1	H-Frame
		2	Pneumatic Cylinder
		3	Foot Pedal
		4	Turntable
		5	Tapered Plugs
		6	Wheel
		7	Inside Attachment

Description

Concept 1 uses an H-Frame design for the base to ensure a stable handling tool. A barber-shop style pneumatic cylinder triggered by a foot pedal allows the user to raise or lower the vane box assembly. Above the actuator lies a turntable which allows the vane box to rotate 360° about the vertical axis. Two arms branch from the base and continue upward through the inside of the vane box, and additional arms extend into four holes located on the vane box. Tapered plugs ensure a secure hold on the vane box. A wheel with the ability to lock and unlock the rotation feature is located on the outside of the vane box; it allows the user to spin the vane box about the horizontal axis until contact is made between the tool and the vane box.

Figure 1: Conceptual design 1

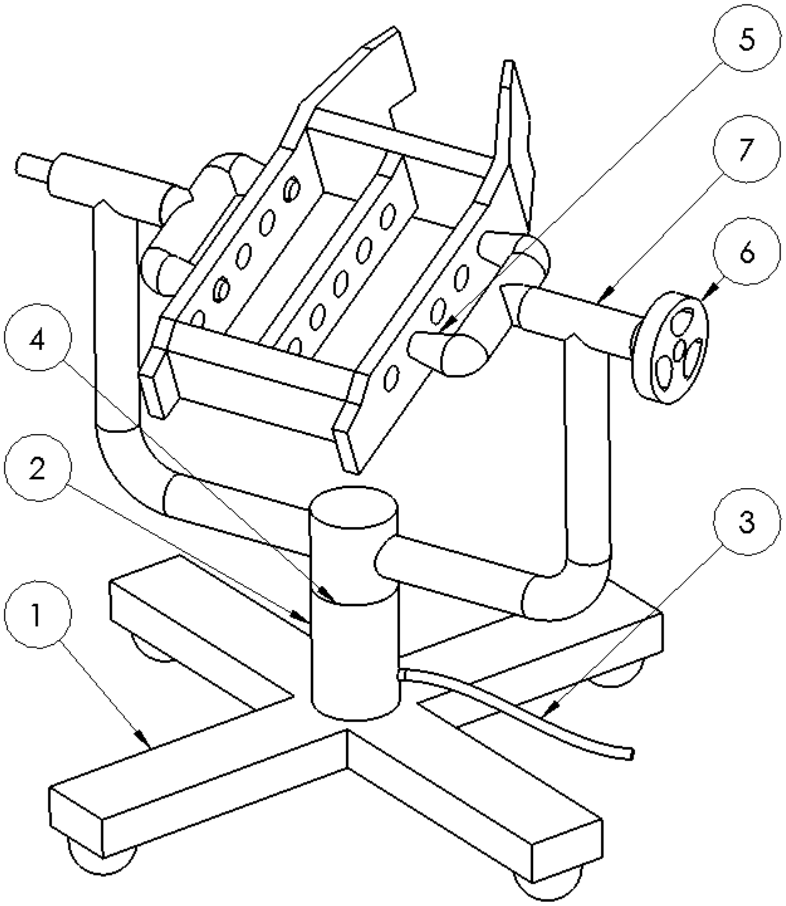
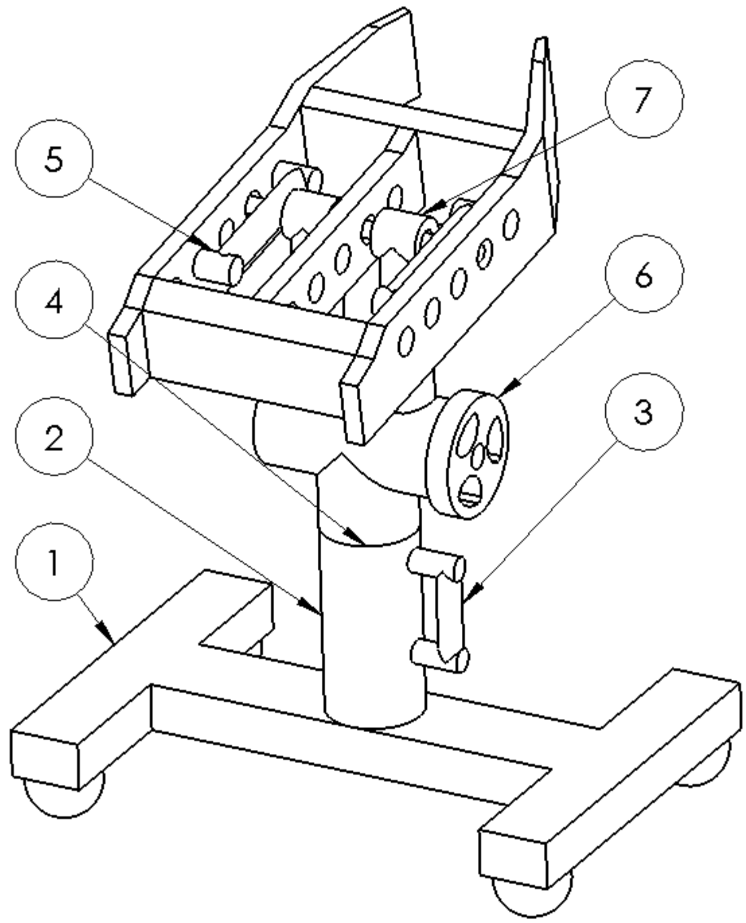
<table>
<tr><th>Name</th><th>CONCEPTUAL DESIGN 2</th><th colspan="2">Key Features</th></tr>
<tr><td colspan="2" rowspan="7">
</td><td>1</td><td>X-Frame</td></tr>
<tr><td>2</td><td>Pneumatic Cylinder</td></tr>
<tr><td>3</td><td>Electronic Control</td></tr>
<tr><td>4</td><td>Turntable</td></tr>
<tr><td>5</td><td>Expanding Plug</td></tr>
<tr><td>6</td><td>Wheel</td></tr>
<tr><td>7</td><td>Outside Attachment</td></tr>
<tr><td colspan="4">Description:</td></tr>
<tr><td colspan="4">Concept 2 uses an X-Frame design for the base. An electronically controlled pneumatic cylinder allows the user to raise or lower the vane box assembly. Above the actuator lies a turntable which allows the vane box to rotate 360° about the vertical axis. Four arms branch outward from the base, continue upward on the outside of the vane box, and grasp a total of four holes located on the vane box. Expanding plugs are used to hold the vane box. A wheel located on the outside of the vane box allows the user to spin the vane box about the horizontal axis a full 360°.</td></tr>
</table>

Figure 2: Conceptual design 2

Name	CONCEPTUAL DESIGN 3

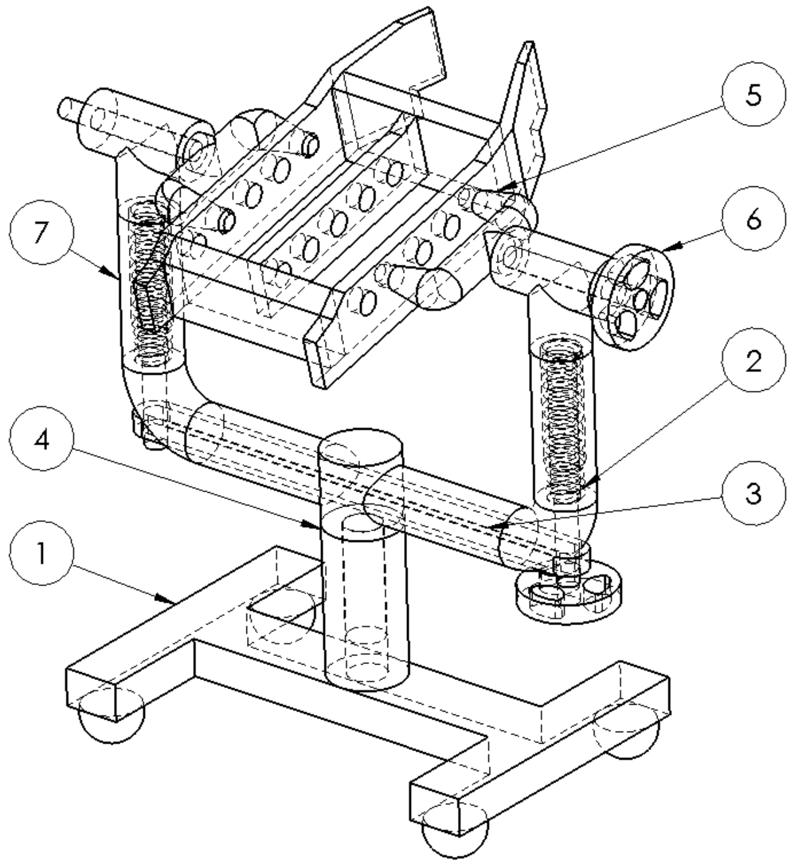


Key Features	
1	H-Frame
2	Spring Assisted Lift
3	Manual Control
4	Turntable
5	Magnetic Plug
6	Wheel (Chain Driven)
7	Inside Attachment

Description:

Concept 3 uses an H-Frame design for the base to ensure a stable handling tool. A spring assisted manual lift allows the user to raise or lower the vane box assembly. A turntable, located below the lift, allows the vane box to rotate 360° about the vertical axis. Four arms branch from the base, continue upward through the inside of the vane box, and grasp four holes located on the on the vane box. Magnetic plugs allow the user to secure the vane box quickly. A wheel, connected to a chain drive, is located below the vane box. The wheel allows the user to spin the vane box about the horizontal axis until contact is made between the handling tool and the vane box.

Figure 3: Conceptual design 3

Name	CONCEPTUAL DESIGN 4	Key Features	
		1	H-Frame
		2	Acme Rod Lift
		3	Chain System
		4	Tapered Plug
		5	Turntable
		6	Wheel
		7	Outside Attachment

Description:

Concept 4 uses an H-Frame design for the base to ensure a stable handling tool. Two acme rods, synchronized by a chain system, allow the user to drive the vane box assembly up or down either manually or automatically. A turntable, located below the lift, allows the vane box to rotate 360° about the vertical axis. Four arms branch outward from the base, continue upward on the outside of the vane box, and grasp a total of four holes located on the on the vane box. Tapered plugs are used to secure the vane box. A wheel located on the outside of the vane box allows the user to rotate the assembly a full 360°

Figure 4: Conceptual design 4

A.2 Selection Criteria

In order to properly compare our concepts we determined several criteria with which we would rank each design. These criteria were the following:

- Ease of Loading/Unloading
- Ergonomics
- Minimal Size
- Ease of Maintenance
- Cost
- Aesthetics
- Safety
- Manufacturability
- Simplicity
- Portability

A.2.1 Criteria Description

The following ten criteria were used to compare our concepts in order to select our final design. We determined that a best possible design for our handling tool is one which best satisfies all criteria below.

A.2.1.1 Ease of Loading/Unloading

Ease of loading and unloading includes all aspects of our design that make loading the vane box into and out of the handling tool safer and easier. The ease with which the vane box can be loaded and unloaded from the handling tool is an important aspect of our design because during this phase the vane box is not fully supported by either the workbench or the handling tool. If the vane box must be lifted or shifted during loading, then the part and assembly tool are at a higher risk of damage and the assemblers may be injured. Additionally, increased loading time and complexity reduce productivity and result in higher assembly costs.

A.2.1.2 Ergonomics

Ergonomics includes aspects of our design that relate to how easily and comfortably assembly technicians can access and rotate the vane box for assembly. Ergonomics are important because if assembly technicians have difficulty accessing certain locations of the vane box during assembly, they are at a higher risk of injuring themselves or damaging the vane box. Additionally, assemblers may develop repetitive strain injuries if they consistently work in awkward positions.

A.2.1.3 Minimal Size

Minimal size is the criterion which evaluates the overall size of our handling tool. Size is important because the handling tool should have a minimal footprint on the factory floor. Inefficient use of space is to be avoided, as factory space is limited and costly. Additionally, a reduced size will allow the handling tool to be moved around the facility more easily.

A.2.1.4 Ease of Maintenance

Ease of maintenance includes all aspects of our design pertaining to the regular preventative maintenance and repair work required on our handling tool. Easier maintenance provides more productivity and less down time. Additionally, workers will be able to provide better care for the machine if access to internal parts is easier.

A.2.1.5 Cost

Cost is the amount of money required to manufacture and assemble our handling tool design. Project costs include, but are not limited to, material, parts, in-house labour, out-of-house labour and design. Cost is important, as we must remain within our budget of $100,000.

A.2.1.6 Aesthetics

Aesthetics is the criterion that displays how pleasing our handling tool design looks. The customer may more readily accept an aesthetically pleasing design.

A.2.1.7 Safety

Safety encompasses all aspects of our design related to the health and safety of employees, damage prevention to the vane box assembly, and damage prevention to the handling tool.

A.2.1.8 Manufacturability

Manufacturability is the criterion with which describes how easily the parts of our handling tool can be machined and assembled. A highly manufacturable design would be more economic and faster to produce.

A.2.1.9 Simplicity

Simplicity is the criterion with which describes how complex the various handling tool mechanisms and assembly procedures are for our design. Increased simplicity will reduce the possibility of failure, decrease production time and costs, and make the handling tool easier to maintain and repair.

A.2.1.10 Portability

The portability criterion describes how easily our system can be moved around the facility. This criterion is important because our handling tool will need to be transported between painting booths and assembling areas often.

A.3 Concept Screening

Each of our concepts was compared to the current vane box handling tool at Magellan Aerospace based on the criteria described above. If a design was determined to be better than the reference design then it was given a plus, equal performances were rated at zero, and poorer performances a minus. Afterwards these ranks were totaled, with each plus, zero, and minus weighted as a +1, 0, and -1 respectively. The concepts were then ranked from highest scoring to lowest and the highest ranked two concepts moved on to further screening. The detailed results from our concept screening can be seen in TABLE I.

To rank our initial concepts we compared each concept with the existing handling tool in each of the previously mentioned categories. If a design was determined to be better than the reference design then it was given a plus, equal performances were rated at zero, and poorer performances a minus. Afterwards these ranks were totalled, with each plus, zero, and minus weighted as a +1, 0, and -1 respectively. The concepts were then ranked from highest scoring to lowest and the highest ranked two concepts moved on to further screening. The detailed results from our concept screening can be seen in TABLE I.

TABLE I: CONCEPT SCREENING

Criteria	Reference	Concept 1	Concept 2	Concept 3	Concept 4
Ease of Loading/Unloading	0	0	-	+	0
Ergonomics	0	+	+	+	+
Minimal Size	0	+	0	+	0
Ease of Maintenance	0	-	-	-	-
Cost	0	-	-	-	-
Aesthetics	0	+	+	+	+

Criteria	Reference	Concept 1	Concept 2	Concept 3	Concept 4
Safety	0	+	0	-	+
Manufacturability	0	-	-	-	-
Simplicity	0	0	0	+	-
Portability	0	0	0	0	+
Sum of +	0	4	2	5	4
Sum of 0	10	3	4	1	2
Sum of -	0	3	4	4	4
Net Value	0	+1	-2	+1	0
Rank	3	1	5	1	3

Through this preliminary screening, Concept 1 and Concept 3 tied for the best concept with a net value of +1, while Concept 4 tied with the reference design as second best concept with a net value of 0. Lastly, Concept 2 was ranked the worst with a net value of -2. Based on this ranking, Concepts 1 and 3 progressed to concept scoring.

A.3.1 Justification for Concept Screening

Justifications for the results of each comparison made during the concept screening have been documented in this section. The section includes the thought process and discussion made by our team.

A.3.1.1 Ease of Loading/Unloading

Concept 3 was seen to perform better than our reference in the ease of loading because the inner holding mechanism allows for easier access to the vane box and the magnetic plugs can be attached very quickly. Concept 1 and Concept 4 were thought to be comparable to the reference due to their outer holding mechanisms and similar rubber plug attachments. Concept 2 fared worse than our reference because of its expanding metal 'whisk' attachment mechanisms which are more difficult to move into and out of the vane box.

A.3.1.2 Ergonomics

We determined that all of our handling tool concepts fared better than the reference in ergonomics as they all allow for easier rotation and easier access to the inside of the vane box.

A.3.1.3 Minimal Size

Concept 1 and Concept 3 were thought to be better than the reference design because their inner holding mechanisms allow for easier access to the vane box. Concept 2 and Concept 4 were ranked the same as the reference concept as their outer holding mechanisms are of a similar style to the reference.

A.3.1.4 Ease of Maintenance

All of our concepts were ranked worse than the reference because they all introduce more moving parts, especially to raise and lower the vane box, which increase complexity and require more frequent maintenance.

A.3.1.5 Cost

As all of our concepts will need to be manufactured they will cost more than the reference design, which has already been built.

A.3.1.6 Aesthetics

We thought that all of our designs were more visually pleasing than the reference model and were therefore ranked higher.

A.3.1.7 Safety

Concept 1 and Concept 4 were determined to be safer than the reference design because of the increased stability of their bases. Concept 2 was thought to be similar to the reference as both have similar stability. Concept 3 was felt to be less safe than the reference due to its manual lift mechanism, which may cause excessive strain to the assemblers.

A.3.1.8 Manufacturability

All of our designs were less manufacturable than the reference due to their increased complexity, thus ranked worse.

A.3.1.9 Simplicity

Concept 3 was determined to be simpler in operation than the reference due to its chain mechanism for rotation and simple manual lift as well as its magnetic plugs for holding the vane box. Concept 1 and Concept 2 were thought to be similar to the reference because they use the same rubber plugs for holding the vane box. Concept 4 was determined to be more complex due to its lead screw driven raising mechanism.

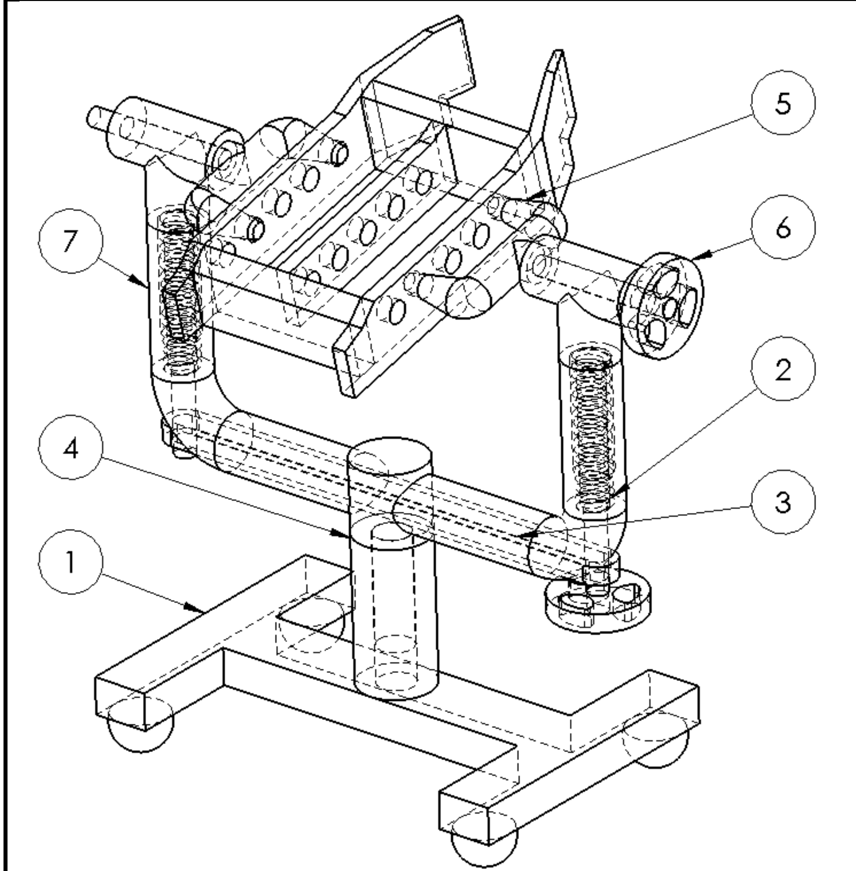
A.3.1.10 Portability

Concept 4 was ranked better than the reference because it could be easily pushed from the perimeter, has a more stable base than the reference, and can be lowered to a lesser height than the other designs, which further increases Concept 4's stability by lowering the tool's centre of gravity. Concepts 1 and 3 were thought to be similar to the reference design because they have more stable bases but contain no supports on the exterior of the vane box to grasp while transporting the handling tool. While concept 2 does have members outside of the vane box, it has a similar base to the reference model therefore concept 2 was also ranked zero.

Each time a concept was determined to be better, worse, or equal to the reference design it was awarded a +1, -1 or 0, respectively. The sum of these comparisons was then totaled and the best designs moved on to concept scoring. Using this system, we determined that concepts 1 and 3 were the most promising and worth further perusal.

A.4 Additional Design Concepts

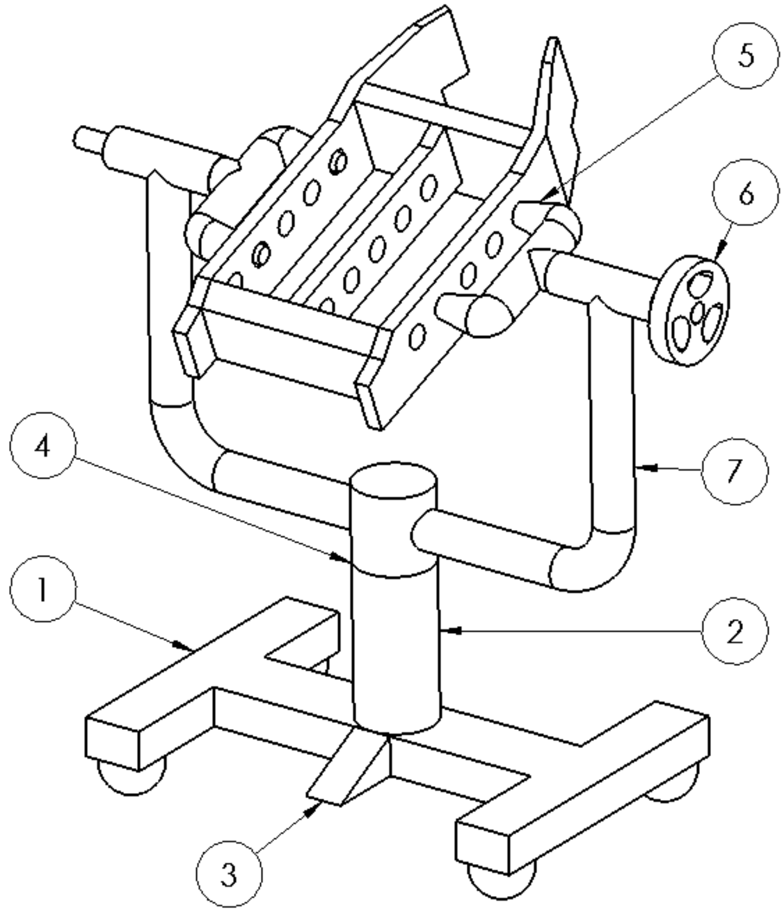
Additional conceptual designs were created based on favourable features from our initial designs. These designs, concepts A, B, and C, can be seen in Figure 5, Figure 6, and Figure 7.

Name	CONCEPTUAL DESIGN A	Key Features	
		1	H-Frame
		2	Acme Rod
		3	Chain System
		4	Thrust Bearing
		5	Magnetic Plugs
		6	Wheel
		7	Outside Attachment

Description:

Concept A uses an H-Frame design for the base. A thrust bearing allows for a full 360° rotation about the vertical axis. Two threaded acme rods connected by a chain and operated by a wheel allows the vane box to be raised or lowered. Four magnetic plugs branch into the side of the vane box for a secure hold. A wheel located on the outside of the vane box allows the user to spin the vane box about the horizontal axis a full 360°.

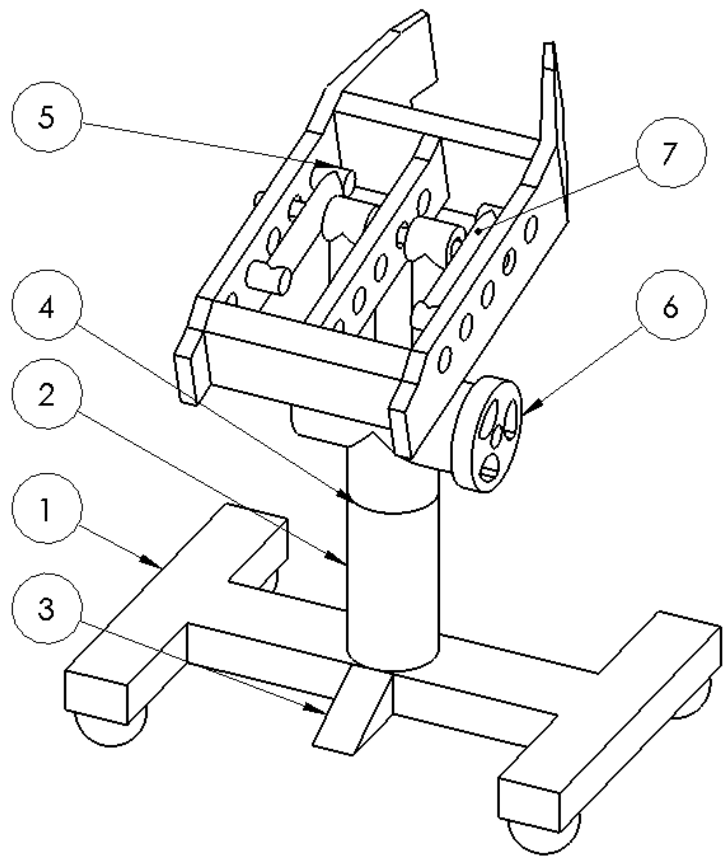
Figure 5: Conceptual design A

Name	CONCEPTUAL DESIGN B	Key Features	
		**1**	H-Frame
		2	Pnuematic Cylinder
		3	Foot Pedal
		4	Turntable
		5	Tapered Plug (Spring)
		6	Wheel
		7	Outside Attachment

Description:

Concept B uses an H-Frame design for the base. A turntable allows for a full 360° rotation about the vertical axis. A pneumatic air cylinder operated by a foot pedal allows the vane box to be raised or lowered. Four spring-loaded tapered plugs branch into the side of the vane box for a secure hold. A wheel located on the outside of the vane box allows the user to spin the vane box about the horizontal axis a full 360°.

Figure 6: Conceptual design B

Name	CONCEPTUAL DESIGN C	Key Features	
		1	H-Frame
		2	Pnuematic Cylinder
		3	Foot Pedal
		4	Turntable
		5	Tapered Plug (Spring)
		6	Wheel (Chain Driven)
		7	Inside Attachment

Description:

Concept C uses an H-Frame design for the base. A turntable allows for a full 360° rotation about the vertical axis. A pneumatic air cylinder operated by a foot pedal allows the vane box to be raised or lowered. Four spring-loaded tapered plugs branch into the side of the vane box from the inside for a secure hold. A chain driven wheel located below the vane box allows the user to spin the vane box about the horizontal axis a full 360°.

Figure 7: Conceptual design C

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A. 5 Criteria Ranking

After developing our refined conceptual designs we proceeded to compare and rank our selection criteria, so that we could use weighted scores to compare our designs. To rank criteria we paired each criterion with all other criteria and determined which out of each pair was of greater importance. The number of times each criterion was the highest ranking in a pair was tallied and divided by the total number of pairs, giving the weighted worth of each criterion. The criteria comparison can be seen in TABLE II and the criteria weights can be seen in TABLE III.

TABLE IIII: CRITERIA COMPARISON

	Ergonomics	Minimal Size	Ease of Maintenance	Cost	Aesthetics	Safety	Manufacturability	Simplicity	Portability
Ease of Loading/ Unloading	Ergonomics	Ease of Loading	Maintenance	Ease of Loading	Ease of Loading	Safety	Manufacturability	Ease of Loading	Ease of Loading
Ergonomics		Ergonomics	Ergonomics	Ergonomics	Ergonomics	Safety	Ergonomics	Ergonomics	Ergonomics
Minimal Size			Maintenance	Cost	Minimal Size	Safety	Manufacturability	Simplicity	Portability
Ease of Maintenance				Maintenance	Maintenance	Safety	Maintenance	Simplicity	Maintenance
Cost					Cost	Safety	Manufacturability	Simplicity	Portability
Aesthetics						Safety	Manufacturability	Simplicity	Portability
Safety							Safety	Safety	Safety
Manufacturability								Simplicity	manufacturability
Simplicity									Portability

TABLE III: CRITERIA RANKING

	Ease of Loading/Unloading	Ergonomics	Minimal Size	Ease of Maintenance	Cost	Aesthetics	Safety	Manufacturability	Simplicity	Portability
Count	5	8	1	6	2	0	9	5	5	4
Percent	11.11%	17.78%	2.22%	13.33%	4.44%	0.00%	20.00%	11.11%	11.11%	8.89%

A.5.1 Justification for Criteria Ranking

The justifications for our decisions in determining which criterion was the best in each pairing were discussed as a team. Our team debated each decision until a consensus was reached, the results of which can be seen below.

A.5.1.1 Ease of Loading/Unloading

We determined that ease of loading/unloading was a higher priority than cost, simplicity, and portability. Ease of loading/unloading was prioritized over cost because simplified loading decreases the risks of damaging the part and handling tool, and injuring the technician. Additionally, increased productivity will result in decreased operational costs even if the handling tool itself is more expensive. Ease of loading was ranked higher than simplicity because the benefits to productivity and safety make this investment worthwhile even if easier loading makes the tool more complex. Finally, ease of loading was determined to be more important than portability because the vane box is at a greater risk of damage when it is not fully attached to the handling tool as is the case during loading and unloading.

A.5.1.2 Ergonomics

We determined ergonomics to be a higher priority than all other categories except for safety because good ergonomics allow for faster assembly, lower risk of worker injury, and a greater acceptance of our design by assemblers.

A.5.1.3 Minimal Size

Minimal size has a higher priority than aesthetics as our handling tool is an industrial design and will not have to appeal to the general public based on its appearance.

A.5.1.4 Ease of Maintenance

We determined that ease of maintenance is of higher importance than ease of loading/unloading, minimal size, cost, aesthetics, manufacturability, and portability. We decided that maintenance was more important than ease of loading/unloading because decreasing the amount of downtime required by our design, during which the handling tool is unusable, is more important for productivity than decreasing the time to load or unload the handling tool. Furthermore, maintenance was ranked higher than minimal size because increasing access to parts of our design is important, even if it increases the handling tool's size. We decided that ease of maintenance was valued more than handling tool cost because reduced downtime will result in fewer delays to production and be more cost effective in the long run. In addition, ease of maintenance was determined to be more important than aesthetics because the handling tool is not a consumer product and so function is a higher priority than form. Our team has also agreed that maintenance is a higher priority than manufacturability because there will be very few handling tools made and they will not be sold commercially, meaning that decreasing tool downtime is more important than increased production costs and time. Finally, ease of maintenance was prioritized over portability because decreased downtime is of higher importance than a slight increase in the ease of moving the handling tool.

A.5.1.5 Cost

Cost was determined to be of greater importance than minimal size and aesthetics. Our team determined cost to be more important than minimal size because the savings gained in floor space by decreasing the size of our design are unlikely to be greater than the increased costs associated with this miniaturization. Cost is ranked higher than aesthetics because this is an industrial tool and our client is not concerned about how our design looks.

A.5.1.6 Aesthetics

Aesthetics was found to be less important than all other criteria because our handling tool is an industrial design which will not be sold commercially and therefore, the functionality of the design is much more important than how it looks. While aesthetics does not affect the scoring of our designs, we have opted to keep this criterion in the event that two of our designs have an equal scoring. In the event of a tie, the design with the higher aesthetic value will be chosen.

A.5.1.7 Safety

Safety was determined to be the most important of our criteria and outranked all others because the safety of our client`s employees is our highest priority. In addition to our ethical responsibility to provide our client with a safe design, any injuries resulting from our handling tool would be very costly for our client and result in our tool being replaced. It is important to note that the previous handling tool is no longer being used due to its poor level of safety.

A.5.1.8 Manufacturability

Manufacturability was ranked as more important than ease of loading/unloading, minimal size, cost, aesthetics, and portability. Manufacturability was chosen over ease of loading and unloading because loading and unloading are expected to occur infrequently due to the low production rates of vane boxes while manufacturability ensures that our design can be easily produced. We determined manufacturability to be of greater importance than minimal size in order to ensure our design is economical. Manufacturability was ranked higher than cost because increased manufacturability should decrease both costs and the time that manufacturing will take, ensuring that our design is put in use sooner. Additionally, we decided that manufacturability was more important than aesthetics because our handling tool is not a consumer product and decreased costs and manufacturing time are more important than how the tool looks. Finally, manufacturability was considered more important than portability as it is more important for our handling tool to be easily made, resulting in the use of our handling tool sooner.

A.5.1.9 Simplicity

Our team decisively determined that simplicity is of higher importance than minimal size, ease of maintenance, cost, aesthetics, and manufacturability. Simplicity was ranked higher than minimal size because we believe that keeping our mechanisms simple and reliable will ensure higher reliability for our handling tool which is more valuable than increased floor space. Likewise, increased reliability will decrease the need for maintenance and offset build costs; thus simplicity has been ranked higher than maintenance, manufacturing, and cost. Finally, simplicity has been ranked higher than aesthetics because aesthetics are not important for an industrial design.

A.5.1.10 Portability

Portability has been ranked higher than minimal size, cost, aesthetics, and simplicity. We determined portability to be more important than minimal size because the ability to move easily around the factory is more important than minimizing the tool`s footprint. Cost was determined to be less important than portability because easy transportation of our tool will help avoid accidental damage to the tool, vane box, and the surroundings which would likely exceed the initial savings of a less portable design. Furthermore, portability was deemed more important than aesthetics because as an industrial design, function is more important than appearance. Finally, portability was ruled more important than simplicity because while a more advanced movement system will add complexity to the design, being able to easily move around the factory justifies this increased intricacy.

A.6 Concept Scoring

In order to select our final design we compared concepts 1 and 3, the winning concepts from the concept screening, with several improved concepts. This was done by ranking how well each concept meets the criteria on a scale of one to five. The meaning of these rankings can be seen in the table below.

TABLE IV: CRITERIA RANKING SCALE

Rank	Definition
5	Fulfills the criterion extremely well
4	Fulfills the criterion well
3	Fulfills the criterion acceptably
2	Does not fully meet the criterion
1	Does not fulfill the criterion

The individual criterion scores were then multiplied by the criterion's weight and the weighted scores added together to determine each concept's final score. The concept scores and rankings can be seen in TABLE V below.

TABLE V: CONCEPT SCORING

		Concept 1		Concept 3		Concept A		Concept B		Concept C	
Criteria	Weight	Score	Weight	Score	Weight	Score	Weight	Score	Weight	Score	Weight
Ease of Loading/Unloading	0.1111	2	0.2222	4	0.4444	5	0.5555	5	0.5555	3	0.3333
Ergonomics	0.1778	3	0.5334	1	0.1778	4	0.7112	5	0.889	3	0.5334
Minimal Size	0.0222	4	0.0888	5	0.111	3	0.0666	2	0.0444	5	0.111
Ease of Maintenance	0.1333	3	0.3999	4	0.5332	2	0.2666	3	0.3999	2	0.2666
Cost	0.0444	5	0.222	2	0.0888	4	0.1776	5	0.222	3	0.1332
Aesthetics	0	3	0	3	0	5	0	4	0	3	0
Safety	0.2	3	0.6	1	0.2	5	1	4	0.8	2	0.4
Manufacturability	0.1111	4	0.4444	2	0.2222	2	0.2222	5	0.5555	3	0.3333
Simplicity	0.1111	3	0.3333	3	0.3333	2	0.2222	4	0.4444	5	0.5555
Portability	0.0889	3	0.2667	3	0.2667	5	0.4445	4	0.3556	3	0.2667
TOTAL			3.1107		2.3774		3.6664		4.2663		2.933
RANK			3		5		2		1		4

A.6.1 Justification for Concept Scoring

The reasoning behind the assigned values for each concept score is justified in this section. The justifications have been debated until a consensus was reached by the entire team.

A.6.1.1 Ease of Loading/Unloading

Concepts A and B were ranked as 5 because they can easily load and unload the vane box from the sides and use fast attaching methods of holding the vane box. Concept 3 was ranked a 4 because while its' internal holding mechanism may be slightly harder to load into than concepts A and B; the magnetic holding method of Concept 3 employs is very fast and simple to use. Concepts 1 and C were assigned a value of 3 because they perform similarly to Concept 3 but the tapered plugs they use require some additional time for mounting.

A.6.1.2 Ergonomics

Concept B was ranked as a 5 because its outer holding mechanism allows the vane box to be rotated 360 degrees, the foot controlled pneumatic lift allows the operator to easily lift the vane box up and down, and the rotation control wheel is at a comfortable height to use. Concept A was ranked as a 4 because the lead screw driven lift must be controlled from a lower and more awkward position but the concept still allows for a full 360 degree rotation of the vane box and a fast and effective method of holding the vane box. Concept 1 was ranked as a 3 because the inner holding mechanism only allows for a partial rotation of the vane box but the rotation wheel and pneumatic pedal are easy for the operator to use. Concept C was ranked as a 2 because it only provides partial rotation similar to Concept 1 and the chain driven rotation mechanism is located lower on the handling tool which is less comfortable for the operator. Concept 3 was ranked as a 1 because it has the same issues as Concept C in addition to a manual lift mechanism which requires the operator to physically lift the vane box and upper portion of the handling tool to adjust the height of the assembly.

A.6.1.3 Minimal Size

Concepts 3 and C were given a rank of 5 because both designs are very compact with internal mounting systems, no protrusions, and a very stable base. Concept 1 was decided to be a 4 because the internal mounting system and base are very similar to Concept C, but the rotation control wheel in concept 1 protrudes from the handling tool which increases its volume. Concept A was given a 3 because it uses an external mounting system which increases the bulk of the design but can also be lowered much more than the other designs which reduces its centre of mass greatly. Concept B was given a 2 because it also uses a bulky external mounting system and cannot be lowered to the same extent as Concept A.

A.6.1.4 Ease of Maintenance

Concept 3 was ranked as a 4 because the manual lift mechanism for height control is simple, robust, and will require little maintenance. Although the chain driven rotational control will require some additional maintenance, therefore this concept was not awarded a 5. Concepts 1 and B were awarded 3's because both concepts use a pneumatic lifting mechanism, which will require regular maintenance, but also employ wheels to rotate the vane box which will require relatively little servicing. Concepts A and C were both rated as 2's because they employ more complicated mechanisms which will require additional servicing. Concept 2 has magnetic plugs for attaching the vane box which will require regular replacement as they lose their magnetic polarity and Concept B uses a pair of lead screws to raise and lower the handling tool which will require regular lubrication and adjustments.

A.6.1.5 Cost

Concepts 1 and B were decided to be 5's for cost as both employ simple systems for rotation and elevation of the vane box which can be made using standard manufacturing methods. Concept A was awarded a 4 because the lead screw method of elevation will be more expensive than the pneumatic cylinders used in other designs but should still be relatively economical. Concept C was determined to be a 3 because it uses magnetic plugs to hold the vane box which will be more difficult to machine and attach and will be expensive to procure. Concept 3 was given a 2 because it uses the same magnetic holding system as Concept C but also requires the manufacturing of the manual lift system which will likely be more expensive in terms of material and machining time than procuring a pneumatic lifting mechanism.

A.6.1.6 Aesthetics

Concept A was rated as a 5 for aesthetics because it has clean lines, few protrusions, and a low profile. Concept B scored a 4 because while it is similar to Concept A the pneumatic foot pedal protrudes and it is taller than A. Concepts 1, 3, and C were decided to be 3's because they all have a similar inner holding mechanism, structure, and methods of rotating the vane box.

A.6.1.7 Safety

Concept A was rated as the safest design with a 5 because its lead screw based height adjustment system keeps the operator from having to move underneath the vane box and gives the design more stability than our other designs. Additionally, the outer holding mechanism does not require the operator to have their hands inside the vane box during loading so if the vane box were to fall or shift suddenly the operator would not have the same risk of injury. Concept B was rated as a 4 because, while it shares many features with Concept A, the pneumatic lift mechanism requires the operator to be closer to the machine when raising or lowering the vane box. Concept 1 was rated as a 3 because the operators must place their hands inside the vane box during loading and unloading which may cause injury if the vane box were to drop or shift suddenly. The pneumatic foot pedal also requires the operator to be partially under the vane box when it is raised or lowered. Concept C was given a 2 because it is similar to Concept 1 but the chain driven rotation system contains numerous pinch points. Concept 3 was ranked as a 1 because it is similar to Concept 1 but with a manual lifting mechanism. This manual mechanism requires the operator to bend and lift at an awkward angle which is likely to cause back injuries.

A.6.1.8 Manufacturability

Concept B was given a 5 for manufacturability because it contains simple mechanisms and does not need to be as compact as the inner holding designs. Concept 1 was rated as a 4 because, while it contains simple mechanisms, its rotation control wheel must include a mechanism for attaching and removing it to allow the vane box to be loaded and unloaded. Additionally the inner holding mechanism requires a slightly more compact design. Concept C was rated as a 3 because while its rotation and lift system are simple to make the magnetic holding mechanism will be difficult to implement and may require the machining of magnets. Concepts 3 and A were rated as 2's because the lead screw based lifting mechanism of Concept A will require more accurate alignments and the lifting mechanism for Concept 3 is large and would be hard to manufacture.

A.6.1.9 Simplicity

Concept C was rated as a 5 because it contains the simplest mechanisms to operate such as a gear based rotation mechanism, tapered plug vane box holders, and a pneumatic lifting system. Concept B was ranked as a 4 because the wheel controlled rotation mechanism is slightly more complicated than that used in Concept C but uses the same tapered plug holders and pneumatic lifting system. Concepts 1 and 3 were determined to be 3s because Concept 3 uses a manual lifting mechanism which is harder for operators to use while Concept 1 uses a pneumatic lift and tapered plugs but a more complex detachable rotation wheel.

A.6.1.10 Portability

Concept A was ranked as a 5 because it can be lowered further than the other concepts which gives it a lower centre of gravity and thus more stability. It is also held from the outside, which gives operators a better point to push from than the concepts that support the vane box from the inside. Concept B was determined to be a 4 in portability because while it has the same outer holding system as Concept A which makes pushing the handling tool easier. Concepts 1, 3, and C were rated as 3's because they all hold the vane box from the inside and do not have easy points to push from without touching the vane box.

By completing this concept scoring system we were able to quantifiably rank our chosen design concepts from which we determined that Concept B was our best design.

A.7 Trystorming

Trystorming was used to further validate our design feasibility, as well as expose any unforeseen flaws in our design. Concept A and Concept B, the top ranked design concepts through our screening and scoring procedure, were selected for trystorming. 3D printing technology was used to create small scale physical models of the concepts. The 3D printed parts allow for an accurate representation of our conceptual design and provide a working model with respect to the support and orientation of the vane box assembly. Figure 8 shows the 3D printed Conceptual Design A (back left) and Conceptual Design B (front right). As shown, the simplified vane box assembly is the blue colored component. The grey and white components contribute to the handling tool conceptual design.

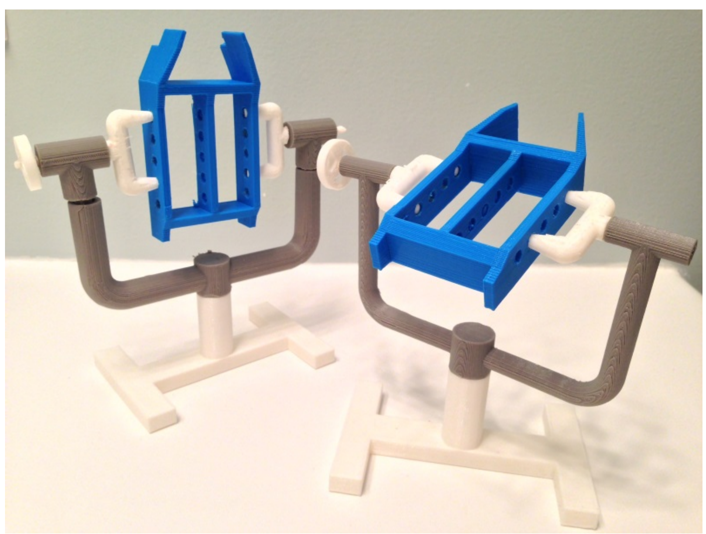

Figure 8: 3D printed conceptual designs

The 3D printed concepts were presented to our clients to better communicate our design ideas. The overall impression of our design was positive with few criticisms, however the 3D printed parts were deemed useful for exposing potential flaws in the design. Our clients expressed concerns with the current handling tool designs regarding the overall height of the handling tool and vane box assembly, the stability of the holding mechanism of concept A, the obstruction of the outer vane box wall due to the large mounting plugs, the effort required to rotate the assembly, the calibration of the acme rods found in Concept A, and the addition of brakes to the system. As these comments focus on specific details of our design, these concerns will be addressed and mitigated in the detailed design phase to come. Overall, the clients unanimously agreed Concept B was their preferred conceptual design.

Appendix B

Details of Technical Analysis

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B.1 Central Axle Base Mounting Plate Analysis

The base mounting plate design was first analyzed through hand calculations to obtain a rough approximation of the sheet metal thickness necessary to withstand the imparted loads with a safety factor of 3. For the worst-case scenario loading, the handling tool reacts to an impact load of 100 [lb] acting laterally through the centre of gravity of the vane box. The centre of gravity of the vane box and main frame is approximated as 4 [ft] above the base of the central axle. The total weight of the components above the central axle is approximated as 300 [lb] and is assumed to act through the centre of gravity. This is an over approximation, but positively simplifies the analysis. From the lateral impact load, the handling tool is assumed to tip a total of 10° to create an off axis eccentric load on the base mounting plate. Figure 1 shows the base mounting plate worst case loading scenario.

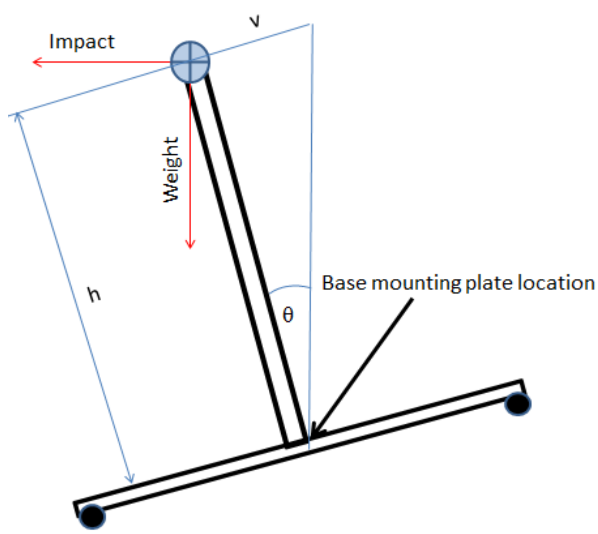

Figure 1: Base mounting plate worst case loading scenario

A summary of the values for the variables found in Figure 1 can be seen in TABLE I.

TABLE I: BASE MOUNTING PLATE WORST CASE LOADING VARIABLE SUMMARY

Variable	Units	Value	Description
$\boldsymbol{W}$	[lb]	300	Weight of components
$\boldsymbol{F}$	[lb]	100	Impact force
$\boldsymbol{h}$	[in]	48	Height of CG to base
$\boldsymbol{\theta}$	[deg]	10	Tipping angle
$\boldsymbol{v}$	[in]	11	Off axis distance

The base mounting plate attaches onto the base frame, and that support is assumed to be fixed. The system is treated as a beam in bending and the off axis load due to the weight can be resolved as a bending moment throughout the beam. Axial loads are neglected as they act through the pneumatic air cylinders and bypass the base mounting plate. The reaction moment at the base can be determined, and therefore the stresses. Incorporating appropriate factors of safety the cross sectional geometry of the beam can be determined. The cross sectional geometry of the beam is essentially the side plates of the base mounting assembly at the location of interest. At the end of the analysis, an appropriate thickness plate will be determined for the base mounting plate. The simplified loading scenario can be seen in Figure 2

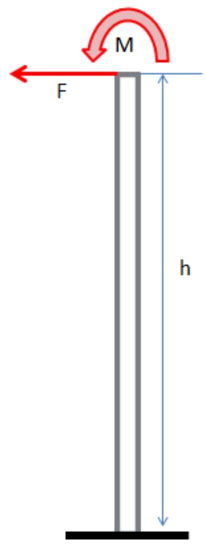

Figure 2: Base mounting plate simplified loading

The analysis performed is as follows. The moment at the top of the beam is determined from the off axis load and the weight of the vane box and mainframe assembly. That is,

$$M = Wv = W \cdot h \cdot tan(\theta) = 300(48)(\tan(10)) = 2540\ [lb \cdot in]$$

The reaction moment at the base location can be found as,

$$M_R = M + Fh = 2540 + \big(100(48)\big) = 7340\ [lb \cdot in]$$

The beam is assumed to be two rectangular cross sections simulating the two plates attached to the pneumatic air cylinder. The height of the cross section, or side plate denoted as 'b', is the width of the pneumatic air cylinder which is 3.375[in]. The required thickness of the base mounting plate walls can now be determined. The governing equation of bending stresses is

$$\frac{\sigma_y}{FOS} = \frac{M_R b}{2I}$$

Where σ_y is the yield stress for AISI 4130 steel, FOS is the safety factor, and I is the moment of Inertia which can be calculated as,

$$I = \frac{1}{12}(2t)b^3$$

Where t is the thickness of the plate. The thickness can be isolated and solved for by the following,

$$t = \frac{3M_r FOS}{\sigma_y b^2} = \frac{3(7340)(3)}{\left(22717(3.375^2)\right)} = 0.255[in]$$

The required thickness for this loading scenario is 0.255[in]. Therefore, 0.25[in] plates will be used for the design of the base mounting plate assembly to be further optimized through FEA software.

B.2 Shaft Stress Calculations

In order to determine the stresses present in the plug actuation mechanism shafts we first calculated the force applied onto the shaft by the plug.

$$P = \frac{mg * FS}{n} = \frac{68 * 9.81 * 5}{4} = 834\ [N]$$

Where p is the resulting load, m is the mass of the vane box, g is acceleration due to gravity, FS is the factor of safety, and n is the number of shafts supporting the load. After this we determined the moment due to the force applied on the shaft by the plug.

$$M = P * L = 834\ [N] * 0.060\ [m] = 50\ [N * m]$$

Where M is the moment and L is the distance from the applied load to the bearing support. Next the second moment of inertia, I, was calculated as follows:

$$I = \frac{\pi r^4}{4} = \frac{\pi * 0.0079375^4}{4} = 3.11 * 10^{-9} [m^4]$$

Where r is the minor radius of the shaft. Displacement of the shaft was calculated using the following equation and assumes that the shaft is being held by the bearing as a cantilever beam.

$$\delta = \frac{PL^3}{3EI} = \frac{834 * 0.06^3}{3 * (2 * 10^{11} * (3.11 * 10^{-9})} = 9.62 * 10^{-5}\ [m] = 0.00962 [mm]$$

Where δ is displacement and E is Young' Modulus. Normal stress, σ, was determined as follows:

$$\sigma = \frac{M}{\pi d^3/32} = \frac{50}{\pi * 0.015875^3/32} = 127\ [MPa]$$

Shear stress, τ, was determined using the following:

$$\tau = \frac{4P}{3A} = \frac{4 * 834}{3 * (\pi * 0.0079375^2)} = 5.62\ [MPa]$$

As the shear stress is significantly less than the normal stress experienced by the shaft the shear stress can be considered negligible and therefore ignored. Because there is a shoulder in this shaft there will be a stress concentration where the major and minor diameters meet. This stress concentration was determined to be 2.0 using the figure below.

Figure 3: Stress concentration factor for a shaft in bending [1]

Using this stress concentration factor, the maximum stress in the shaft is expected to be 255 [MPa]. This stress is far smaller than the shaft`s yield stress of 2.00 [GPa], and results in a factor of safety for the shaft of 39.3 including the previously used factor of safety.

B.3 Bearing Stress Calculations

B.3.1 Bearing Fastener Stress

To determine the stresses that the bolts which hold the bearing in place experience the following analysis was performed. First, a statics diagram was created to determine the forces, which the bolts would be subjected to, as seen in Figure 4 below. In this figure, P represents the load on the bearing from the shaft, R and –R are the reactionary forces from the bolts, L_1 is the distance from the applied load to the flange, and L_2 is the centre to centre distance of the bolts. L_1 is 0.0989 [m], L_2 is 0.03646 [m], and P is 834 [N].

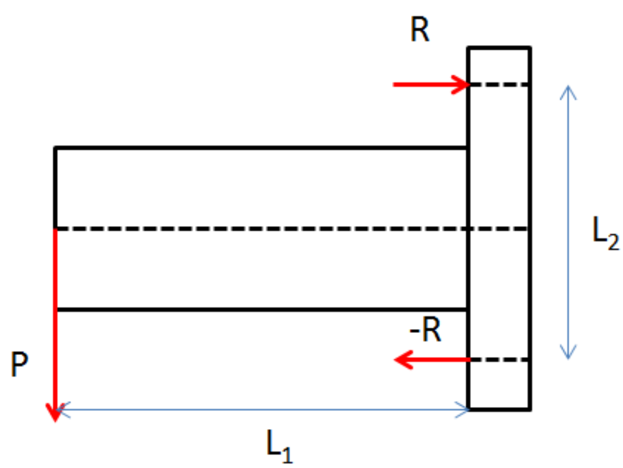

Figure 4: Bearing statics diagram

The reactionary forces were determined using the following equation:

$$PL_1 = RL_2 \rightarrow R = \frac{PL_1}{L_2} = \frac{834\ [N] * 0.0989\ [m]}{2 * 0.03646\ [m]} = 1131\ [N]$$

Note that the above equation was divided by two because each reactionary force represents two bolts. The maximum force which can be exerted on the bolts was calculated below, with σ_{max} being the maximum allowable stress, A being the cross sectional area of the bolt, and P_{max} being the maximum allowable force on the bolt.

$$\sigma_{max}A = P_{max} = 480\ [MPa] * \pi 0.00213^2[m] = 8817[N]$$

The factor of safety of the bolts can be seen in the equation below. Note that as a factor of safety of 5 had been previously applied this is accounted for in the equation.

$$FS = \frac{P_{max}}{P} = \frac{8817 * 5}{417} = 39$$

B.3.2 Bearing Stress

The main frame assembly utilizes pillow block bearings inside the mechanical hub to support the main shaft. The stress in the bearing can be readily determined by the following equation [2]

$$P = \frac{Bearing\ load}{Bearing\ diameter\ x\ Bearing\ length} = \frac{150[lb]}{0.625[in]x\ 0.875\ [in]} = 274\ [psi]$$

B.4 References

[1] F. P. Beer, E. R. Johnston, J. T. DeWolf and D. F. Mazurek, Mechanics of Materials, New York: McGraw Hill, 2014.

[2] "McMaster-Carr," [Online]. Available: http://www.mcmaster.com/#about-flanged-bearings/=utuqkf. [Accessed 15 11 2014].

Appendix C

Manufacturing and Assembly Process

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During the designing process for the F-35 Vane Box Handling Tool, manufacturing and assembly considerations were well-thought-out to keep the final design easy to manufacture and maintain. It is important to note that Magellan Aerospace plans to manufacture one handling tool from the final design; therefore manufacturing custom parts are permitted but still avoided where possible. Since the design is not mass produced, the manufacturing and assembly considerations are not restricted to certain amount of machining time, assembly time, or maintenance issues. In this appendix, the manufacturing and assembly process of the handling tool design is outlined.

C.1 Base Frame Manufacturing

The manufacturing of the base frame requires the construction of only one custom component. All other structures within the assembly need only to have holes drilled for the fastening. The process for constructing the base frame is outlined below:

1. Fabricate the gusset plate from 1[in] thick 6061-T6 aluminum plate. The engineering drawing of the gusset plate is located in section C.7. The component will require machining time to be fabricated. Our team considered removing the contour from the I-beam instead of fabricating the contour onto a gusset plate but to do that on an I-beam is more complicated than manufacturing the contour of the gusset plate.
2. In two 4[in] x 4[in] x 72.75[in] American Standard I-beams, with a flange and web thickness of 5/16[in], drill holes as indicated in the lateral I-beam drawing located in section C.7. The holes are to be counterbored to allow the

bolts to have a flat surface to fasten to since American Standard I-beams have a tapered flange.

3. In a third American Standard I-beam of the same dimensions, drill holes as indicated in the center I-beam drawing presented in section C.7.
4. With one of the I-beams constructed from step 2, attach a single fixed caster at each end with 5/16”-18 bolts, washers, and nylon-locking nuts located below the baseplate of the caster. An exploded view of the fastening process to provide a better understanding of assembly is shown in Figure 1.

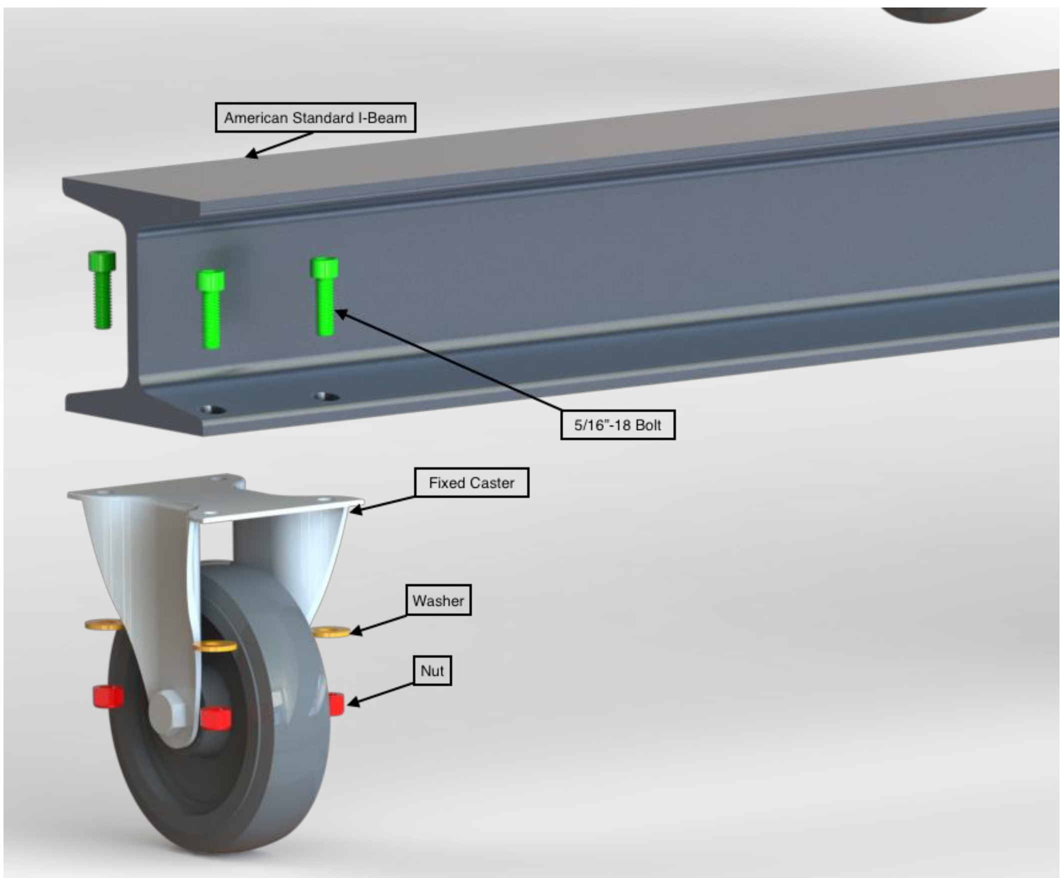


Figure 1: Exploded view of fastening a fixed caster to an I-beam

5. With the remaining I-beam from step 2, repeat the process from step 4, but exchange the non-rotating casters with two rotating casters.
6. Align the central holes on the lateral I-beams with the distal holes on the central I-beams. Place a 3/8”-16 bolt through each of the aligned holes. Figure 2 provides a visual aid of this step.

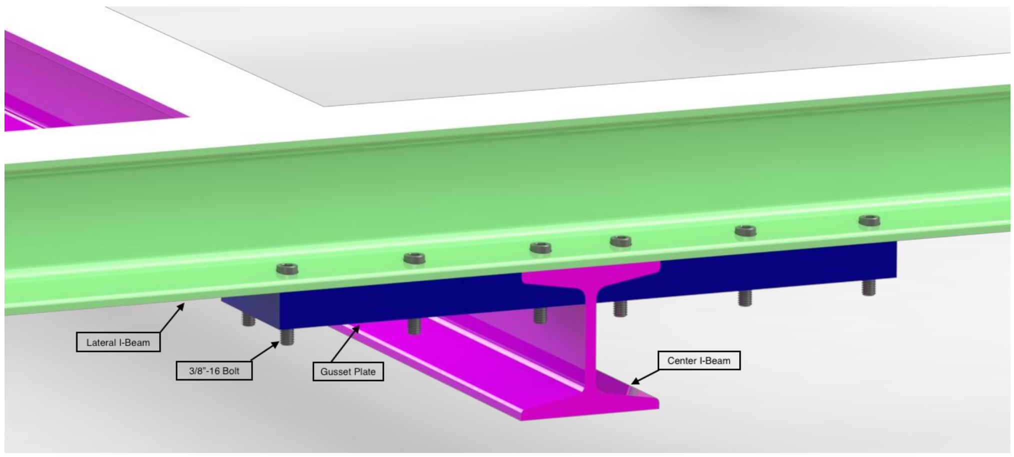


Figure 2: I-Beam intersection joint

7. Align the holes located within the channel on the gusset plates with the bolts placed between the I-beams in step 6 as shown in Figure 2. Run those bolts through the holes, ensuring that the wide portion of the plate mates with the lateral I-beam.
8. Thread the remaining 3/8”-16 bolts for all holes between the I-beams and the gusset plates except for the four located on one side of the I-beam with the rotating casters, threads a washer and a nylon locking nut.

9. Upon the four remaining bolts, align the threaded end of the bolts with the slots located in the friction floor-lock. Mate the baseplate of the floor lock with the lower surface of the fastening plate, and secure it with a washer and nylon-locking nut with each of the remaining bolts as shown in Figure 3.

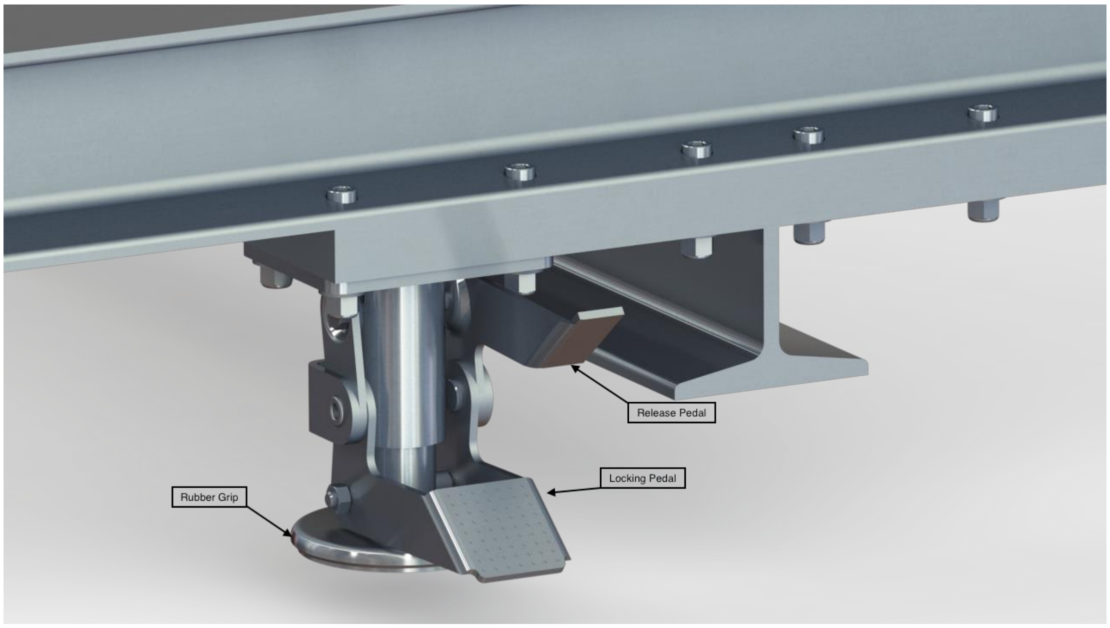


Figure 3: Assembled floor lock

C.2 Central Axle Manufacturing

The manufacturing of the central axle consists of two custom made parts to be fastened with two pneumatic air cylinders and a turntable. The entire assembly mounts the base frame as well as the main frame assemblies.

1. Machine the base mounting plate components to the specifications in section C.7 Engineering Drawings
2. On a flat level surface, weld the components together to form the base mounting plate assembly.
3. On a flat level surface, attach the pneumatic air cylinders to each side of the base mounting plate using eight 5/16-24 x 0.5 [in] socket head button screws with 5/16 [in] plain aluminum washers for the four upper hole locations, and four 5/16 [in] clipped stainless steel washers for the four bottom hole locations. The base mounting plate has now been fully assembled with two pneumatic air cylinders fastened to each side. Refer to Figure 4 for a visual aid.

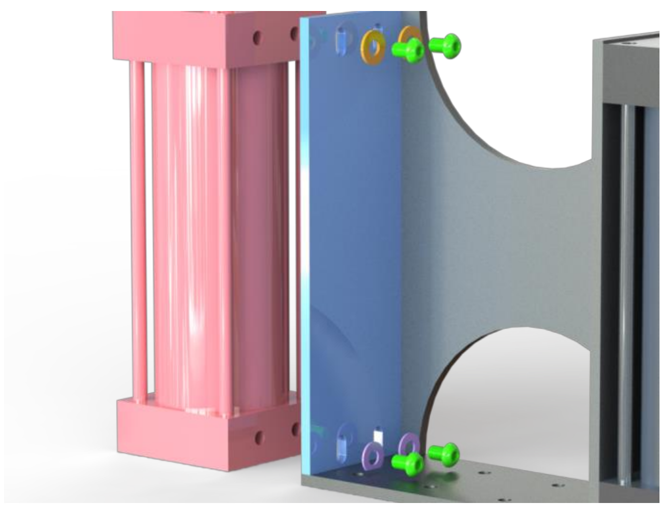


Figure 4: Pneumatic cylinder to base plate fastening

4. Thread, fully, the 3/4 x 10 [in] plain hex nut with a 3/4[in] oversized aluminum washer onto the aluminum air cylinder rod end.
5. Machine the cross mounting plate to the specifications seen in section C.7
6. Place the cross mounting plate onto air cylinder rods through the holes located at the ends of the cross mounting plate. Rest the plate on the oversized aluminum washers that were assembled in step 4. Place an oversized aluminum washer over top of the rod to rest on the top of the plate. Thread a 3/4-10[in] thin wide hex nut onto the rod and secure tightly. The cross mounting plate has now been securely fastened to the pneumatic air cylinders. Refer to Figure 5 as a visual aid.

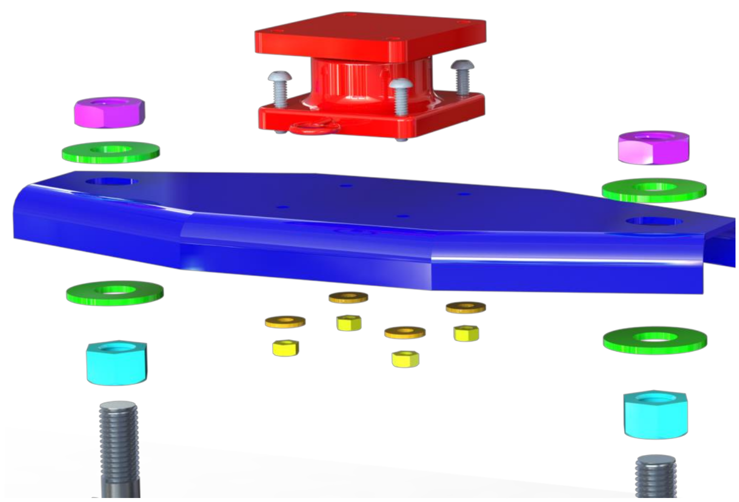


Figure 5: Cross plate fastening

7. Secure the turntable to the cross mounting plate using four 1/4-20x1 [in] socket head button screws with 1/4[in] plain aluminum washers and a corresponding1/4 [in] plain hex nut. The central axle assembly is now complete
8. ***Step 8 to be completed after all assemblies C.1, C.2, C.3, C.4, C.5 are fabricated. See section C.6 for more details.*** To fasten the central axle assembly to the base frame, place the central axle on the midpoint of the base frame I-beam. Align the

eight ¼[in] through holes on the central axle base to the corresponding holes on the base frame I-beam. Orientation of central axle is arbitrary as it is symmetric. Secure central axle to base frame using eight 1/4 - 20 x 1 [in] socked head button screws with a 1/4 [in] stainless steel washer and corresponding 1/4[in]-20 plain hex nut. The central axle is now assembled to the base frame.

C.3 Main Frame Manufacturing

The process of manufacturing custom components for the main frame and assembling all requisite parts for the main frame was considered in the final design. The required manufacturing and assembly process will be detailed in sequence.

1. Cut one 2[in] x 4[in] 6061-T6 aluminum tube to 62.385[in] for the horizontal tube and drill the appropriate holes shown in the engineering drawing located in section C.7.
2. Cut two 2[in] x 4[in] 6061-T6 aluminum tube to 45[in] for the upright tubes and cut out the appropriate sections and holes. All dimensions for this part are presented in the upright tube drawing in section C.7.
3. Install the four handles onto the upright tubes with ¼"-20 buttonhead cap screws.
4. Cut four 6[in] x 6[in] x 1/4[in] 6061-T6 aluminum plates into the appropriate dimensions for the corner gusset plates. Found in C.7 is the engineering drawing for the corner gusset plate that presents all the required dimensions to fabricate the part. The gusset plates are designed to be easy to manufacture and would not require a highly skilled machinist to manufacture. It consists of one straight cut and seven drilled holes on a flat plate. An alternative to manufacturing in-house would be outsourcing the manufacturing of the gusset plates to be water jet, CNC, or laser cut. The alternatives would provide accurate dimensions and hole locations but would cost more than manufacturing in-house. The hole locations are particularly important to be accurate because they are to be countersunk and would automatically center about the hole.

5. Attach the horizontal tube with both upright tubes by installing the countersunk bolts with the corner gusset plates. It is important to use lock washers with the nut when tightening the countersunk bolt to prevent loosening of the bolt. Figure 6 demonstrates the assembling process for this step.

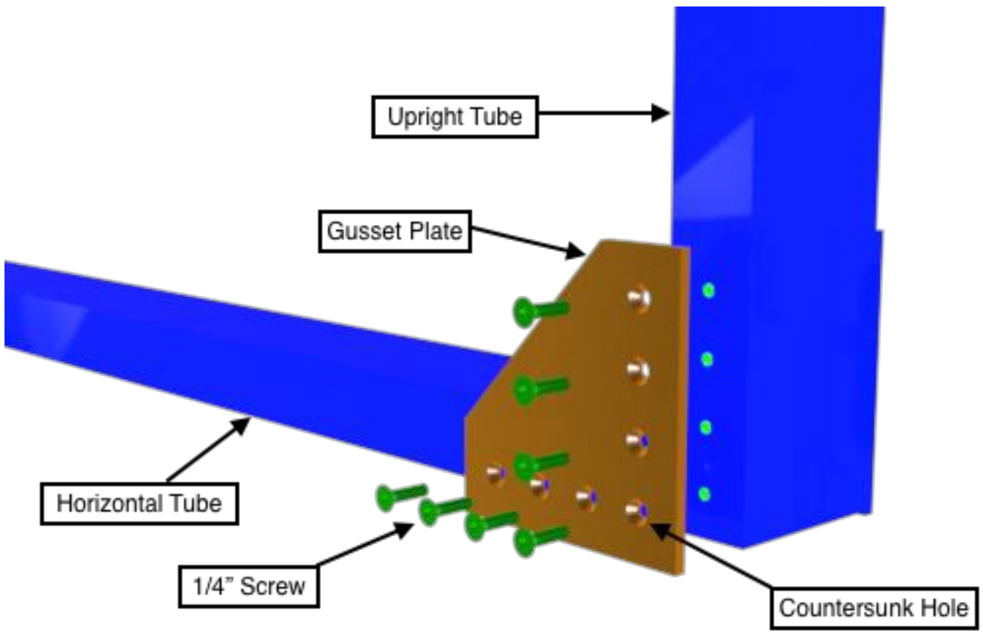


Figure 6: Exploded view of corner gusset plate

6. Cut two 4[in] x 4[in] 6061-T6 aluminum tube to 6[in] for the mechanical hubs. The driving and driven mechanical hubs are slightly different. Drill the appropriate countersunk and counterbore holes to the noted dimensions for each mechanical hub on the engineering drawings. The driving and driven mechanical hub engineering drawings can be seen in section C.7.
7. Cut four 6061-T6 aluminum bars for the bearing mounting blocks for both mechanical hubs. The dimensions of the aluminum bars are shown on the engineering drawing in section C.7, as well as the hole size and locations. The clearance holes are drilled through appropriately.

8. Fasten the pillowblock bearings to both mechanical hubs along with the bearing mounting block with 5/16-18 countersink bolts and appropriate nuts. Figure 7 shows the exploded view of this step to better demonstrate the assembly process.

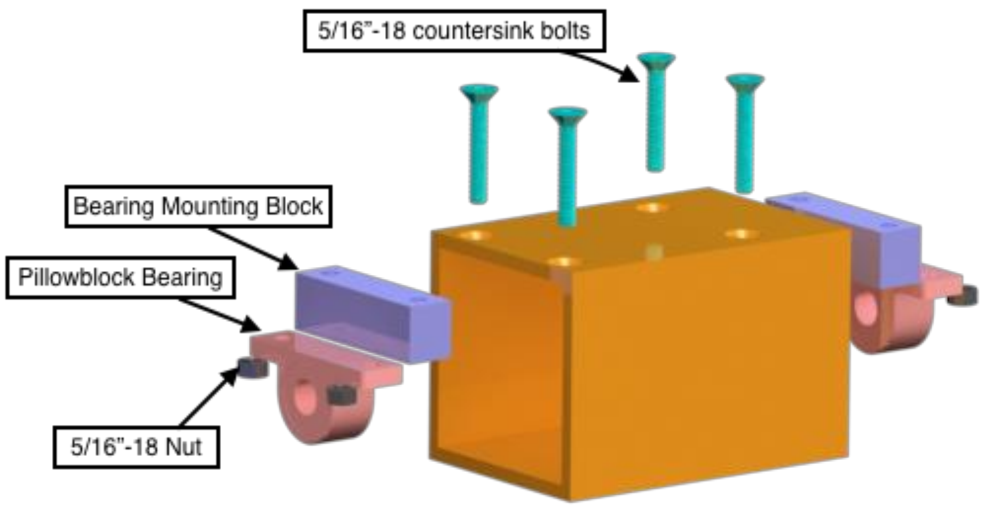


Figure 7: Exploded view of mechanical hub subassembly

9. Cut one 4[in] x 4[in] 6061-T6 aluminum plate with a thickness of 1/2 [in] to the correct dimensions for the gear mounting plate. The engineering drawing for the component is pictured in section C.7. The holes on the side need to be drilled and tapped and the main holes need to be cut out. It is important to note that the holes on the side of the plate are tapped and the larger diameter hole cutout does not go all the way through but is 1/4 [in] deep.
10. Weld the ring gear to the gear mounting plate with the gas metal arc welding method or commonly known as MIG welding. MIG welding is chosen because it is relatively easy to learn and use, especially when welding aluminum is more

difficult than steel. Figure 8 shows the location and the recommended weld bead size and location. Other methods of attaching the ring gear to the mounting plate were considered such as friction fit. Friction fitting the ring gear would be an easier manufacturing process but since the handling tool is to be constructed once, welding would be preferred to ensure that the ring gear is secure on the mounting plate.

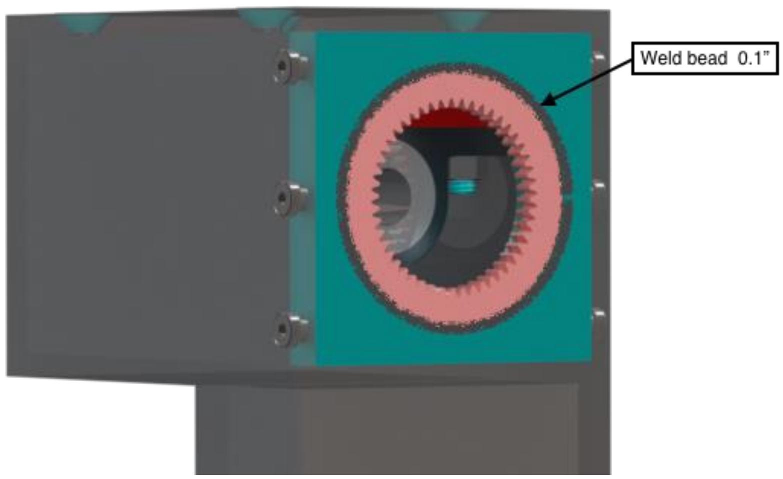


Figure 8: Weld bead location and size between gear mounting plate and ring gear

11. Install the gear mounting plate and ring gear subassembly onto one of the mechanical hubs with 1/4-20 low-profile counterbore bolts. An exploded view of the driving mechanical hub subassembly is provided in Figure 9 as a visual aid in describing this step.

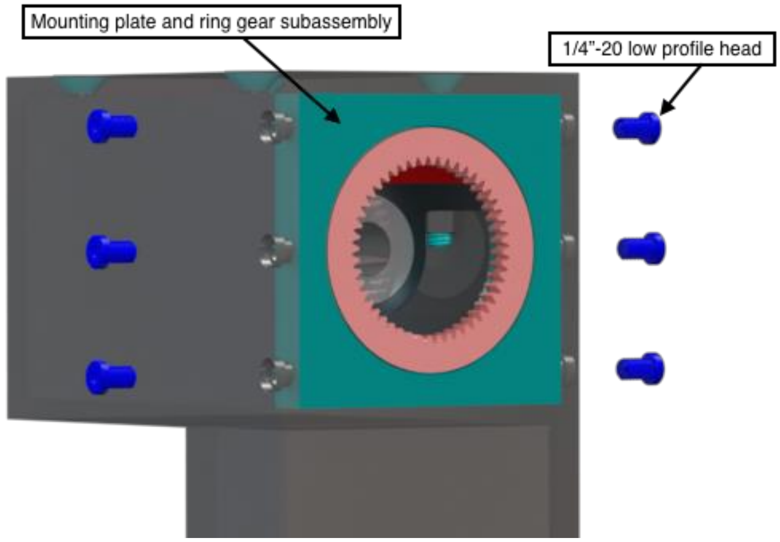


Figure 9: Fastening mounting plate subassembly to driving mechanical hub subassembly

12. Cut two stiffeners to the correct dimensions from 6061-T6 aluminum stocks. An engineering drawing shown in section C.7 lists all the required dimensions.
13. Weld both the driving and driven mechanical hubs onto the appropriate upright tubes. The method of welding is also MIG welding for the same reasons as step 10. The weld joint is located along the aluminum stiffener showcased in Figure 10.

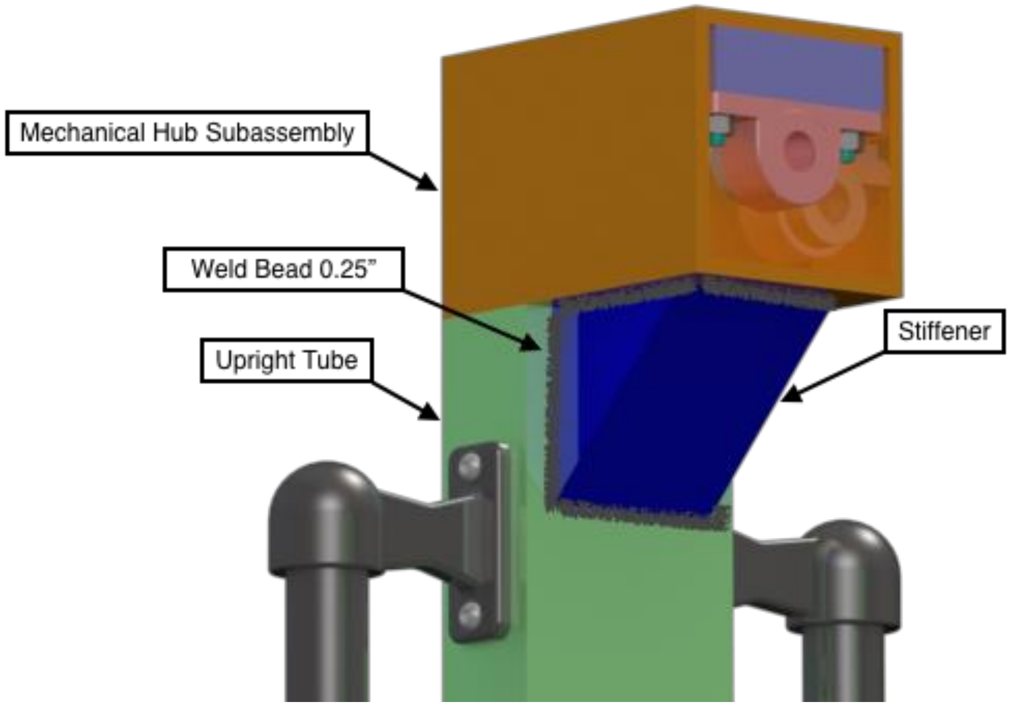


Figure 10: Weld bead location and size between upright tube, mechanical hub, and stiffener

14. Cut two 2 [in] x 5[in] 6061-T6 aluminum tube to the appropriate length for the rotating forks. There is a driving and driven rotating fork and there is a slight difference between the two. The dimensions, hole locations, and hole sizes of the driving and driven rotating fork are found in their respective engineering drawings in section C.7. The top holes are countersunk while all other holes on the rotating fork are through holes.
15. Cut two 6061-T6 aluminum bar to the required size for the bearing mounting block that is mounted on both rotating forks. The mounting block drawing is shown in section C.7 and presents all the required dimensions needed to construct the component.

16. Mount a pillowblock bearing to both rotating fork tubes using countersunk bolts, lock washers and nuts. An exploded view of the process is shown in Figure 11 for a better understanding of the process. The bearing mounting block acts as a spacer to allow the center of the pillowblock bearing to be aligned with the center of the rotating fork.

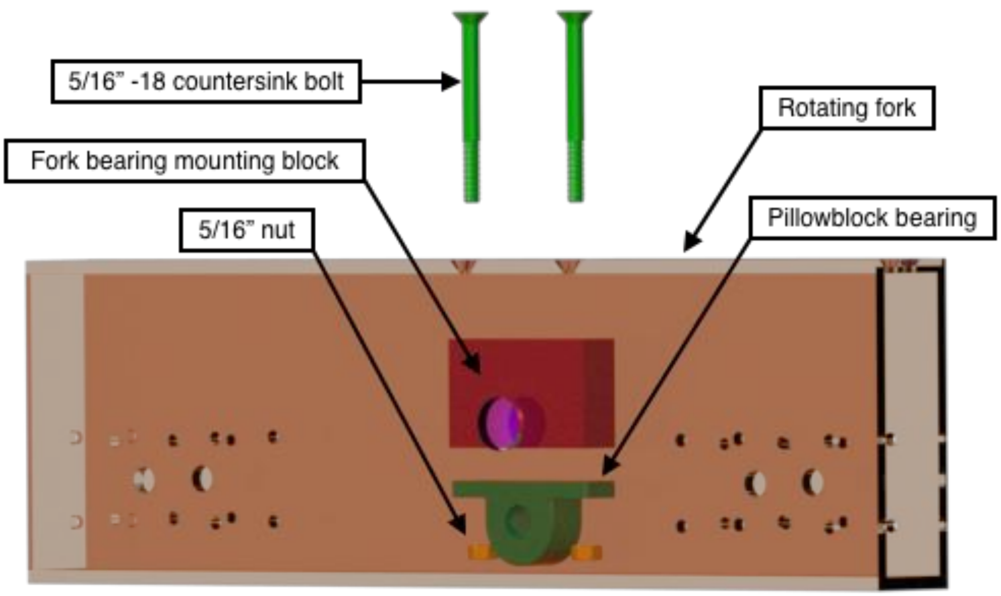


Figure 11: Attaching a pillowblock bearing to the rotating fork

17. Mount the vane box to plug interface system onto both rotating forks. See section C.4 for more details.
18. For the driven mechanical hub, cut a 2024-T4 aluminum shaft to the appropriate length shown on the corresponding engineering drawing in section C.7. Insert the aluminum shaft through the two bearings on the mechanical hub and clamp two shaft collars on the shaft at correct locations. The locations of the shaft collars are presented in the driven mechanical hub assembly drawing in section C.7.
19. Slide the driven rotating fork onto the driven mechanical hub shaft.

20. For the driving rotating fork, fabricate the two custom aluminum cross plates to the appropriate dimensions. The internal cross plate and external cross plate drawings are shown in section C.7.

21. Using the MIG welding technique, weld the internal cross plate to the driving rotating fork as shown in Figure 12.

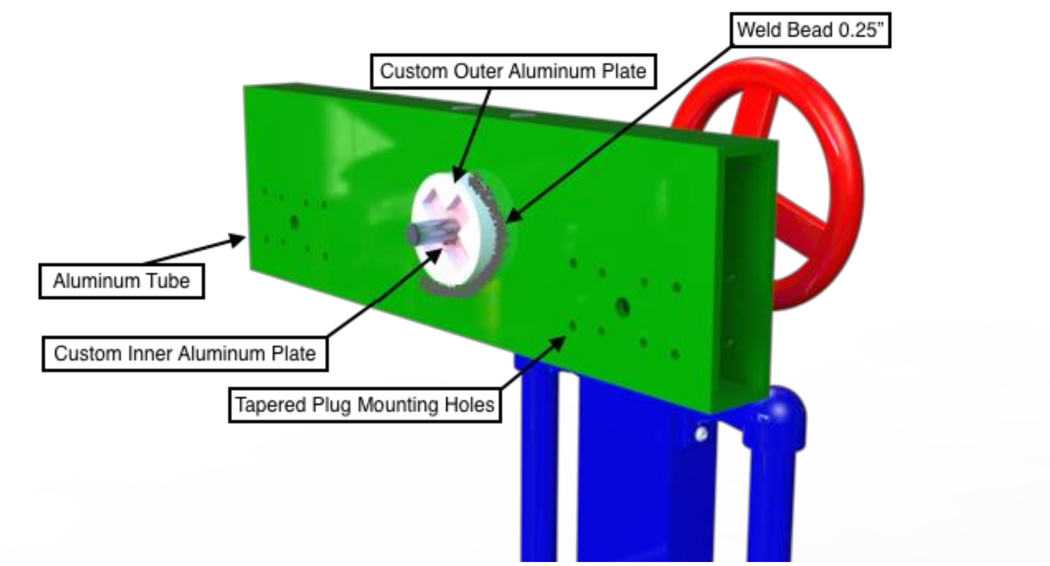


Figure 12: Weld bead location and size between custom aluminum plate and driving rotating fork

22. Cut a 2024-T4 aluminum shaft to the appropriate length shown in the engineering drawing found in section C.7. Insert the shaft through the two bearings and spring on the mechanical hub and clamp on two shaft collars to the correct distances as shown in the driving mechanical hub assembly drawing.

23. Lastly, slide the driving rotating fork onto the driveshaft. Then attach the spur gear, external cross plate, and hand wheel with a key and setscrew at the designated locations.

C.4 Plug Actuation Mechanism

The manufacturing and assembly process of the plug actuation mechanism are detailed in the following steps.

1. Machine four spacer plates from 6061-T6 aluminum stock as shown in the engineering drawing found in section C.7.
2. Mount the non-rotating compact air cylinders to the rotating forks from section C.3, with the spacer plate placed between the cylinders and fork, using ¼-24 socket-head cap screws and washers. Figure 13 provides an exploded view of this step.

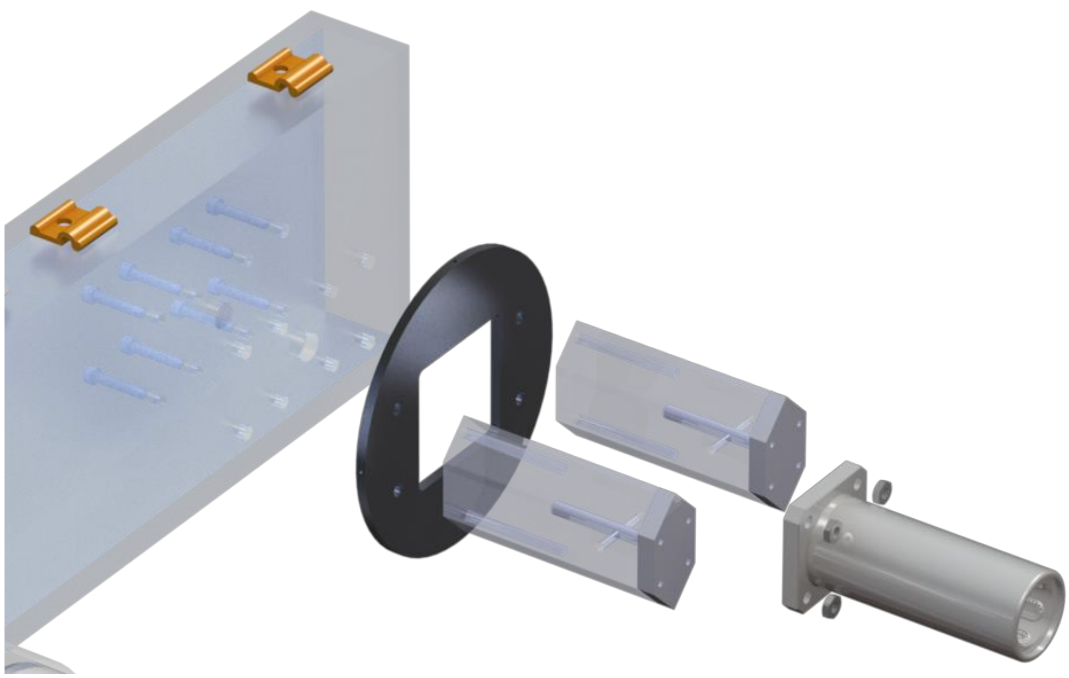


Figure 13: Exploded view of fastening spacer plate, air cylinders, and linear bearing

3. Mount the flange mounted linear bearings to the forks using 10-24 socket-head socket cap screws, nuts, and washers.

4. Insert the shaft into the bearing with the threaded portion of the shaft facing away from the bearing.
5. Shorten the compression springs to a total length of 7.625 [in] and place the spring onto the bearing.
6. Machine four slider plates from 6061-T6 aluminum stock as shown in the engineering drawing found in section C.7. Compress the spring and attach the slider plate to the air cylinders using 8-32 flat-head socket cap screws. Next let the spring extend fully. Figure 14 provides a visual aid in demonstrating steps 4 – 6.

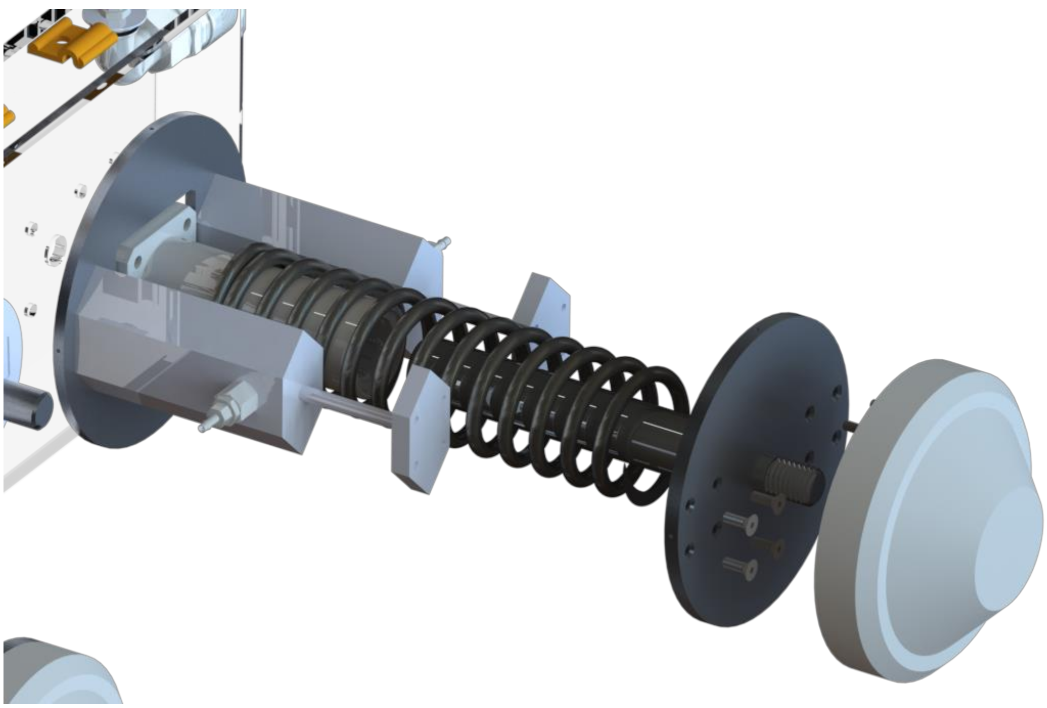


Figure 14: Assembly of shaft, spring, slider plate and tapered plug

7. Machine four plugs from Teflon® as shown in the engineering drawing found in section C.7 and screws the plugs onto the shafts.

8. Attach four 1/8 [in] male NPT pipe to 10-32 male NPT pipe adapters to four 1/8 [in] NPT male pipe to 1/8" ID barbed hose fittings using Teflon® tape between the threaded components.
9. Attach the assembly created in step 8 to the upper port, located furthest from the rotating fork, in the air cylinders using Teflon® tape between the threaded portions.
10. Machine four inner safety shields as shown in the engineering drawing found in section C.7 and attach these to the spacer plates using 2-56 flat-head socket cap screws.
11. Machine four outer safety shields as shown in the engineering drawing found in section C.7 and attach these to the spacer plates using 2-56 flat-head socket cap screws.

C.5 Pneumatic Control System

Please see the following figures for detailed assembly instructions of the pneumatic fittings. Ensure that Teflon® tape is used for all threaded connections and two hose clamps are used for each hose-to-pipe connection. Adhesive hose clamps should be used to secure the hose to the frame as needed.

To simplify these diagrams, various numbered symbols have been used to designate each part. These designations can be seen in TABLE I below.

TABLE I: PNEUMATIC COMPONENTS

Number	Description	Source	Part No.
1	ARO shape hose coupling, push-to-connect, brass, 1/8" NPT female, 1/4" coupling size	McMaster-Carr	5343K15
2	Type 316 stainless steel barbed hose fitting, 1/8" hose ID x 1/8" NPT male pipe	McMaster-Carr	53505K61
3	Brass barbed tee hose fitting, 1/8" ID	McMaster-Carr	91355K57
4	Pop-safety valve with test ring, brass, medium flow, 1/8" NPT male	McMaster-Carr	9889K15
5	Air control valve switch, 3 ports, 1/8" NPT female inlet/outlet	McMaster-Carr	62475K41
6	Brass barbed hose fitting adapter, 1/8" hose ID x 1/8" NPTF female pipe	McMaster-Carr	5346K81
7	Rear Mount Pressure gauge with 1/8 male NPT thread 0-160 PSI	McMaster-Carr	3847K73
8	Type 304 stainless steel threaded pipe fitting, 1/8" pipe size, 90 deg elbow	McMaster-Carr	4464K11
9	Air flow control tuning valve, 1/8" NPT female x 1/8" NPA male	McMaster-Carr	8346K15
10	Brass hex nipple, 1/8" pipe size	McMaster-Carr	5485K21
11	Stainless steel threaded pipe fitting, 1/8" pipe x 10-32 thread	McMaster-Carr	2684K19
12	13/32 [in] ID, 1 [in] OD Washer	McMaster-Carr	90107A051
13	Type 304 stainless steel threaded pipe fitting, 1/8" pipe size, 90 deg elbow, female x male	McMaster-Carr	4464K35
14	High pressure brass thread tee pipe fitting, 1/4" pipe size	McMaster-Carr	9171K156
15	Low pressure brass threaded pipe fitting, 1/4" x 1/8" pipe size, 90 deg elbow	McMaster-Carr	4429K131
16	L Bracket		
17	3/8 Male/female NPT Elbow	McMaster-Carr	4464K37
18	3/8 f to 1/8 m reducer	McMaster-Carr	51205K312
19	ARO shape hose coupling, plug, zinc plated steel, 1/8" NPT male, 1/4" coupling size	McMaster-Carr	5343K12

Figure 15 shows the layout of the pneumatic control box. Please note that the tuner assemblies are shown in Figure 16.

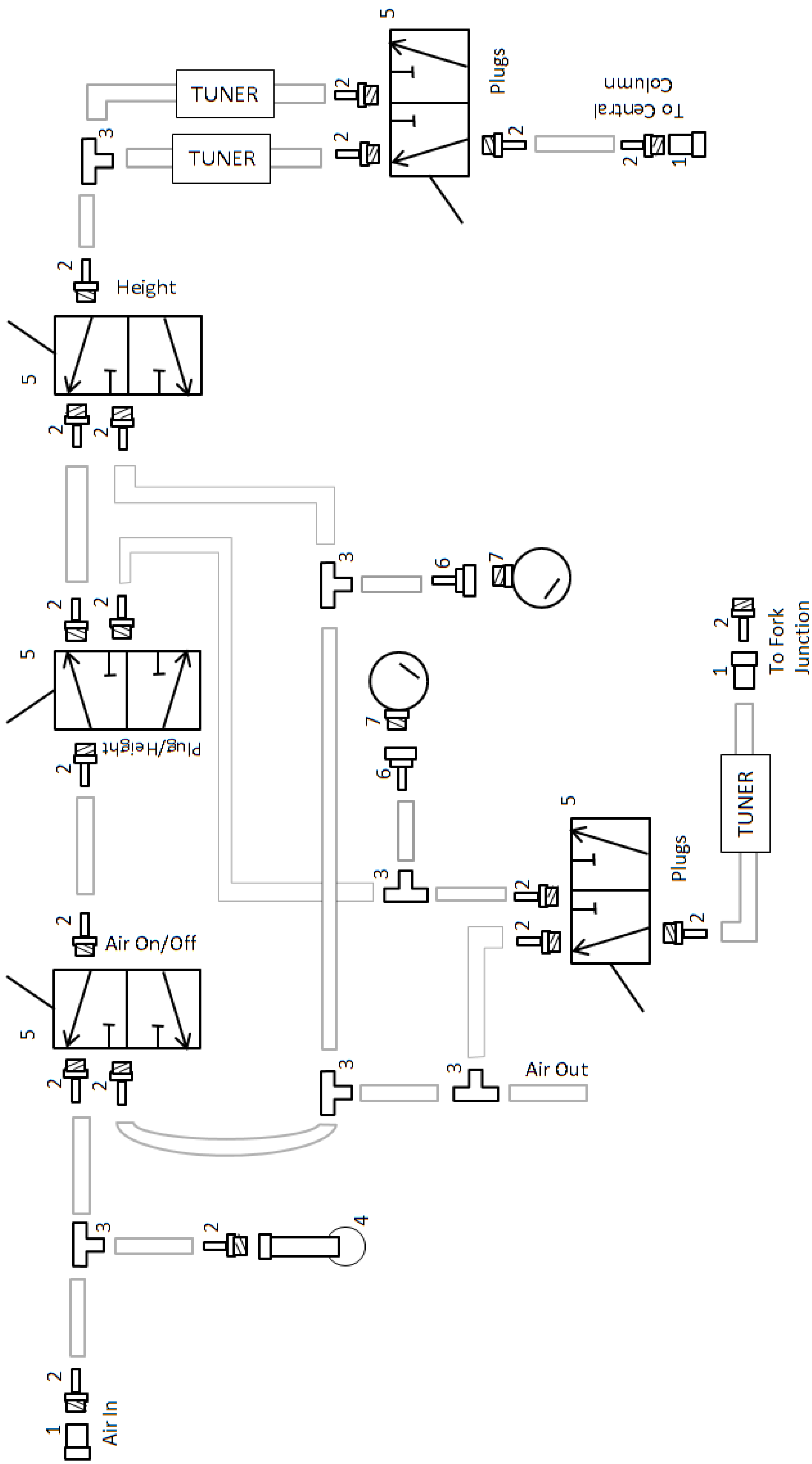


Figure 15: Control box pneumatic diagram

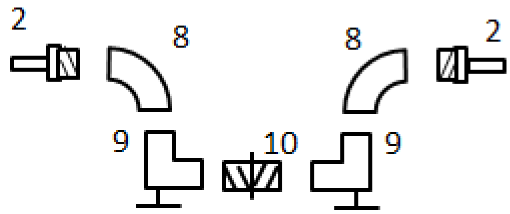


Figure 16: Tuner assembly pneumatic diagram

In addition to the control box, there are two sets of four air cylinders mounted onto the rotating forks to control the actuation of the plug assemblies. The layout for each rotating arm can be seen in Figure 17.

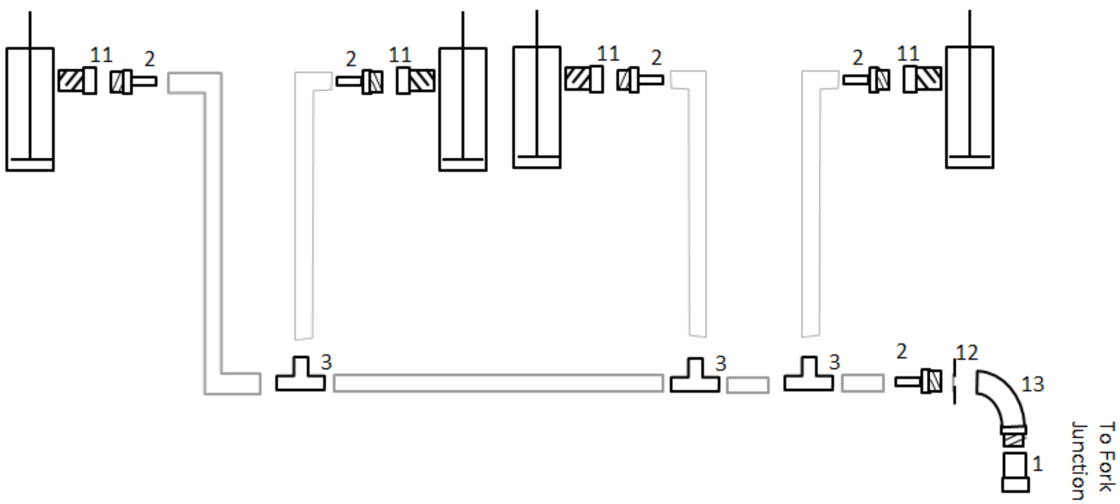


Figure 17: Plug actuation pneumatic diagram

To connect the plug actuation mechanisms to the control box, and to allow the control box to be easily added and removed from the assembly, the fork junction shown in Figure 18 has been included.

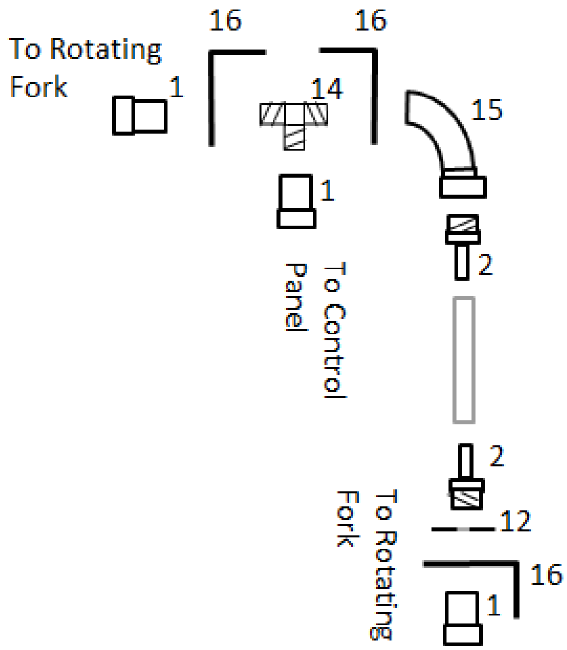


Figure 18: Fork junction pneumatic diagram

To connect the height adjustment air cylinders, which control the height of the handling tool, to the control panel the layout in Figure 19 has been developed.

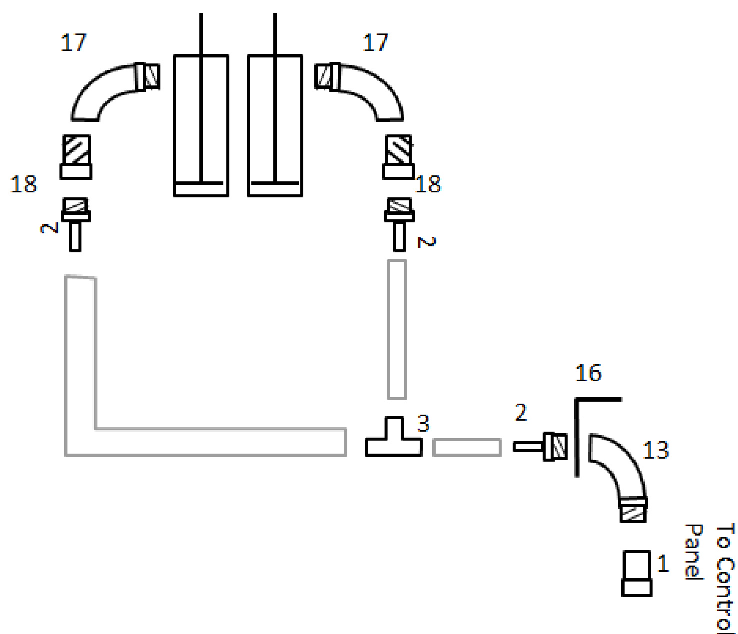


Figure 19: Height adjustment pneumatic diagram

Finally, to easily connect and disconnect the various subsystems described above, a quick-connect hose system shown in Figure 20 has been designed. Four versions of varying length are required to connect the fork junction to the control box, height adjustment subsystem to the control box, and the two plug actuation subsystems to the fork junction.

Figure 20: Quick-connect hose pneumatic diagram

C.6 Final Assembly

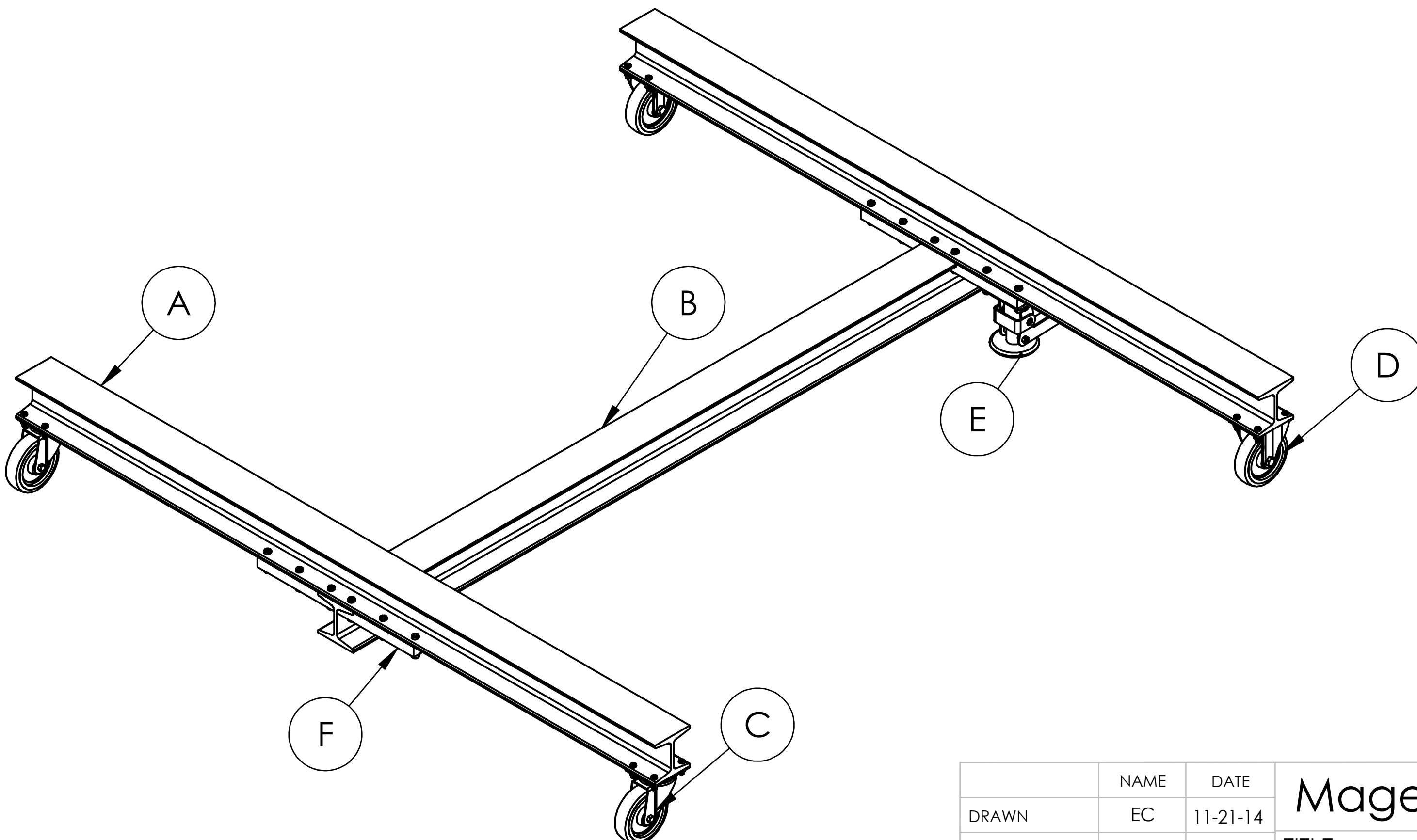
The final assembly of the F-35 vane box handling tool consists of attaching the four subassemblies constructed in sections C.1, C.2, C.3, C.4. Furthermore, the assembly of the pneumatic control system described in section C.5 will be attached to the handling tool. With the completion of the final assembly, the vane box handling tool can be implemented into Magellan Aerospace's system for use. The final assembly steps are listed in the following.

1. Attach the base frame and central axle assembly with 1/4 – 20 buttonhead bolts, nuts and washers.
2. Fasten the main frame onto the turntable of the central axle assembly with ¼ – 20 buttonhead bolts, nuts, and washers.
3. Attach all requisite hoses, adhesive hose clips, and control panel to the handling tool.

C.7 Engineering Drawings

This section contains all the required engineering drawings in order to complete the assembly. It is important to note that these are preliminary engineering drawings and should be reviewed before moving forward with manufacturing.

Item	Part	Quantity
A	Lateral I-Beam	2
B	Center I-Beam	1
C	Swivel Caster	2
D	Fixed Caster	2
E	Floor Lock	1
F	Gusset Plate	4



	NAME	DATE
DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

Magellan Aerospace

TITLE:

Base Frame Assembly

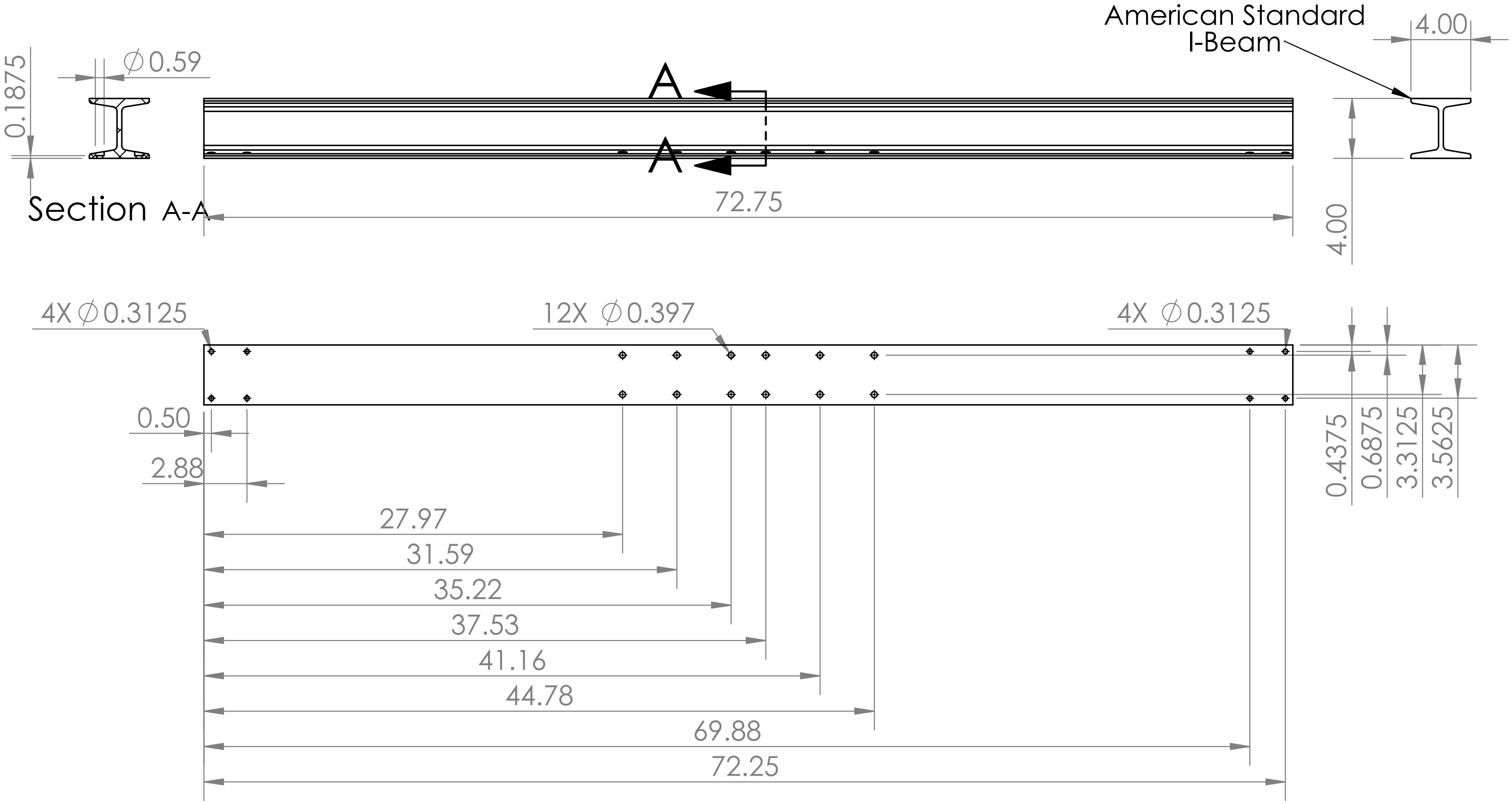
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

MATERIAL
N/A

MECH 4860

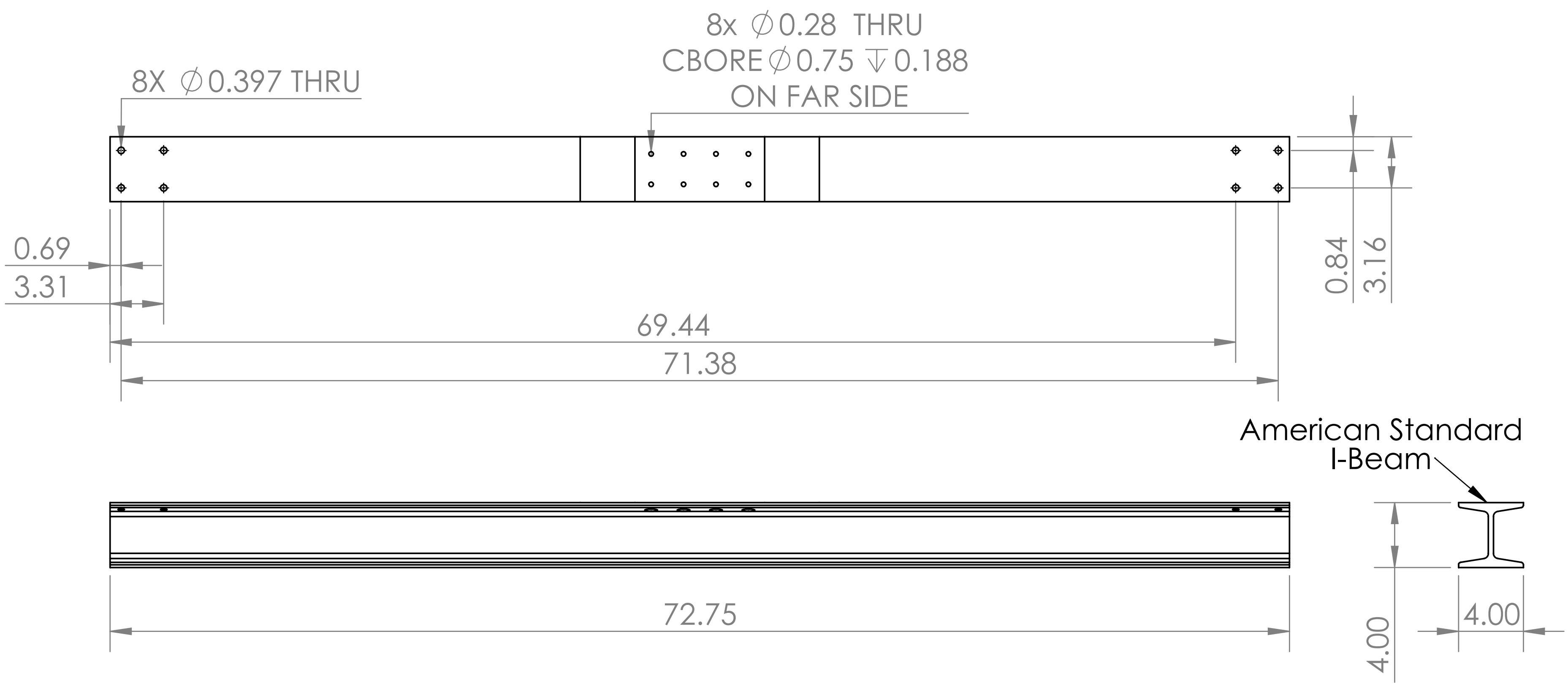
SIZE A | DWG. NO. Base Frame | REV 1

SCALE: 1:15 | WEIGHT: | SHEET 1 OF 4



	NAME	DATE	Magellan Aerospace
DRAWN	EC	11-21-14	TITLE: Lateral I-Beam
CHECKED	RM	11-23-14	
ENG APPR.			
MFG APPR.			
Q.A.			
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES	MATERIAL 6061-T6 Aluminum		SIZE A; DWG. NO. Base Frame; REV 1
MECH 4860			SCALE: 1:10; WEIGHT:32.28 lbs; SHEET 2 OF 4

5 4 3 2 1



	NAME	DATE
DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

MATERIAL
6061-T6 Aluminum

MECH 4860

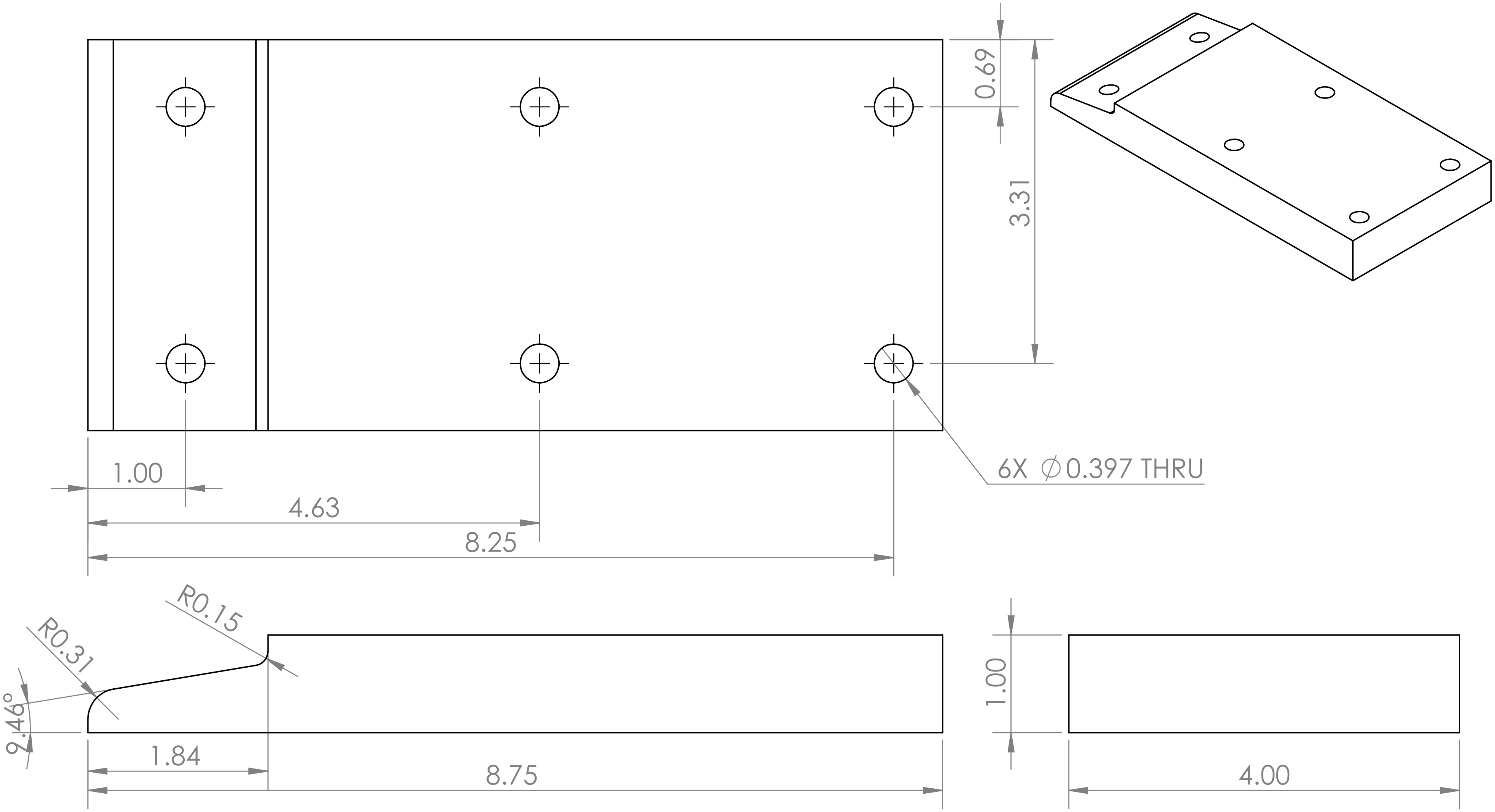
Magellan Aerospace

TITLE:
Center I-Beam

SIZE A | DWG. NO. Base Frame | REV 1

SCALE: 1:10 | WEIGHT:32.37 lbs | SHEET 3 OF 4

5 4 3 2 1



	NAME	DATE
DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

MATERIAL
6061-T6 Aluminum

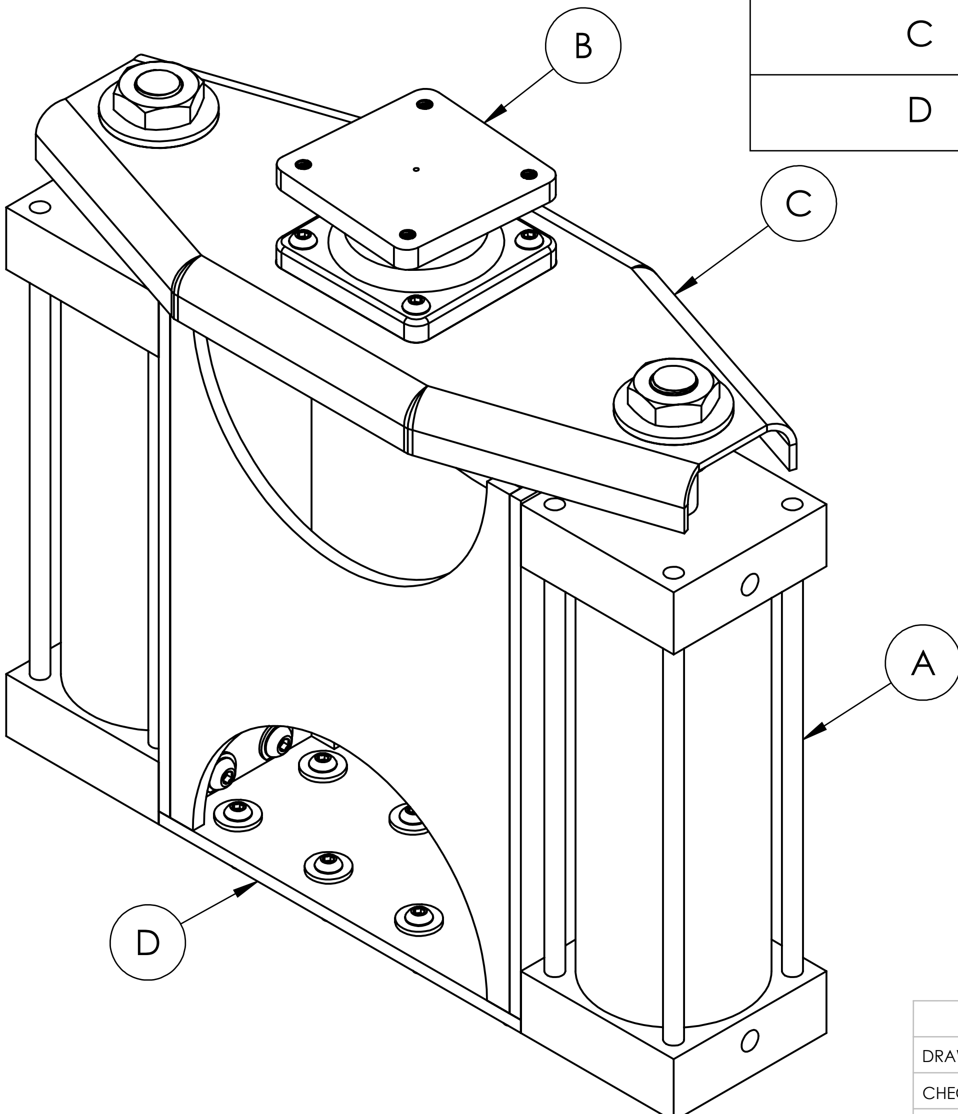
MECH 4860

Magellan Aerospace

TITLE:
Gusset Plate

SIZE A | DWG. NO. Base Frame | REV 1

SCALE: 2:3 | WEIGHT: 1.12 lbs | SHEET 4 OF 4



Item	Part	Quanitity
A	Air Cylinder	2
B	Turntable	1
C	Cross Mounting Plate	1
D	Base Mounting Plate	1

	NAME	DATE
DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

MATERIAL
N/A

MECH 4860

Magellan Aerospace

TITLE:
Central Axle Assembly

SIZE A

DWG. NO. Central Axle

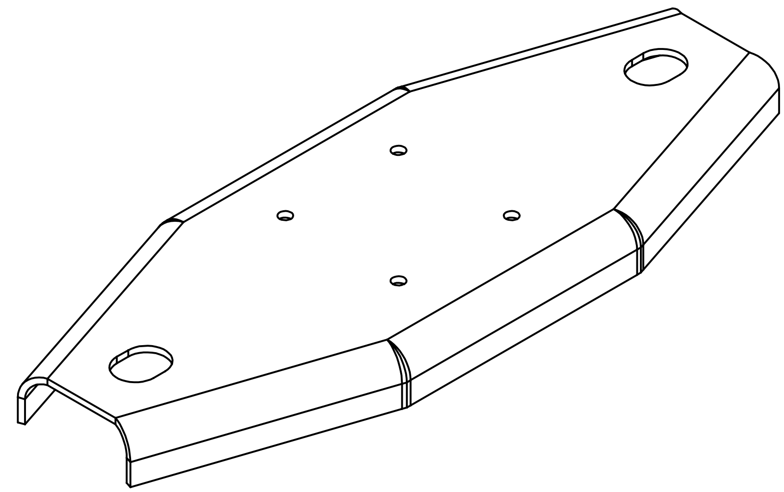
REV 1

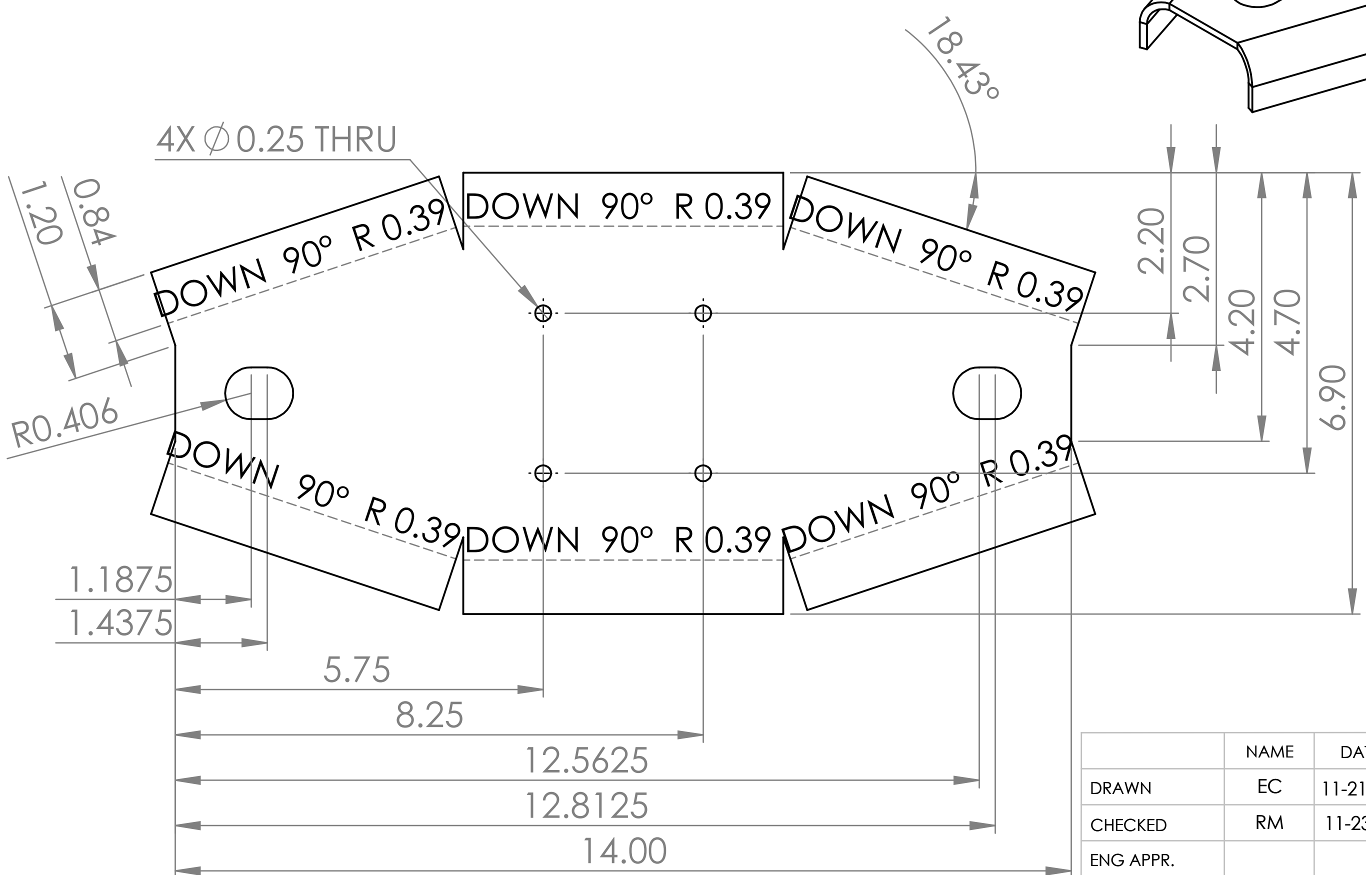
SCALE: 1:3

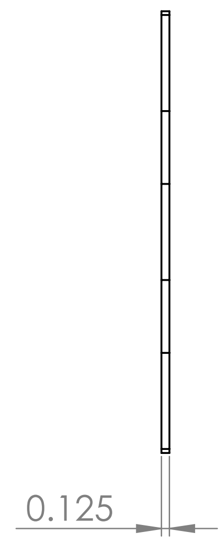
WEIGHT:

SHEET 1 OF 4

5 4 3 2 1







	NAME	DATE
DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

Magellan Aerospace

TITLE:
Cross Mounting Plate

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

MATERIAL
4130 Steel normalized at 870 C

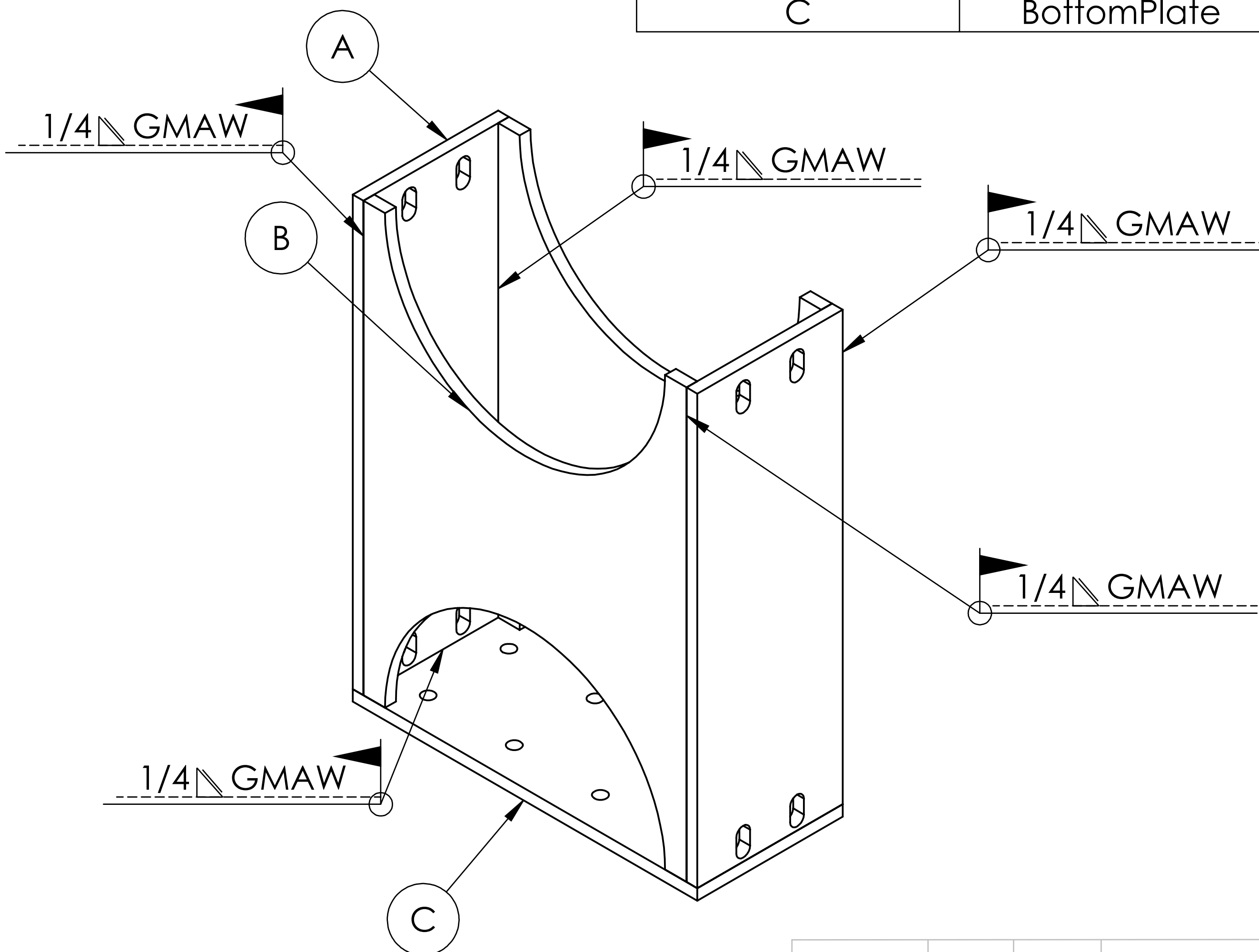
MECH 4860

SIZE	DWG. NO.	REV
A	Central Axle	1

SCALE: 1:3 WEIGHT: SHEET 2 OF 4

5 4 3 2 1

Item	Part	Quantity
A	Side Plate	2
B	Front Plate	2
C	BottomPlate	1



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DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

Magellan Aerospace

TITLE: Base Mounting Plate

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES

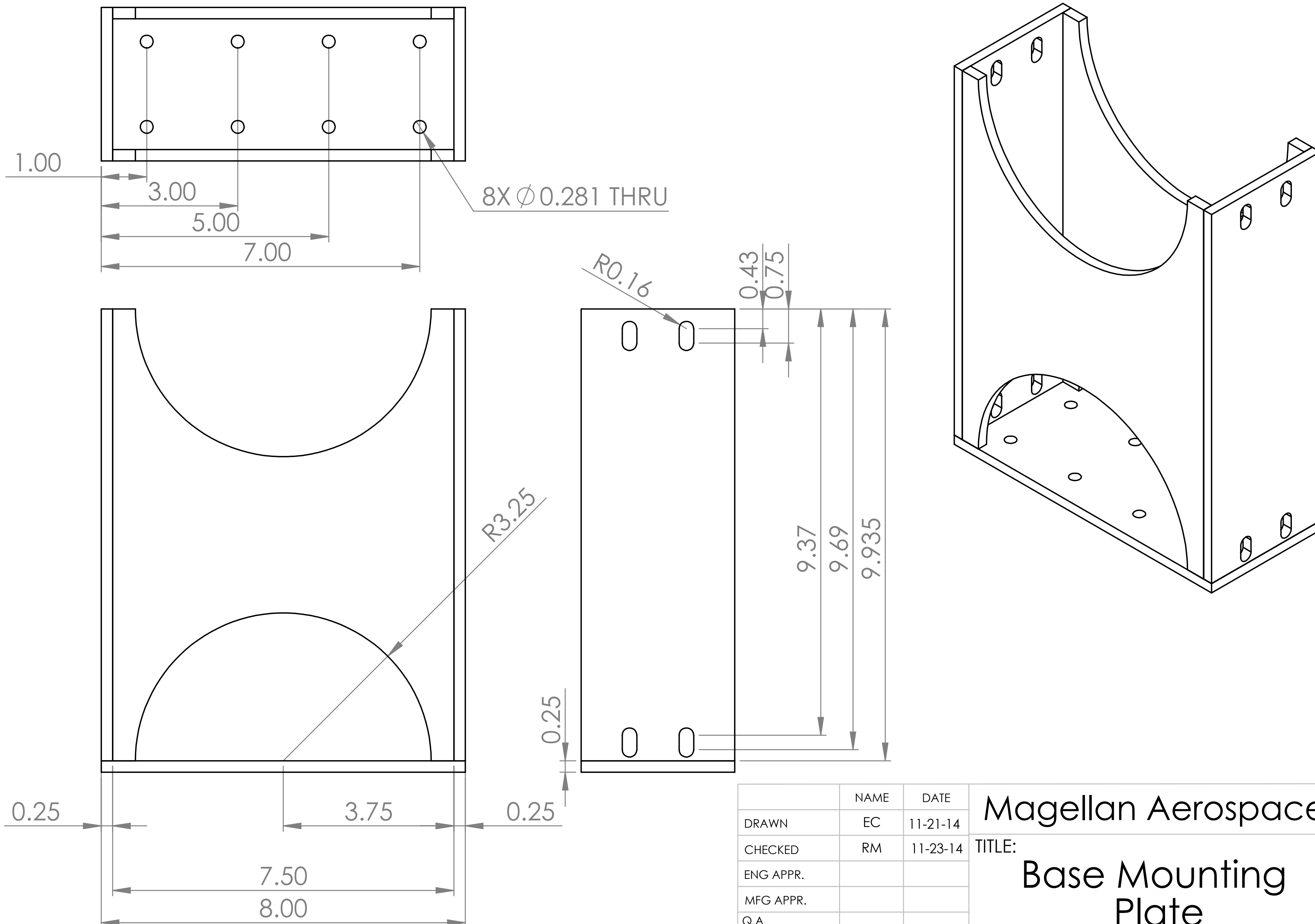
MATERIAL 4130 Steel normalized at 870 C

MECH 4860

SIZE A | DWG. NO. Central Axle | REV 1

SCALE: 1:3 | WEIGHT: | SHEET 3 OF 4

5 4 3 2 1



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MFG APPR.		
Q.A.		

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

MATERIAL
4130 Steel normalized at 870C

MECH 4860

Magellan Aerospace

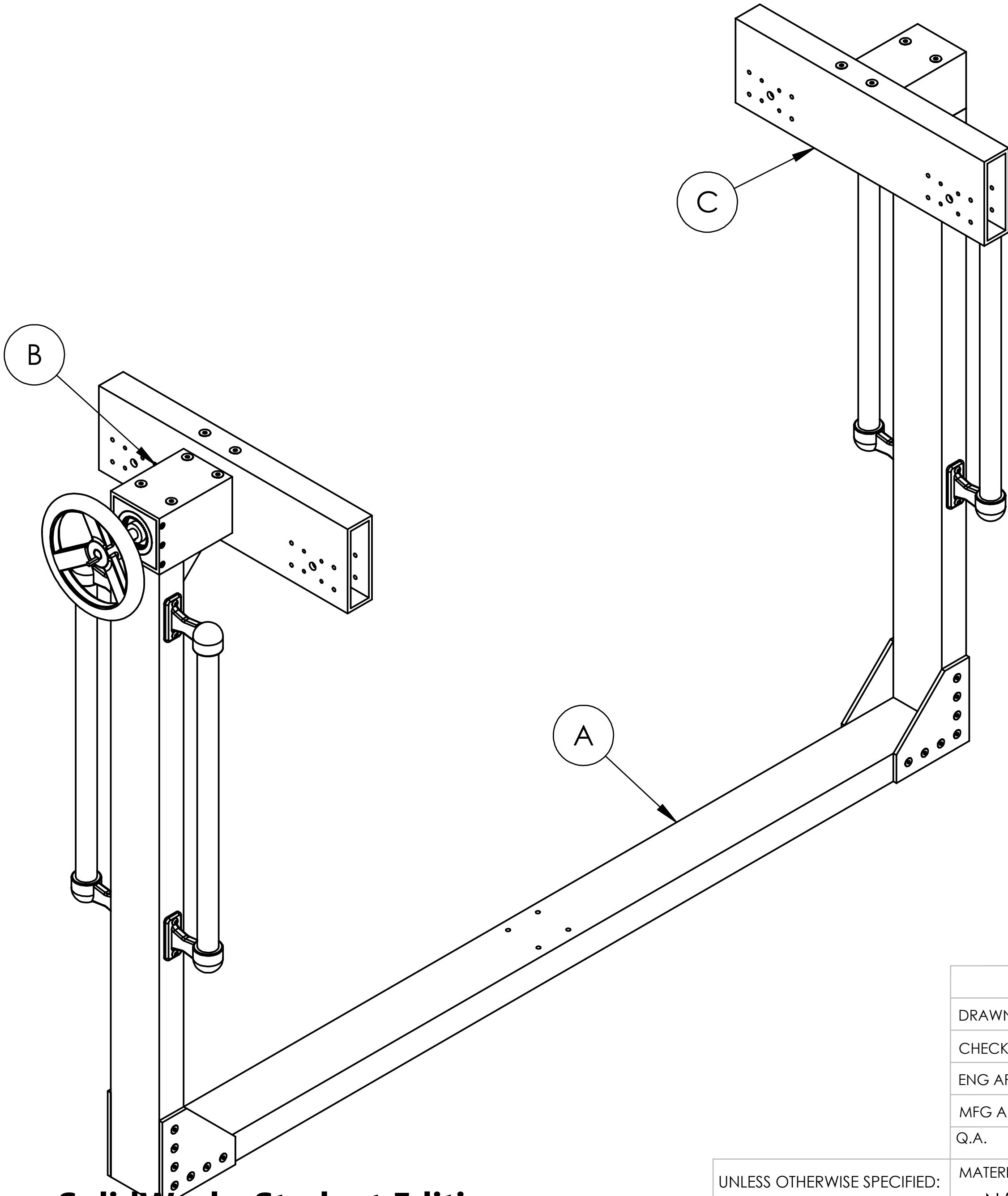
TITLE:
Base Mounting Plate

SIZE A | DWG. NO. Central Axle | REV 1

SCALE: 1:3 | WEIGHT: | SHEET 4 OF 4

5 4 3 2 1

	Feature	Quantity
A	Structural Frame	1
B	Mechanical Hub	2
C	Rotating Fork	2



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CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

MATERIAL
N/A

MECH 4860

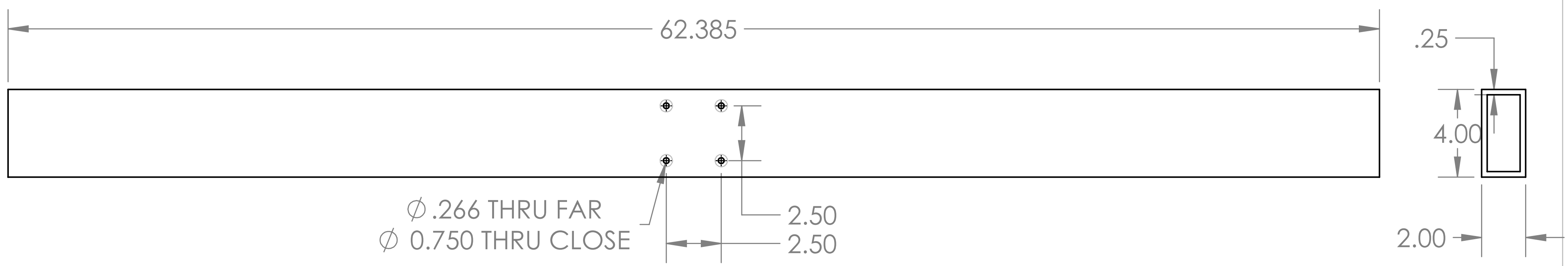
Magellan Aerospace

TITLE:
Main Frame Assembly

SIZE A | DWG. NO. Main Frame | REV 1

SCALE: 1:10 | WEIGHT: | SHEET 1 OF 18

5 4 3 2 1



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DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

MATERIAL
6061-T6 Aluminum

MECH 4860

Magellan Aerospace

TITLE:
Horizontal Tube

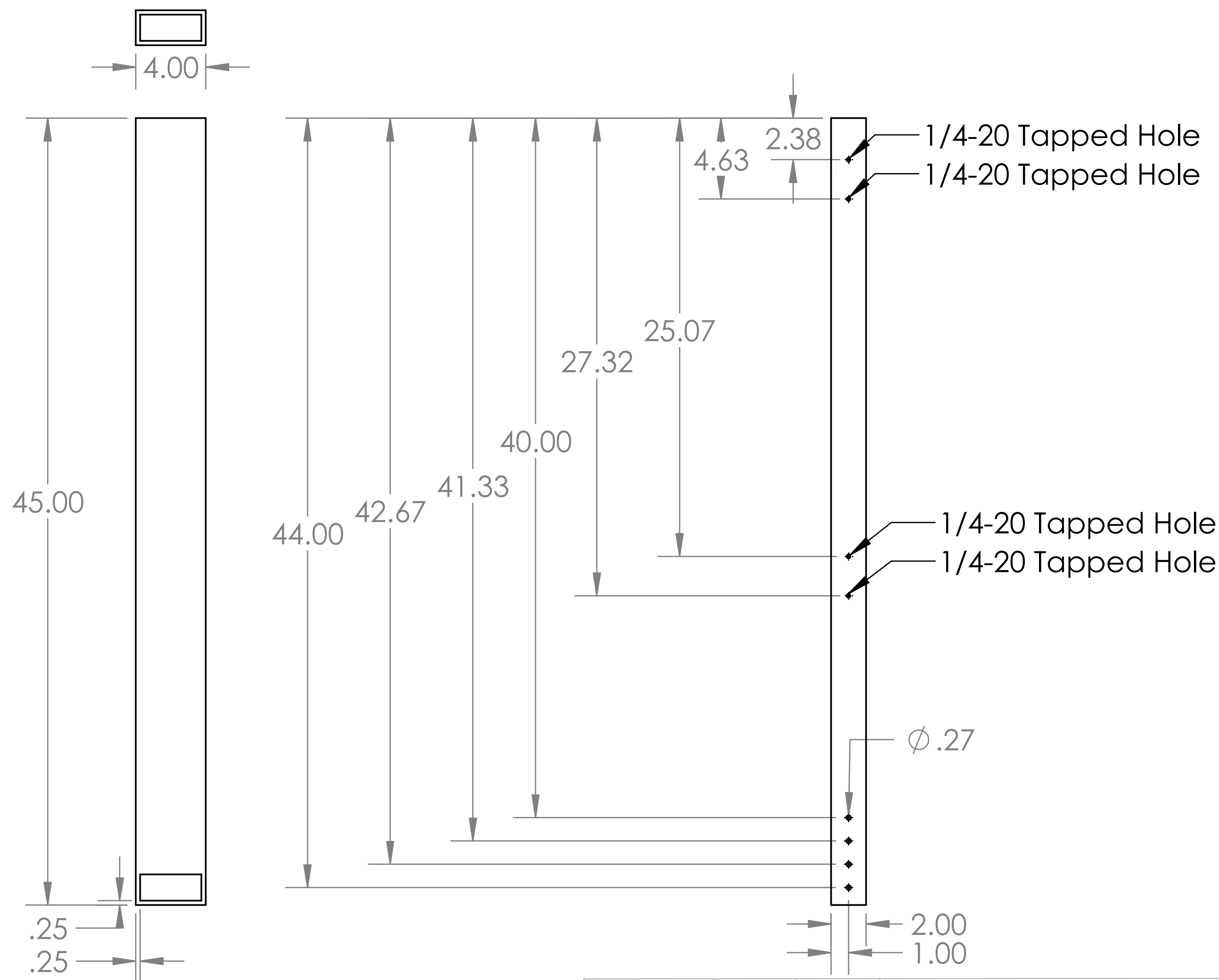
SIZE A

DWG. NO. Main Frame

REV 1

SCALE: 1:7 WEIGHT: SHEET 2 OF 18

5 4 3 2 1



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DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

Magellan Aerospace

TITLE:

Upright Tube

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

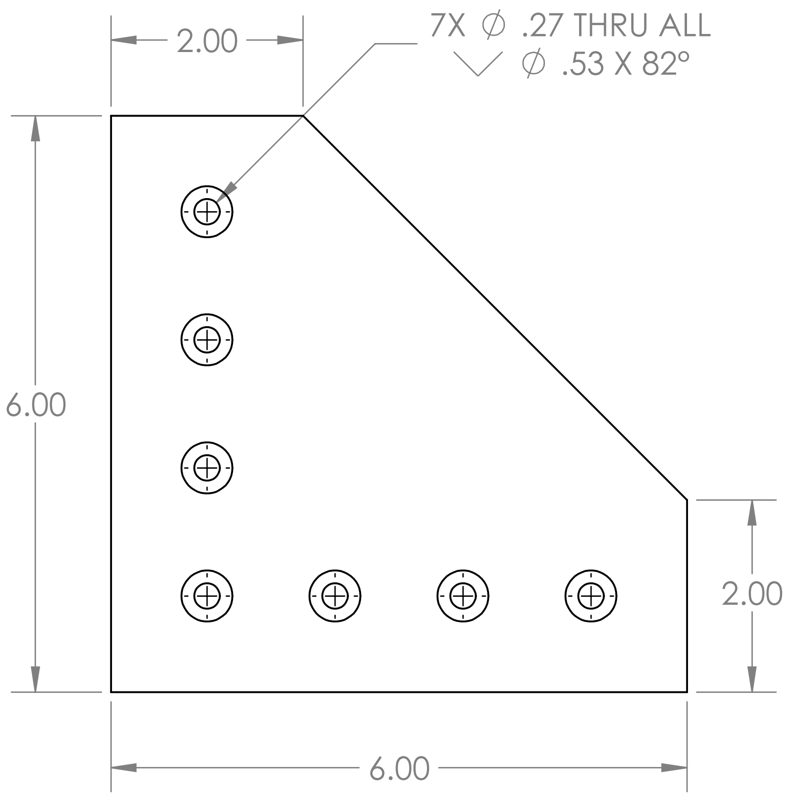
MATERIAL
6061-T6 Aluminum

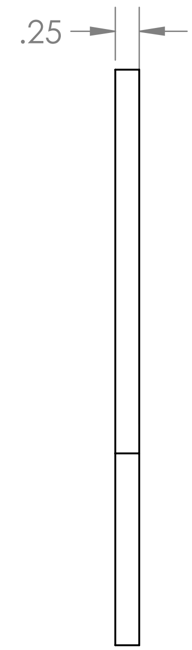
MECH 4860

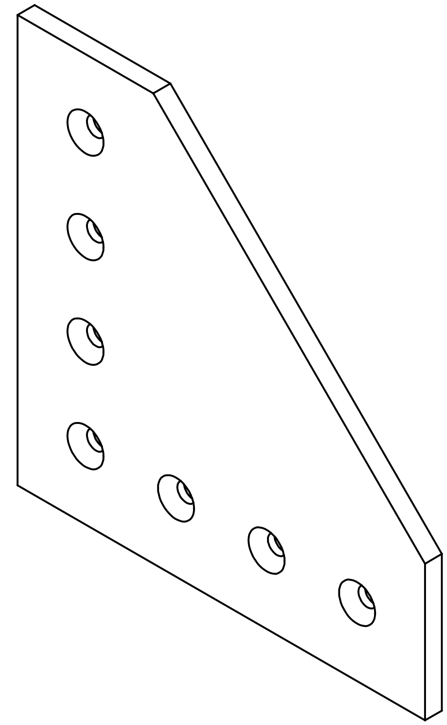
SIZE A | DWG. NO. Main Frame | REV 1

SCALE: 1:10 | WEIGHT: | SHEET 3 OF 18

5 4 3 2 1







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CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

MATERIAL
6061-T6 Aluminum

MECH 4860

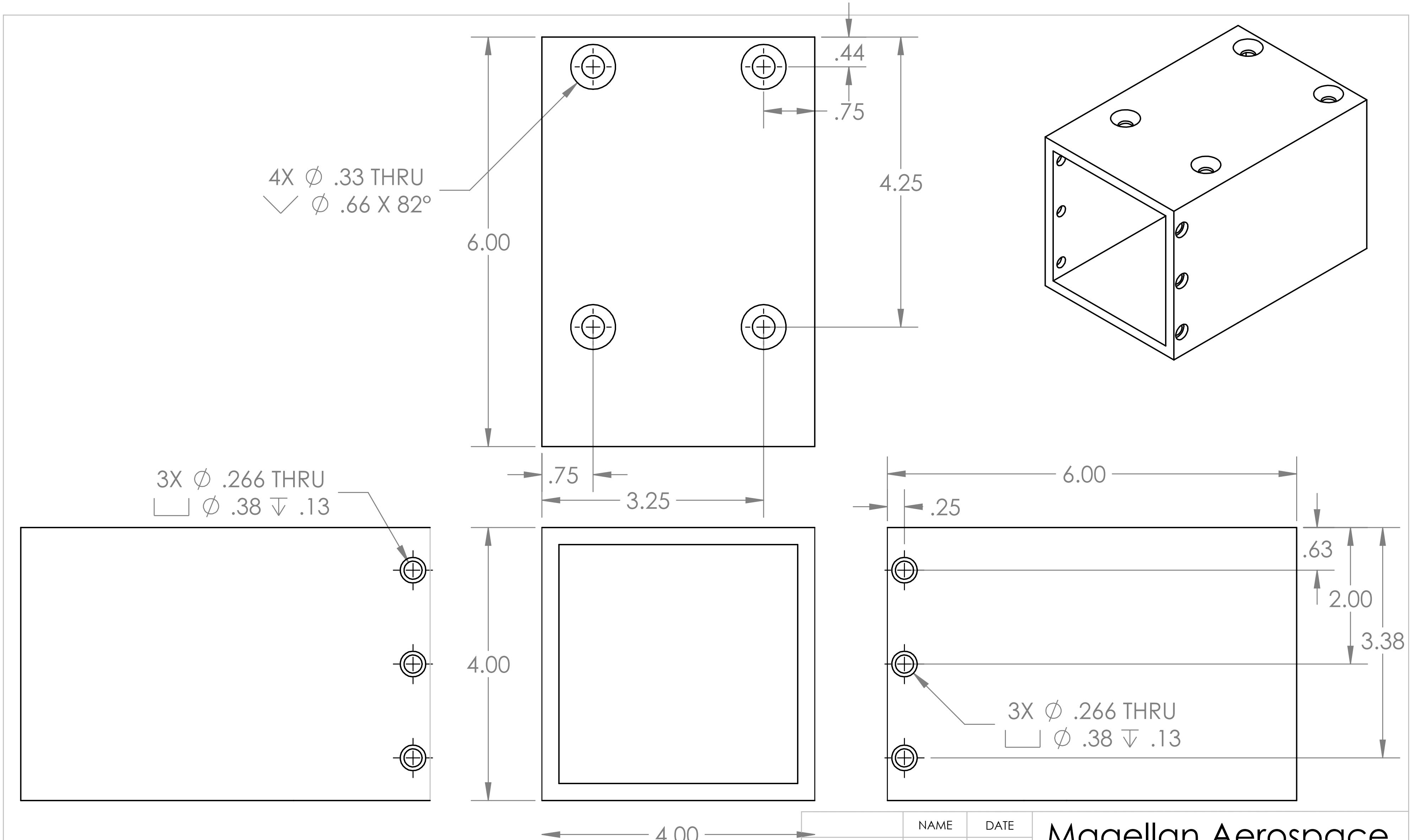
Magellan Aerospace

TITLE:
Corner Gussset Plate

SIZE	DWG. NO.	REV
A	Main Frame	1

SCALE: 1:2 WEIGHT: SHEET 4 OF 18

5 4 3 2 1



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DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

Magellan Aerospace

TITLE:

Driving Mechanical Hub

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

MATERIAL
6061-T6 Aluminum

MECH 4860

SIZE	DWG. NO.	REV
A	Main Frame	1

SCALE: 1:2 | WEIGHT: | SHEET 5 OF 18

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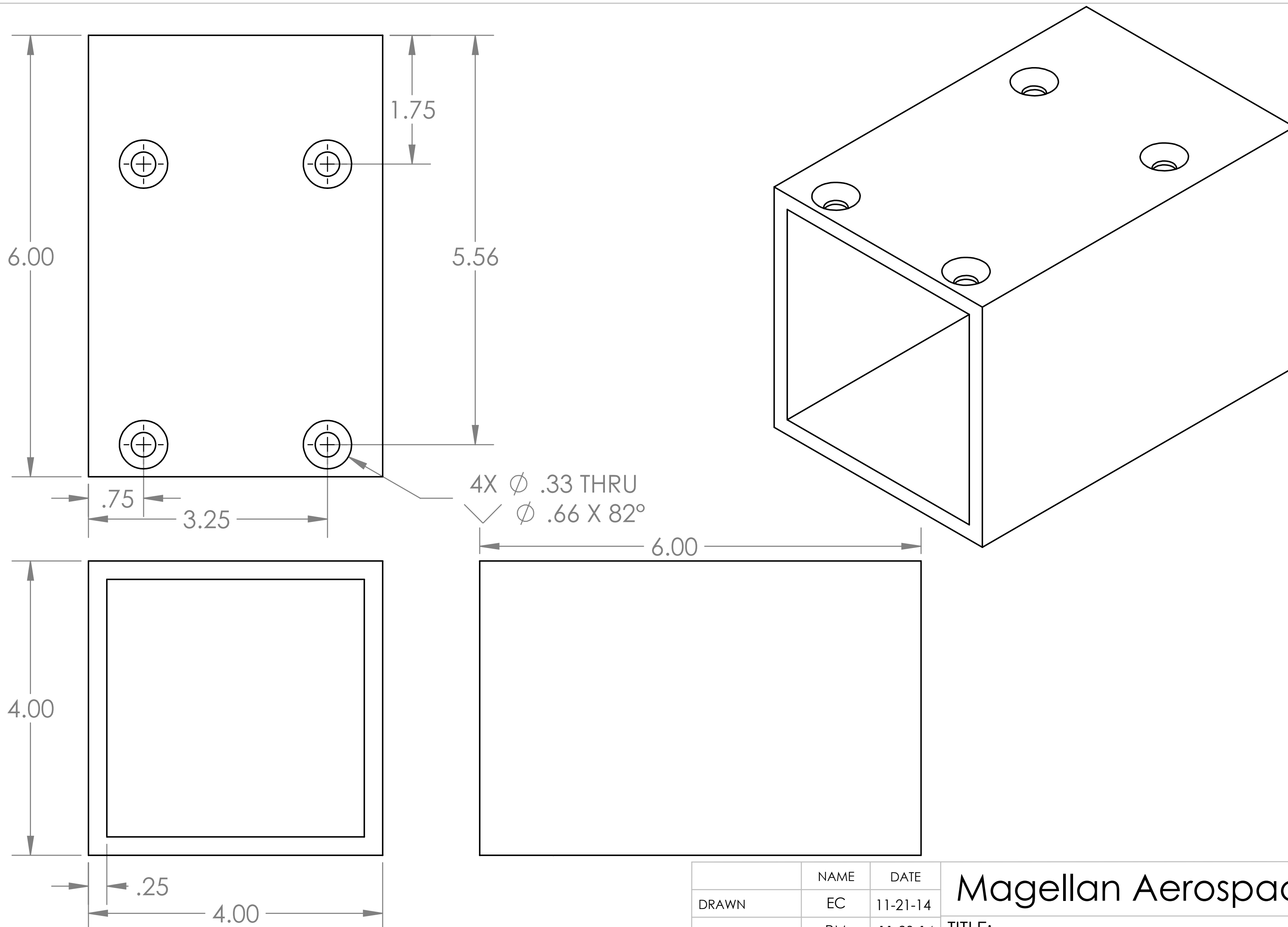
5 4 3 2 1



	NAME	DATE
DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

Magellan Aerospace

TITLE:

Driven Mechanical Hub

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

MATERIAL
6061-T6 Aluminum

MECH 4860

SIZE	DWG. NO.	REV
A	Main Frame	1

SCALE: 1:2	WEIGHT:	SHEET 6 OF 18

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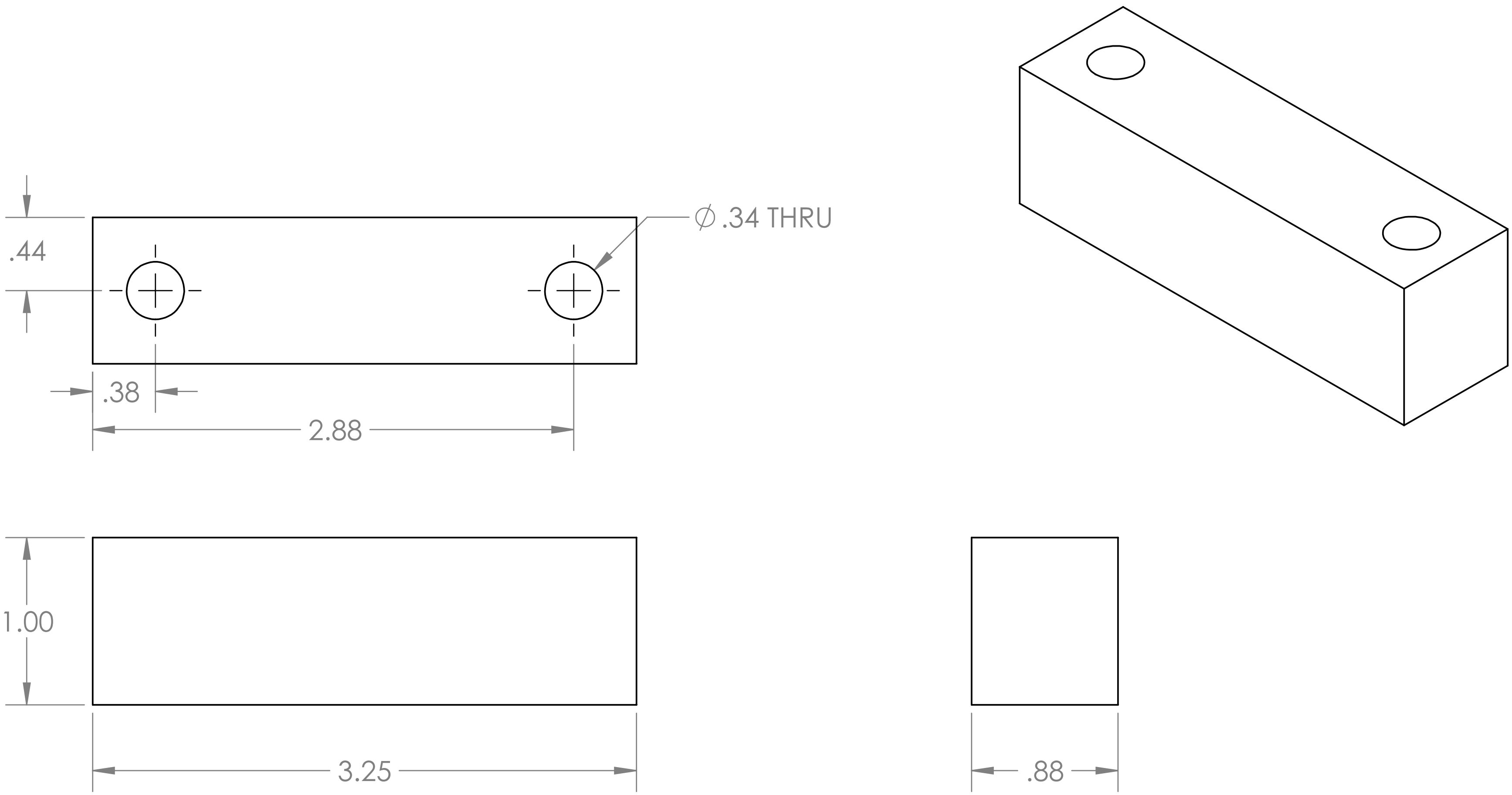
5 4 3 2 1



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DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

MATERIAL
6061-T6 Aluminum

MECH 4860

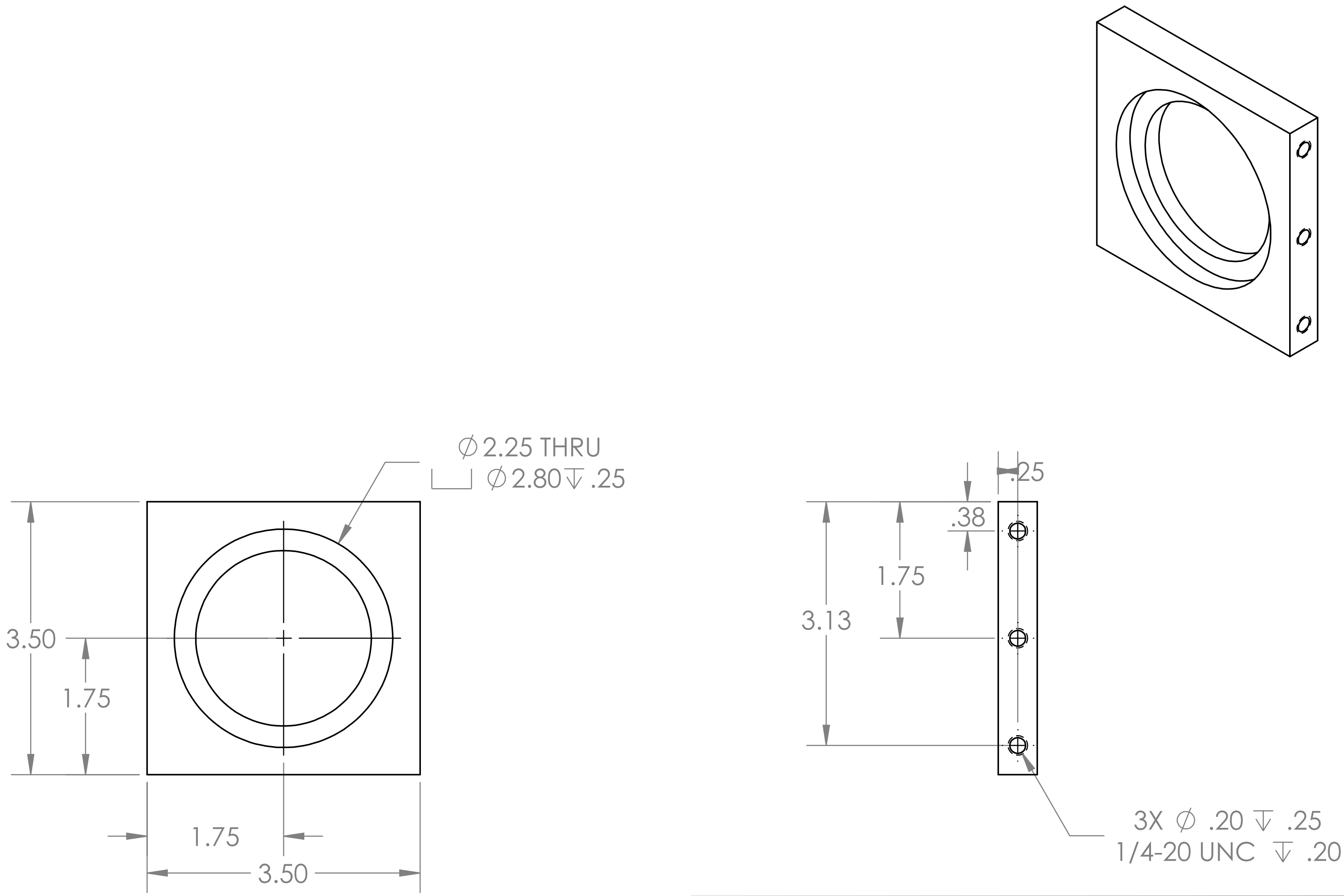
Magellan Aerospace

TITLE:
Hub Bearing Mounting Block

SIZE A | DWG. NO. Main Frame | REV 1

SCALE: 1:1 | WEIGHT: | SHEET 7 OF 18

5 4 3 2 1



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CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

MATERIAL
6061-T6 Aluminum

MECH 4860

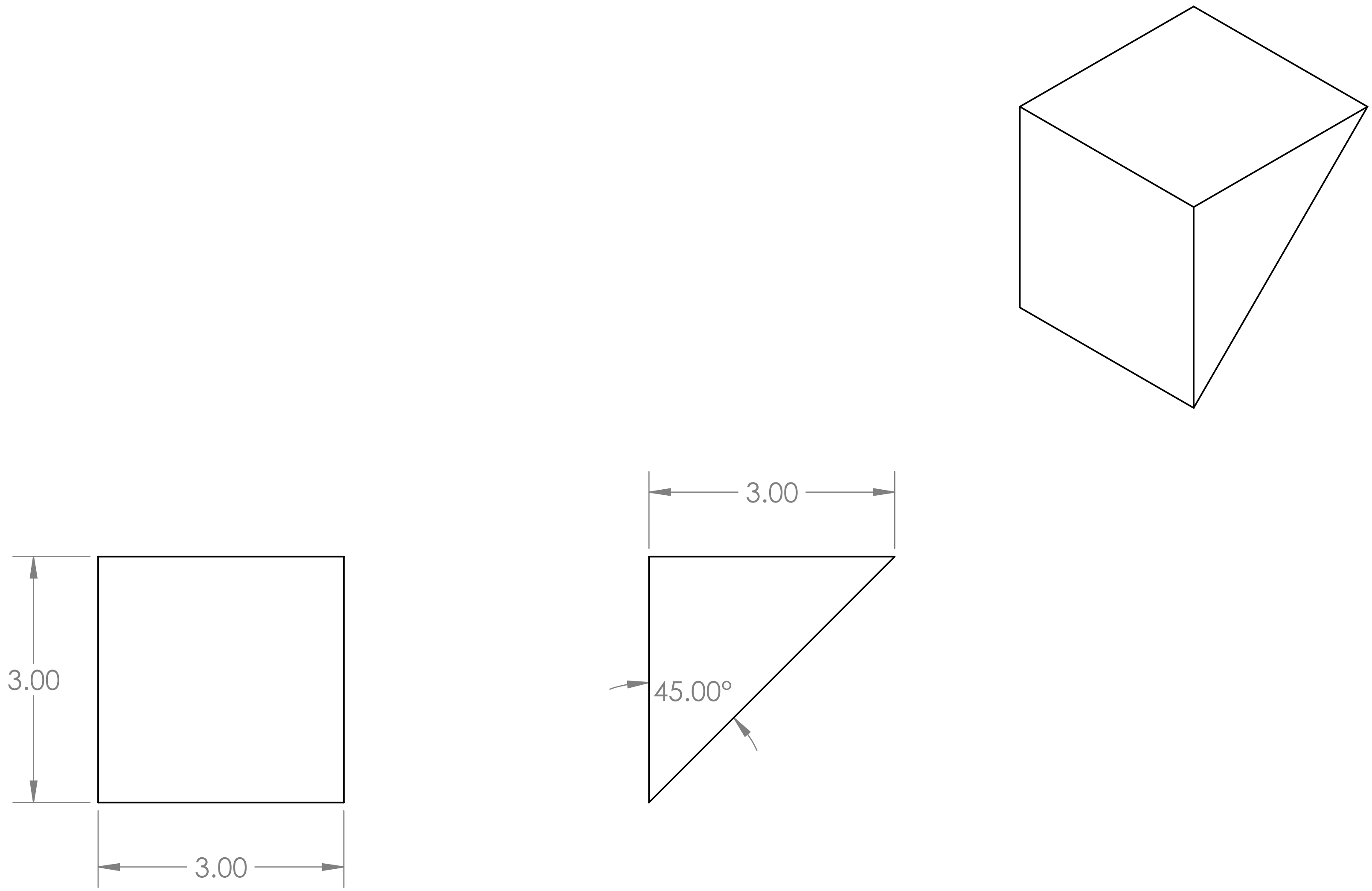
Magellan Aerospace

TITLE:
Gear Mounting Plate

SIZE A | DWG. NO. Main Frame | REV 1

SCALE: 1:2 | WEIGHT: | SHEET 8 OF 18

5 4 3 2 1



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CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

MATERIAL
6061-T6 Aluminum

MECH 4860

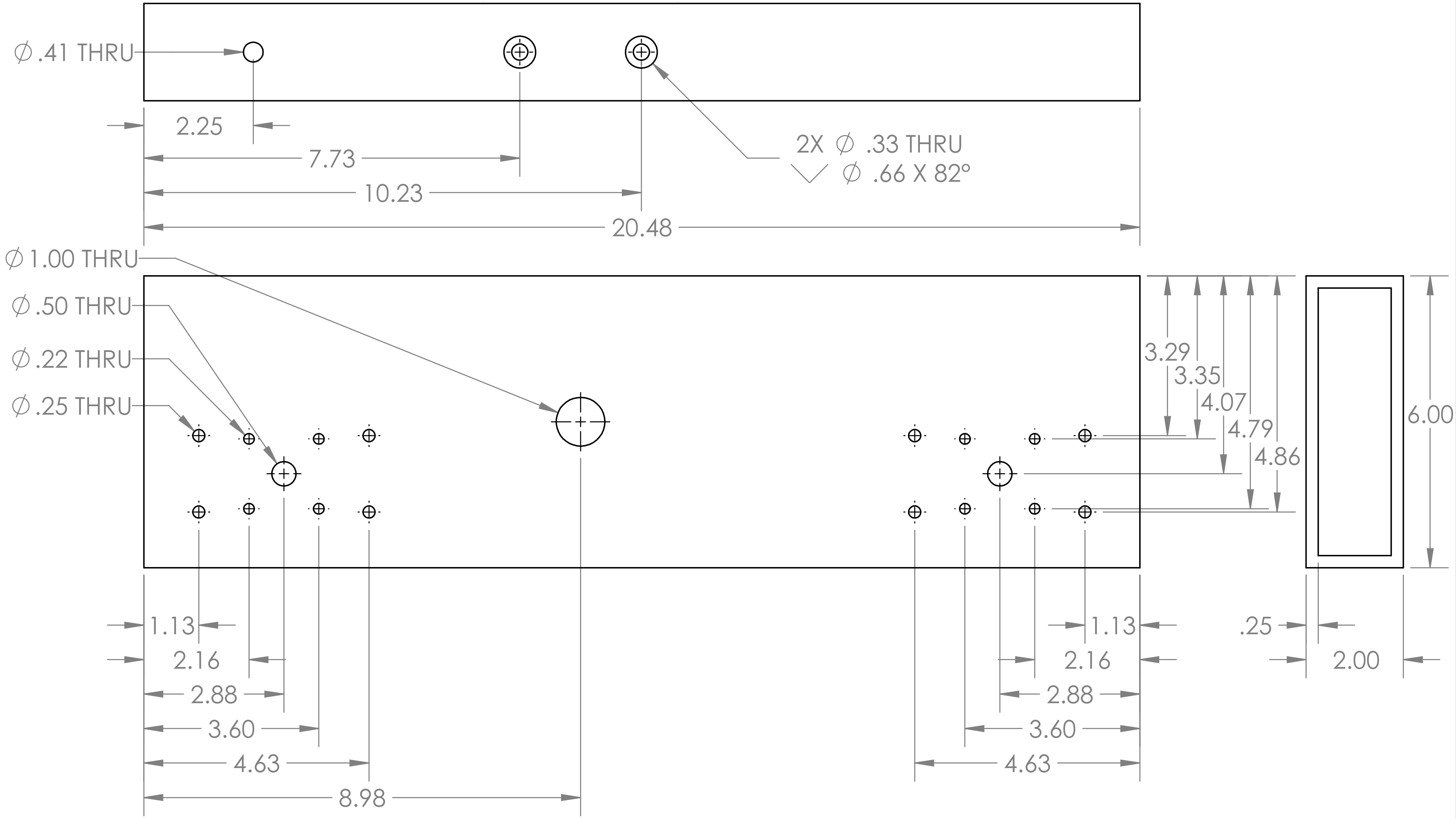
Magellan Aerospace

TITLE:
Stiffener

SIZE	DWG. NO.	REV
A	Main Frame	1

SCALE: 1:2	WEIGHT:	SHEET 9 OF 18

5 4 3 2 1



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DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

Magellan Aerospace

TITLE:
Driving Rotating Fork

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

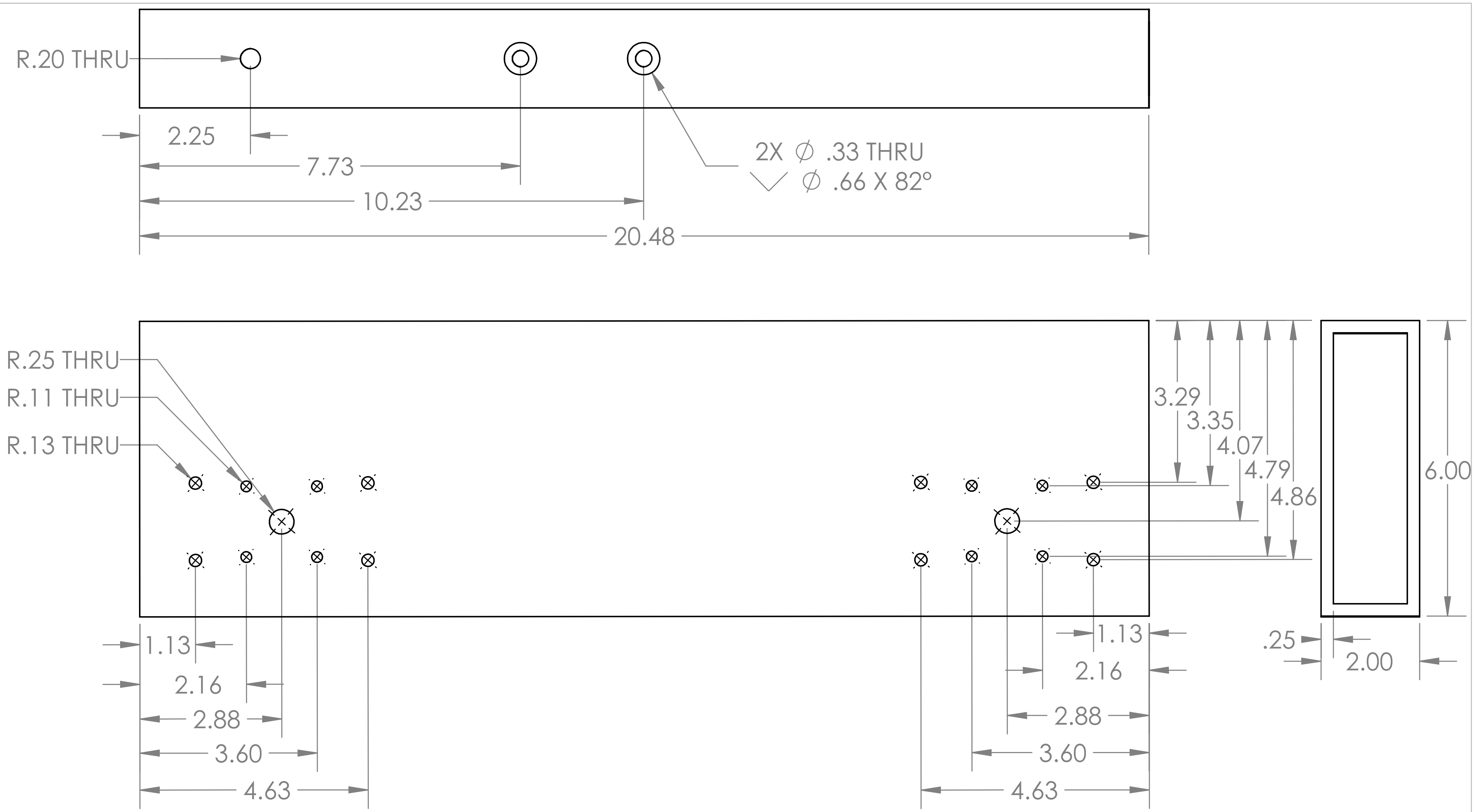
MATERIAL
6061-T6 Aluminum

MECH 4860

SIZE A | DWG. NO. Main Frame | REV 1

SCALE: 1:3 | WEIGHT: | SHEET 10 OF 18

5 4 3 2 1



	NAME	DATE
DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

Magellan Aerospace

TITLE: Driven Rotating Fork

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES

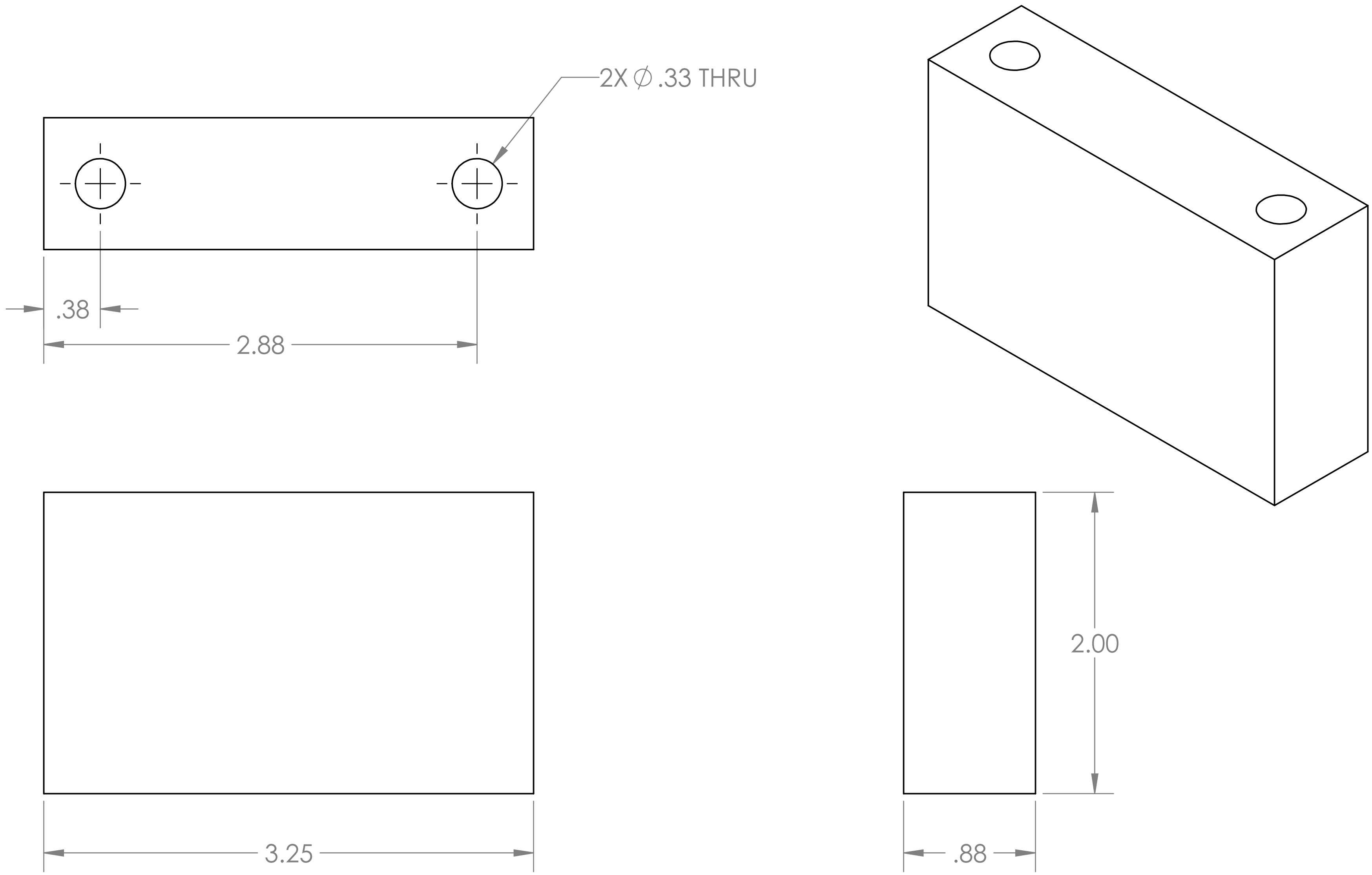
MATERIAL 6061-T6 Aluminum

MECH 4860

SIZE A | DWG. NO. Main Frame | REV 1

SCALE: 1:3 | WEIGHT: | SHEET 11 OF 18

5 4 3 2 1



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DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

MATERIAL
6061-T6 Aluminum

MECH 4860

Magellan Aerospace

TITLE:
Fork Bearing Mounting Block

SIZE	DWG. NO.	REV
A	Main Frame	1

SCALE: 1:1	WEIGHT:	SHEET 12 OF 18

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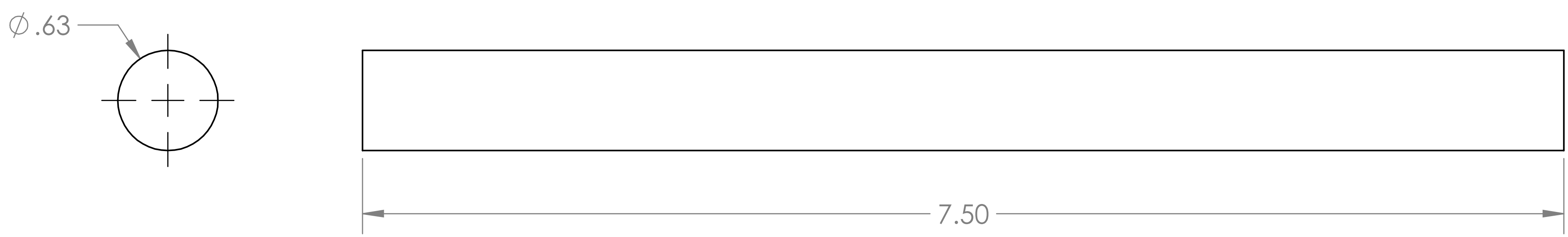
5 4 3 2 1



	NAME	DATE
DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

Magellan Aerospace

TITLE: Driven Shaft

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

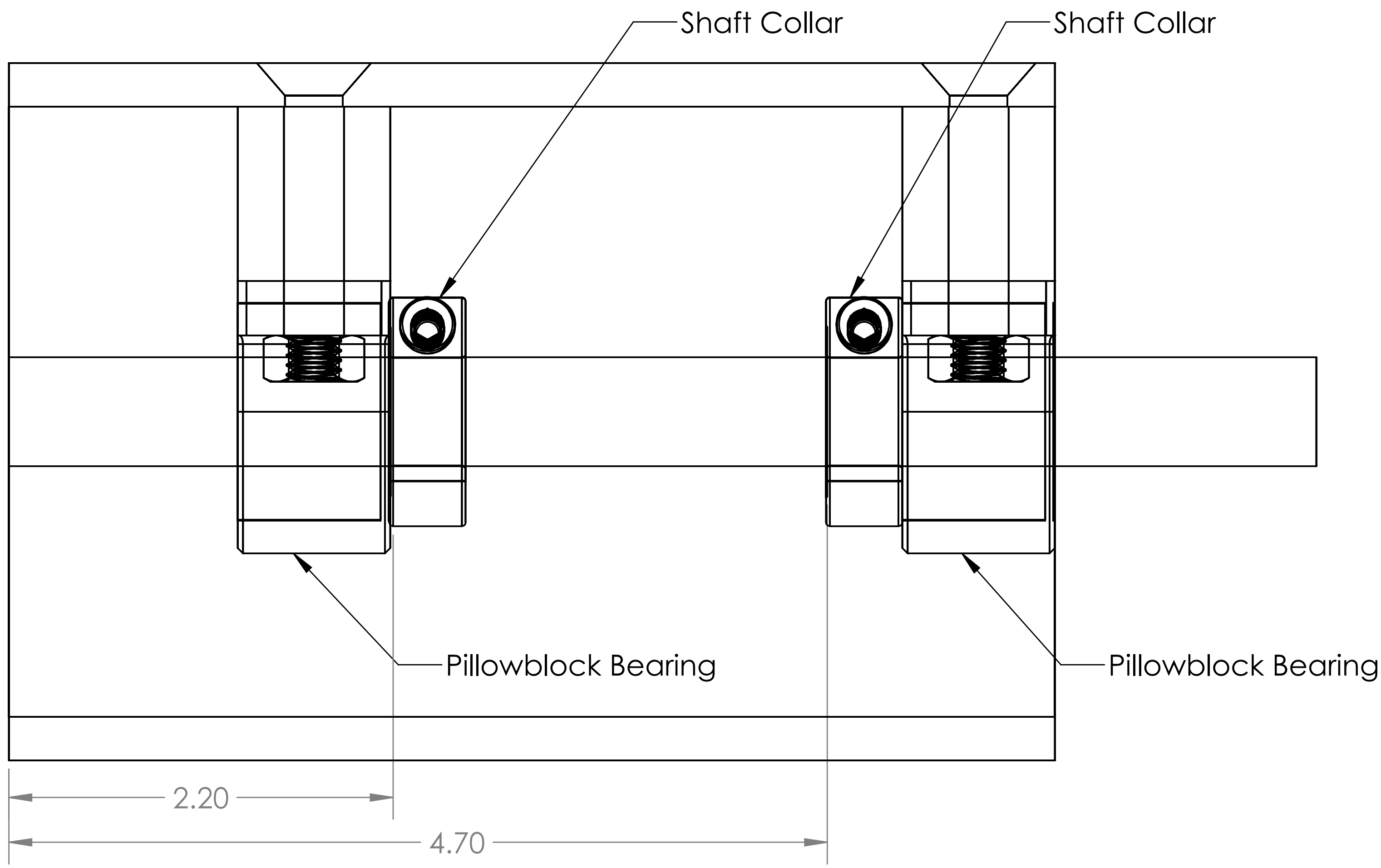
MATERIAL
2024-T4 Aluminum

MECH 4860

SIZE	DWG. NO.	REV
A	Main Frame	1

SCALE: 1:1 | WEIGHT: | SHEET 13 OF 18

5 4 3 2 1



	NAME	DATE
DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

Magellan Aerospace

TITLE:

Main Frame Assembly

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

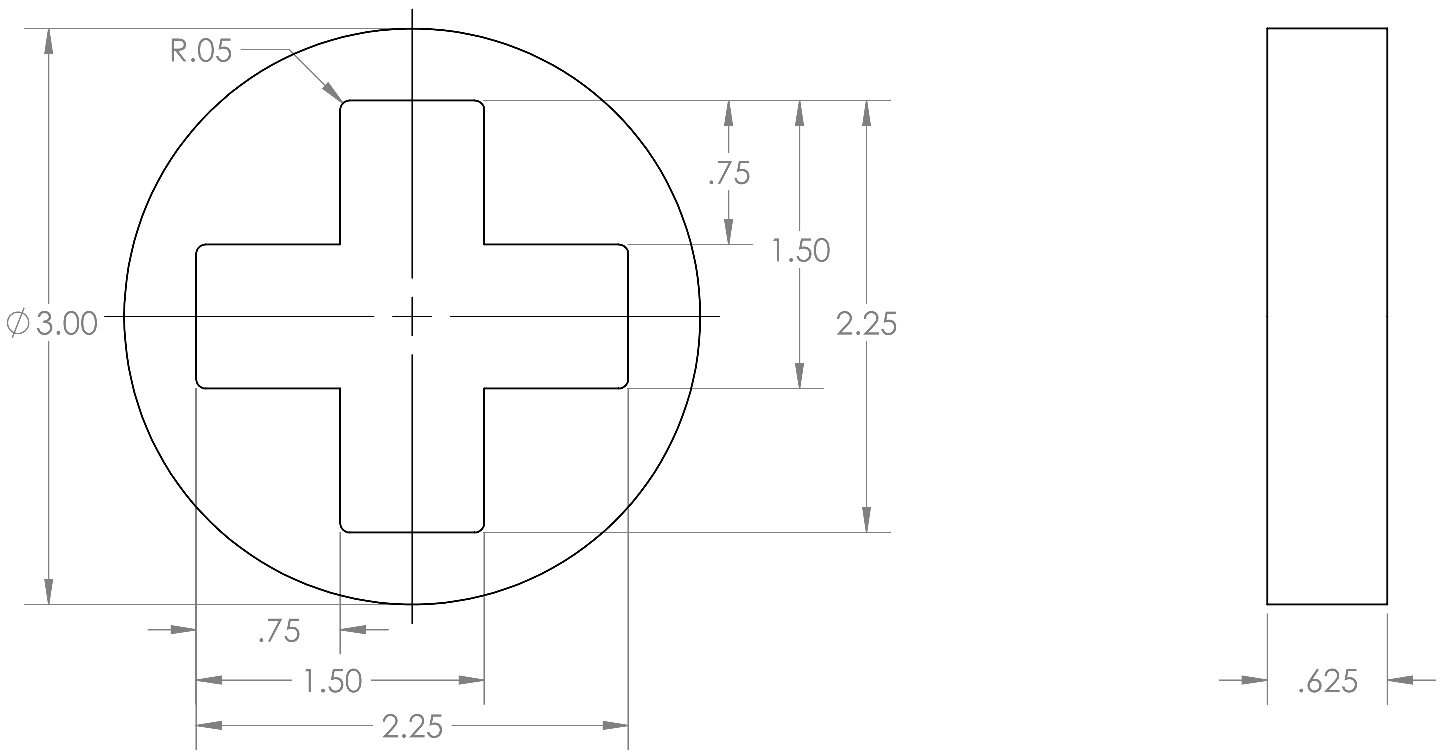
MATERIAL
N/A

MECH 4860

SIZE A
DWG. NO. Main Frame
REV 1

SCALE: 1:1 WEIGHT: SHEET 14 OF 18

5 4 3 2 1



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DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

Magellan Aerospace

TITLE:

Internal Cross Plate

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

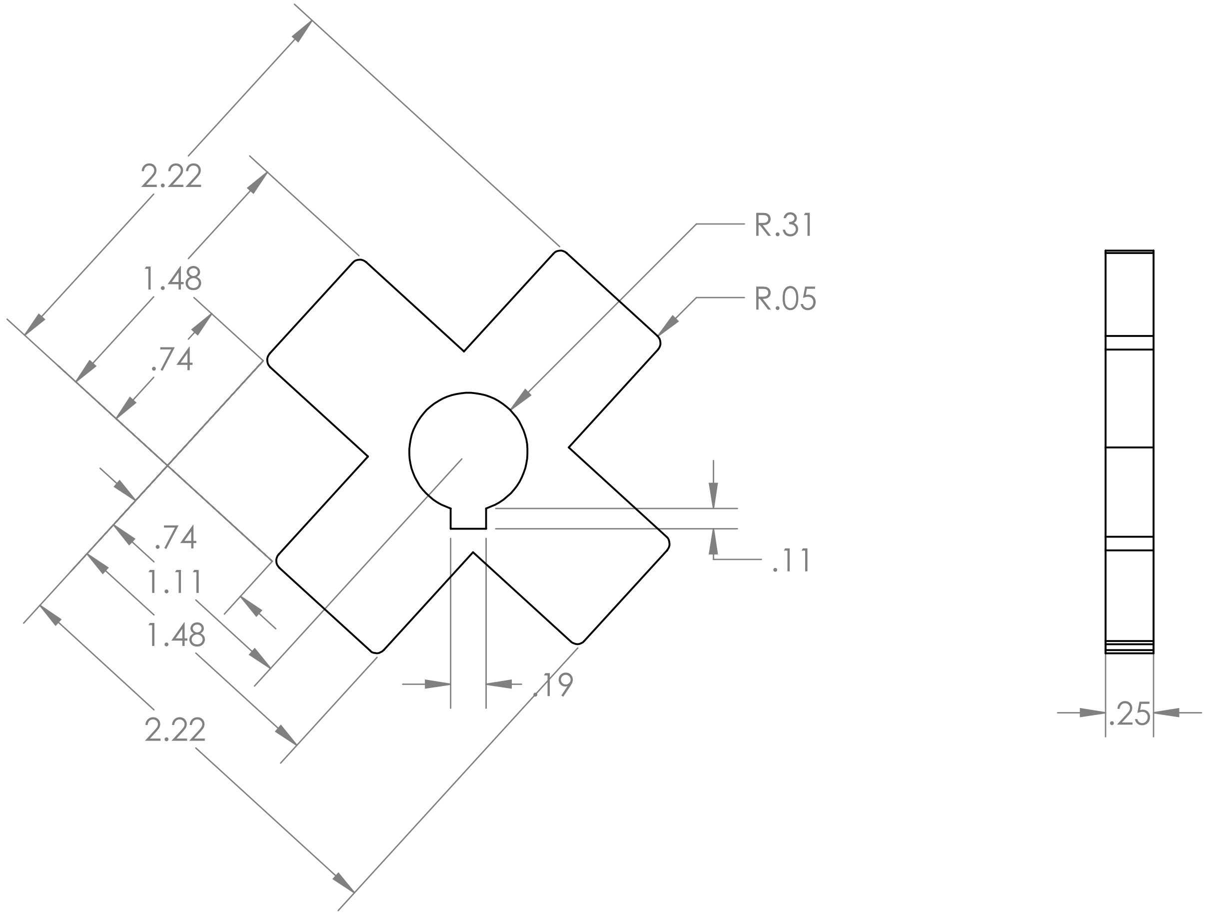
MATERIAL
6061-T6 Aluminum

MECH 4860

SIZE	DWG. NO.	REV
A	Main Frame	1

SCALE: 1:1	WEIGHT:	SHEET 15 OF 18

5 4 3 2 1



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DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

MATERIAL
6061-T6 Aluminum

MECH 4860

Magellan Aerospace

TITLE:
External Cross Plate

SIZE A | DWG. NO. Main Frame | REV 1

SCALE: 1:1 | WEIGHT: | SHEET 16 OF 18

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5 4 3 2 1

	NAME	DATE
DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

MATERIAL
6061-T6 Aluminum

MECH 4860

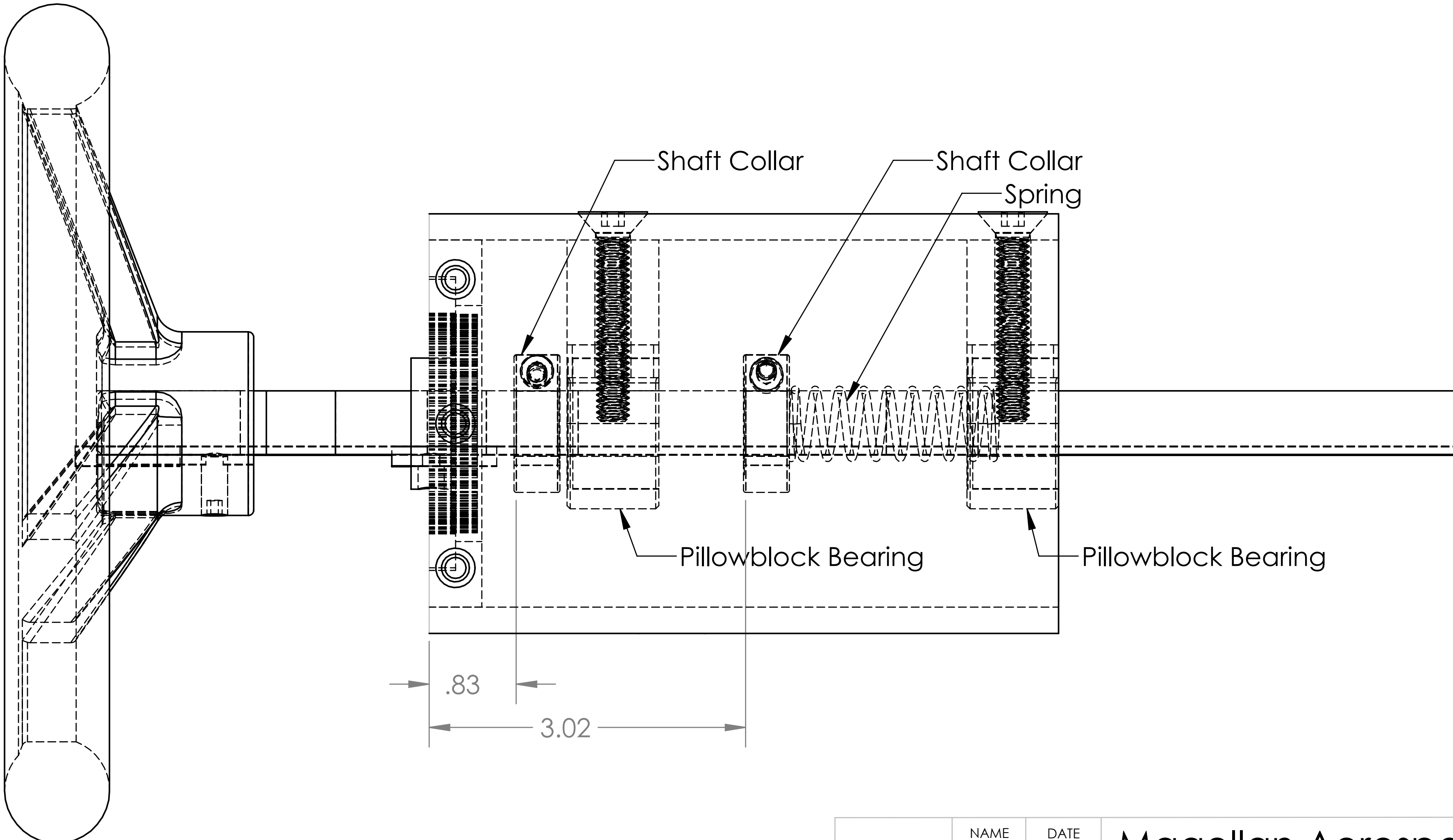
Magellan Aerospace

TITLE:
Driveshaft

SIZE	DWG. NO.	REV
A	Main Frame	1

SCALE: 2:3	WEIGHT:	SHEET 17 OF 18

5 4 3 2 1



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CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES

MATERIAL N/A

MECH 4860

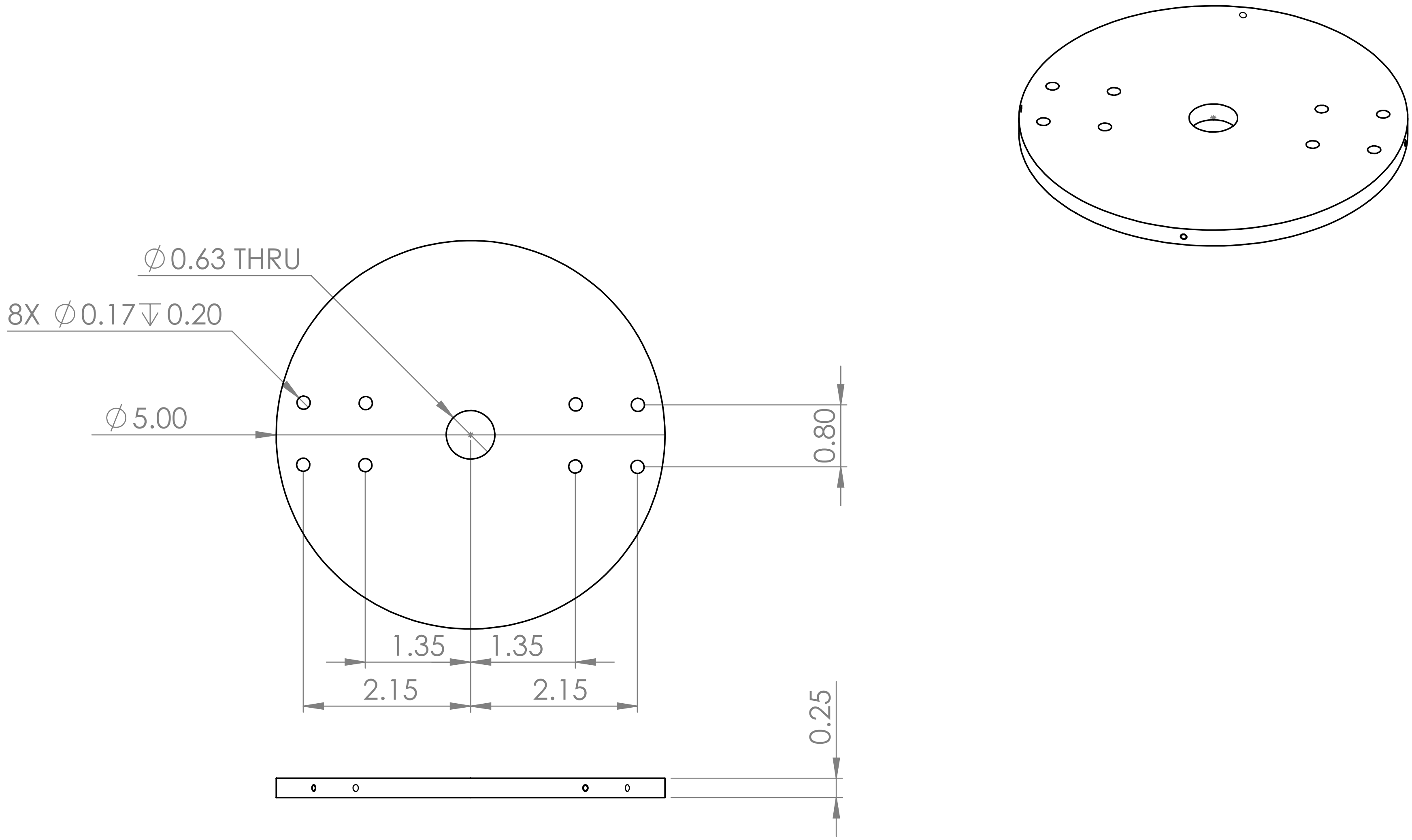
Magellan Aerospace

TITLE: Main Frame Assembly

SIZE A | DWG. NO. Main Frame | REV 1

SCALE: 2:3 | WEIGHT: | SHEET 18 OF 18

5 4 3 2 1



	NAME	DATE
DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

Magellan Aerospace

TITLE:

Slider Plate

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

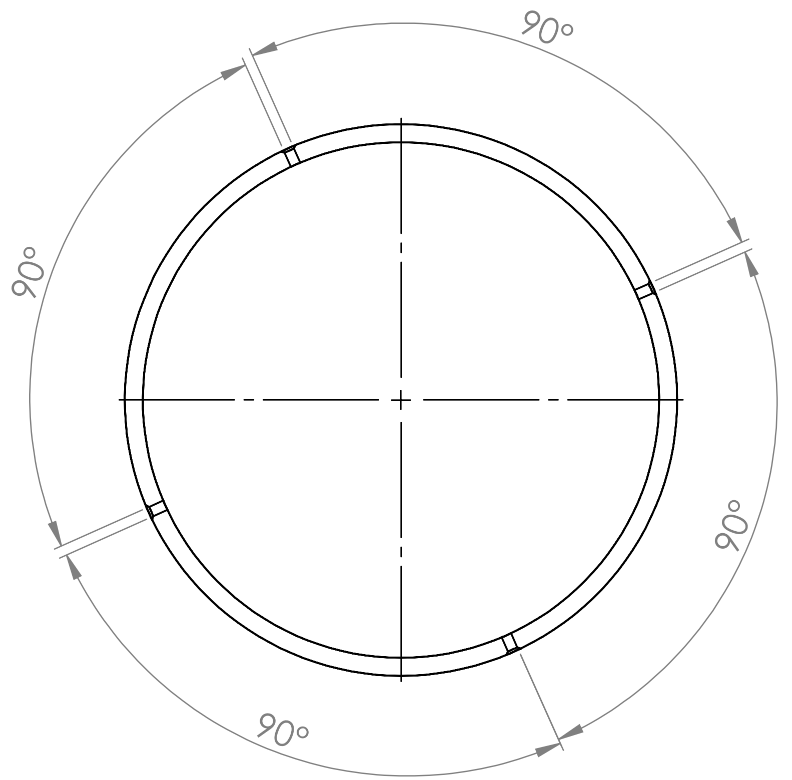
MATERIAL
6061-T6 Aluminum

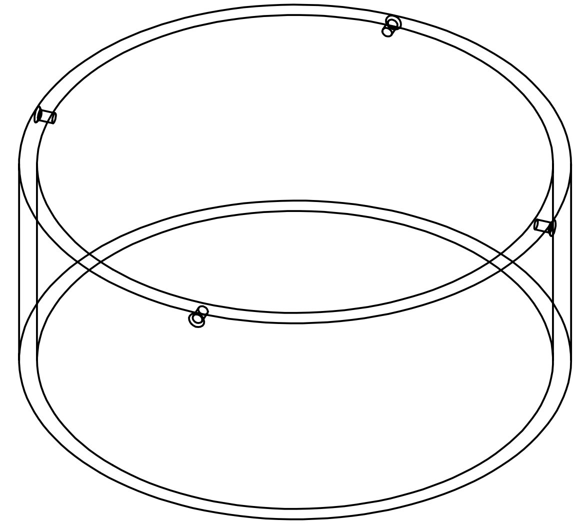
MECH 4860

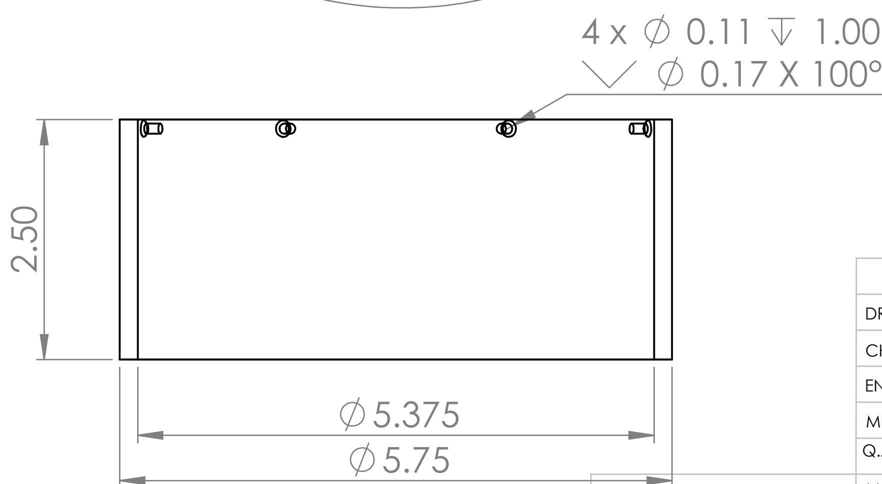
SIZE A | DWG. NO. Plug Actuation Mechanism | REV 1

SCALE: 1:2 | WEIGHT: 0.47 lbs | SHEET 1 OF 5

5 4 3 2 1







	NAME	DATE
DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

Magellan Aerospace

TITLE:
Outer Safety Shield

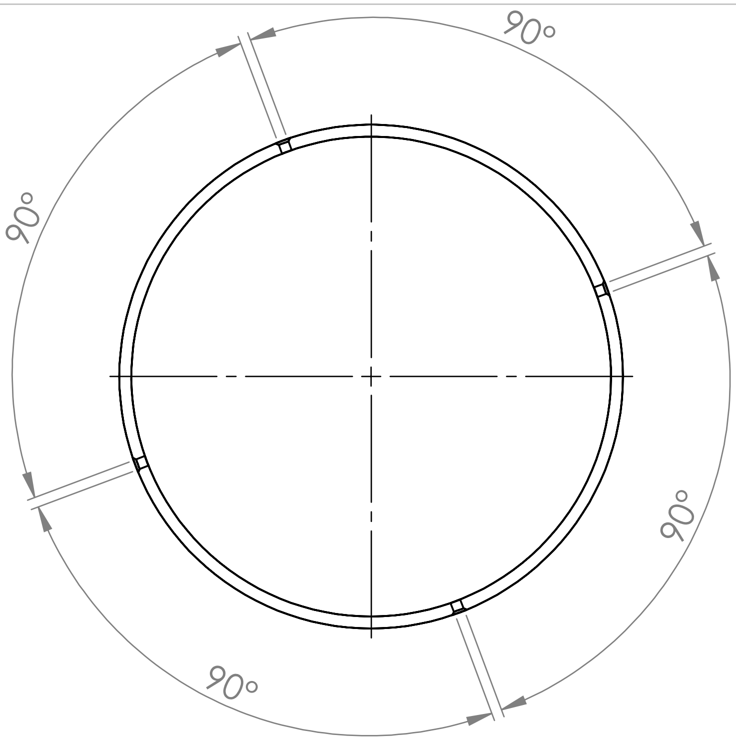
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

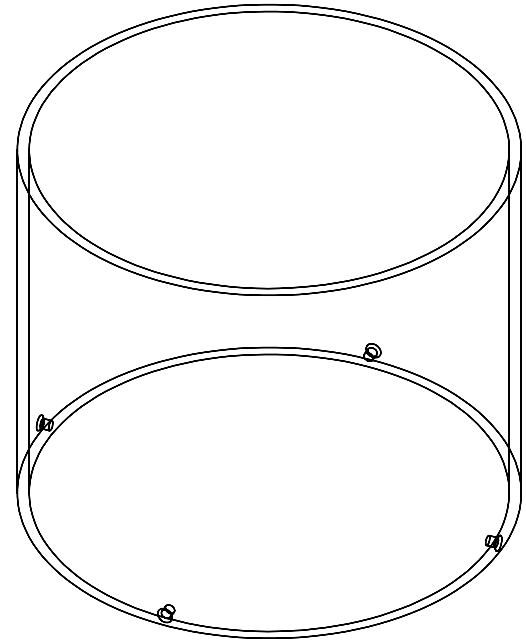
MATERIAL
Acrylic

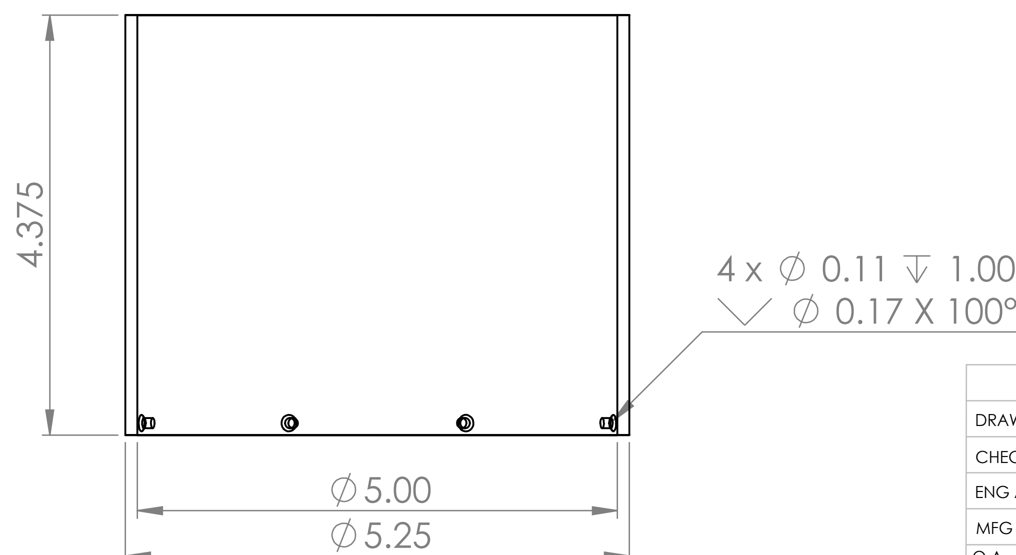
MECH 4860

SIZE	DWG. NO.	REV
A	Plug Actuation Mechanism	1

SCALE: 1:2 | WEIGHT: 0.35 lbs | SHEET 2 OF 5







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	NAME	DATE
DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

MATERIAL
Acrylic

MECH 4860

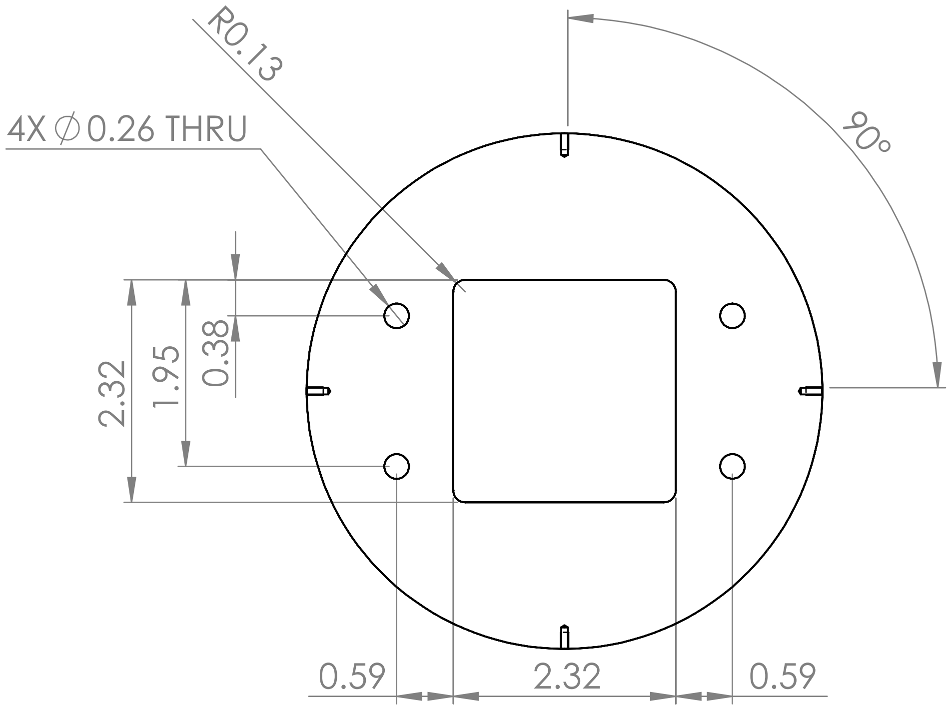
Magellan Aerospace

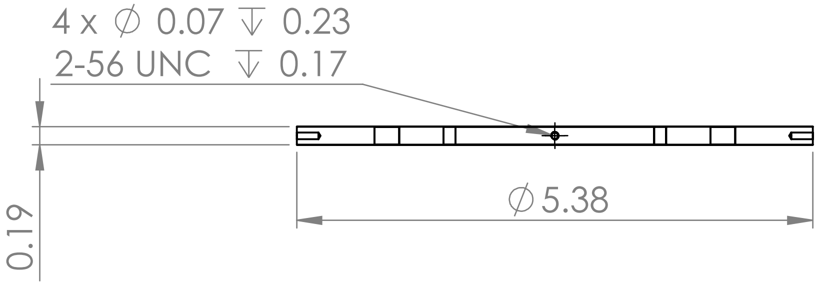
TITLE:
Inner Safety Shield

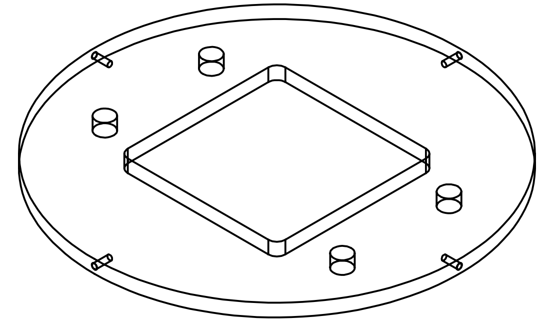
SIZE	DWG. NO.	REV
A	Plug Actuation Mechanism	1

SCALE: 1:2	WEIGHT: 0.38 lbs	SHEET 3 OF 5

5 4 3 2 1







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	NAME	DATE
DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

MATERIAL
6061-T6 Aluminum

MECH 4860

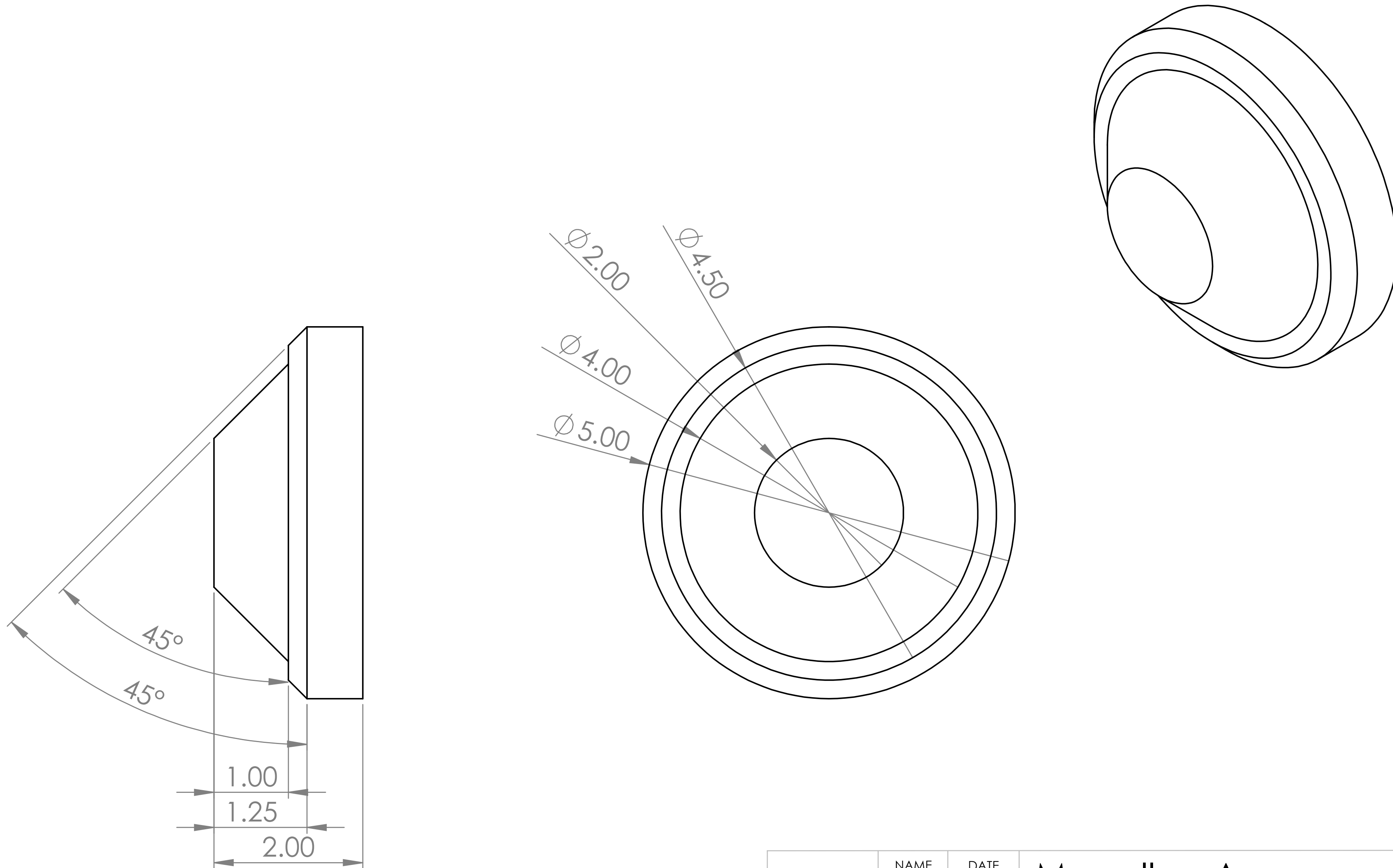
Magellan Aerospace

TITLE:
Base Spacer Plate

SIZE	DWG. NO.	REV
A	Plug Actuation Mechanism	1

SCALE: 1:2 WEIGHT: 0.31 lbs SHEET 4 OF 5

5 4 3 2 1



	NAME	DATE
DRAWN	EC	11-21-14
CHECKED	RM	11-23-14
ENG APPR.		
MFG APPR.		
Q.A.		

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

MATERIAL
Teflon

MECH 4860

Magellan Aerospace

TITLE:
Tapered Plug

SIZE	DWG. NO.	REV
A	Plug Actuation Mechanism	1

SCALE: 1:2	WEIGHT: 2.2lbs	SHEET 5 OF 5

5 4 3 2 1

Appendix D

Detailed Cost Analysis

Table of Contents

List of Tables

D.1 Bill of Materials

A detailed cost breakdown of all parts and materials are tabulated in TABLE I. TABLE I includes the description, sketch, supplier, part number, quantity needed, cost per unit, and total cost. It should be noted that some items come in packages of more than one unit, therefore even if one unit is required; the full package is quoted cost. Furthermore, the bill of materials does not include taxes, shipping fees or custom fees if applicable.

TABLE I: BILL OF MATERIALS [1] [2]

	Description	Sketch	Supplier	Part #	QTY	Unit Cost	Total Cost
Raw Materials	6061-T6 Aluminum Tube, 2" x 4", 0.25" thickness, 6' length	[redacted]	McMaster-Carr	6546K29	3	$148.61	$445.83
	6061-T6 Aluminum Tube, 2" x 6", 0.25" thickness, 6' length	[redacted]	McMaster-Carr	6546K77	1	$172.38	$172.38
	6061-T6 Aluminum Tube, 4" x 4", 0.25" thickness, 2' length	[redacted]	McMaster-Carr	6546K33	1	$75.81	$75.81
	6061-T6 Aluminum Plate, 6" x 6", 0.25" thickness	[redacted]	McMaster-Carr	9872T71	4	$17.47	$69.88
	6061-T6 Aluminum Plate, 4" x 4", 0.5" thickness	[redacted]	McMaster-Carr	9057K248	3	$65.58	$196.74
	6061-T6 Aluminum Plate, 4" x 12", 1" thickness	[redacted]	McMaster-Carr	8975K242	4	$30.11	$120.44

	Description	Sketch	Supplier	Part #	QTY	Unit Cost	Total Cost
Raw Materials	6061-T6 Aluminum Cube, 4"x4"x4"	[redacted]	McMaster-Carr	8975K572	1	$50.50	$50.50
	6061-T6 Aluminum Bar, 1" x 0.875", 24" length		McMaster-Carr	9872T162	1	$25.18	$25.18
	6061-T6 Aluminum Bar, 0.75" x 3.5", 6" length		McMaster-Carr	9872T152	1	$23.09	$23.09
	6061-T6 Aluminum Bar, 0.25" x 3.5", 6" length		McMaster-Carr	9872T67	1	$15.01	$15.01
	Aluminum Keystock, 3/16" x 3/16", 12" length		McMaster-Carr	99108A080	1	$26.10	$26.10
	6061-T6 Aluminum American Standard I-beam. 4" x 4", 0.313" web, 0.29" thickness, 84" length		Online Metals	N/A	3	$146.28	$438.84
	4130 Steel sheet, 12" x 24" x 1/8"		McMaster-Carr	4459T248	1	$52.61	$52.61
	4130 Steel sheet, 24" x 24" x 1/4"		McMaster-Carr	4459T271	1	$138.62	$138.62
	Teflon PTFE, 5" Diameter, 12" length		McMaster-Carr	8546K34	1	$497.74	$497.74
	Clear acrylic tube, 5-3/4" OD x 5-3/8" ID, 12" length		McMaster-Carr	8486K957	1	$46.17	$46.17
	Clear acrylic tube, 5-1/4" OD x 5" ID, 12" length		McMaster-Carr	8486K952	2	$36.38	$72.76

	Description	Sketch	Supplier	Part #	QTY	Unit Cost	Total Cost
Fasteners	Countersink Bolts, 5/16" -18 Diameter, 82 deg, 316 Stainless Steel, 2" length	[redacted]	McMaster-Carr	90585A590	3	$7.93	$23.79
	Countersink Bolts, 1/4" -20, 82 deg, 316 Stainless Steel, 1" length		McMaster-Carr	90585A542	3	$5.14	$15.42
	Counterbore low-profile bolt, 1/4"-20, 3/8" length, 18-8 Stainless Steel		McMaster-Carr	93615A405	1	$5.64	$5.64
	Coated alloy steel socket head cap screw, 3/8"-16 thread, 1-3/4" length		McMaster-Carr	91274A320	5	$6.33	$31.65
	Coated alloy steel socket head cap screw, 5/16"-18 thread, 1" length		McMaster-Carr	91274A244	1	$7.89	$7.89
	Buttonhead bolt, 1/4"-20, 5/8" length, 316 Stainless Steel		McMaster-Carr	98164A212	3	$9.01	$27.03
	Buttonhead bolt,5/16"-24, 1/2" length, 316 Stainless Steel		McMaster-Carr	98164A528	1	$6.73	$6.73
	Aluminum Nut, 5/16"-18		McMaster-Carr	90670A030	1	$8.68	$8.68

	Description	Sketch	Supplier	Part #	QTY	Unit Cost	Total Cost
Fasteners	Aluminum Nut, 1/4"-20	[redacted]	McMaster-Carr	90670A029	1	$6.41	$6.41
	Type 316 Stainless Steel nut, 3/4"-10	[redacted]	McMaster-Carr	94804A360	1	$7.31	$7.31
	Type 316 Stainless Steel nut, 3/4"-10, thin and wide	[redacted]	McMaster-Carr	94804A360	2	$3.68	$7.36
	Type 316 Stainless Steel Nylon-Insert hex nut, 3/8"-16 thread, 9/16" width	[redacted]	McMaster-Carr	90715A145	2	$8.00	$16.00
	Type 316 Stainless Steel Nylon-Insert hex nut, 5/16"-18 thread, 1/2" width	[redacted]	McMaster-Carr	90715A135	1	$9.83	$9.83
	18-8 stainless steel 1/4" Washer	[redacted]	McMaster-Carr	92141A029	1	$3.37	$3.37
	18-8 stainless steel 3/8" Washer	[redacted]	McMaster-Carr	93852A103	1	$5.60	$5.60
	18-8 stainless steel 7/16" Washer	[redacted]	McMaster-Carr	93852A104	5	$3.31	$16.55
	18-8 stainless steel 3/4" Washer	[redacted]	McMaster-Carr	92141A056	1	$5.37	$5.37
	18-8 stainless steel countersink Phillips machine screw, 82 deg	[redacted]	McMaster-Carr	91771A169	1	$5.37	$5.37

	Description	Sketch	Supplier	Part #	QTY	Unit Cost	Total Cost
Commercially Available Parts	Aluminum Internal Gear, Pitch = 24, 48 teeth, PA =20, Face Width = 0.25"	[redacted]	Rush Gears	YIA2448	1	$997.50	$997.50
	Aluminum Spur Gear, Pitch = 24, Teeth = 48, PA=20, Pitch Diameter = 2", Bore Diameter = 0.625", Face Width = 0.25", Set-screw 10-32, Keyway = 3/16" x 3/32"		Rush Gears	1054-6225	1	$897.50	$897.50
	Pillowblock Bearing, 5/8" Bore Diameter, Aluminum, PTFE-filled Bronze		McMaster-Carr	2820T7	6	$20.59	$123.54
	Keyed Shaft, 5/8" Diameter, 3/16" x 3/32" keyway, T4-2024 Aluminum, 24" length		McMaster-Carr	1570K53	1	$38.51	$38.51
	3 Spoked Aluminum Hand Wheel, 8" Wheel Diameter, 5/8" Bore Diameter, Set-screw = 1/4" - 20, 3/16" x 3/32" keyway		McMaster-Carr	3724T54	1	$67.27	$67.27

	Description	Sketch	Supplier	Part #	QTY	Unit Cost	Total Cost
Commercially Available Parts	One Piece Clamp Shaft Collar, 5/8" Bore Diameter, 1 5/16" Outer Diameter	[redacted]	McMaster-Carr	6157K15	4	$2.67	$10.68
	Spring, 20lbs/in, 0.72" Outer Diameter, 0.072 Wire Diameter		McMaster-Carr	9434K148	1	$5.71	$5.71
	Front Pedal friction Floor Lock, 5-5/8" extended, 4-7/8" retracted		McMaster-Carr	2478T61	1	$57.02	$57.02
	Fixed Caster, 5" wheel diameter, 6.125" mount height, nylon wheel, 485 lbs load capacity		McMaster-Carr	27115T3	2	$22.61	$45.22
	Swivel Caster, 5" wheel diameter, 6.125" mount height, nylon wheel, 485 lbs load capacity		McMaster-Carr	27115T1	2	$24.53	$49.06
	Tempered Steel Spring, 1/4" wire diameter, 8" length, 61.80 lbs/inch, 275 lbs max load.		McMaster-Carr	96485K164	4	$12.53	$50.12

	Description	Sketch	Supplier	Part #	QTY	Unit Cost	Total Cost
Commercially Available Parts	Linear Ball Bearing, Flange mount, For 1" shaft diameter, 353 lbs load capacity	[redacted]	McMaster-Carr	6483K86	4	$153.56	$614.24
	Hardened 52100 steel shaft, 1" diameter, 7-1/4" length, 5/8"-11 threaded one end		McMaster-Carr	8350T69	4	$46.36	$185.44
	Pop-safety valve with test ring, brass, medium flow, 1/8" NPT male		McMaster-Carr	9889K15	1	$9.19	$9.19
	Nonrotating compact air cylinder, 1" bore, 2" stroke length.		McMaster-Carr	6277T23	8	$127.14	$1,017.12
	Air control valve switch, 3 ports, 1/8" NPT female inlet/outlet		McMaster-Carr	62475K41	5	$24.06	$120.30
	Permanently lubricated industrial turntable, steel, lockable, 1000 lbs capacity		McMaster-Carr	9443T1	1	$263.82	$263.82
	Aluminum tie rod air cylinder with cushion, 3" bore, 5" stroke length		McMaster-Carr	6491K77	2	$202.68	$405.36

	Description	Sketch	Supplier	Part #	QTY	Unit Cost	Total Cost
Commercially Available Parts	Air flow control tuning valve, 1/8" NPT female x 1/8" NPA male	[redacted]	McMaster-Carr	8346K15	6	$16.74	$100.44
	Brass hex nipple, 1/8" pipe size		McMaster-Carr	5485K21	3	$1.40	$4.20
	Type 304 stainless steel threaded pipe fitting, 1/8" pipe size, 90° elbow		McMaster-Carr	4464K11	6	$4.90	$29.40
	Type 316 stainless steel barbed hose fitting, 1/8" hose ID x 1/8" NPT male pipe		McMaster-Carr	53505K61	41	$20.17	$826.97
	Brass barbed tee hose fitting, 1/8" ID		McMaster-Carr	91355K57	11	$8.40	$92.40
	ARO shape hose coupling, push-to-connect, brass, 1/8" NPT female, 1/4" coupling size		McMaster-Carr	5343K15	10	$9.72	$97.20
	ARO shape hose coupling, plug, zinc plated steel, 1/8" NPT male, 1/4" coupling size		McMaster-Carr	5343K12	8	$1.75	$14.00

	Description	Sketch	Supplier	Part #	QTY	Unit Cost	Total Cost
Commercially Available Parts	Brass barbed hose fitting adapter, 1/8" hose ID x 1/8" NPTF female pipe	[redacted]	McMaster-Carr	5346K81	10	$13.30	$133.00
	Stainless steel threaded pipe fitting, 1/8" pipe x 10-32 thread		McMaster-Carr	2684K19	8	$10.07	$80.56
	Type 304 stainless steel threaded pipe fitting, 1/8" pipe size, 90° elbow, female x male		McMaster-Carr	4464K35	3	$6.94	$20.82
	Adhesive backed nylon clamp, 1/4" OD		McMaster-Carr	2978T62	2	$7.92	$15.84
	High pressure brass thread tee pipe fitting, 1/4" pipe size		McMaster-Carr	9171K156	1	$19.42	$19.42
	Low pressure brass threaded pipe fitting, 1/4" x 1/8" pipe size, 90° elbow		McMaster-Carr	4429K131	1	$10.14	$10.14
	Rear Mount Pressure gauge with 1/8" male NPT thread 0-160 PSI		McMaster-Carr	3847K73	2	15.38	$30.76

	Description	Sketch	Supplier	Part #	QTY	Unit Cost	Total Cost
Commercially Available Parts	3/8 Male/female NPT Elbow	[redacted]	McMaster-Carr	4464K37	2	$8.34	$16.68
	3/8" female to 1/8" male reducer		McMaster-Carr	51205K312	2	16.69	$33.38
	1/8" ID nylon hose x 50 ft		McMaster-Carr	5644K11	1	23.94	$23.94

A summary for each category in the bill of materials is shown in TABLE II to exhibit the distribution of cost for the materials. Additionally, the total cost of materials is $9238.10.

TABLE II: SUMMARY OF MATERIAL COSTS

Category	Cost
Raw Material	$2,537.58
Fasteners	$209.99
Commercially Available Parts	$6,490.91
Total	$9,238.10

D.2 Machining Costs

For each custom component in the F-35 vane box handling tool, machining costs have to be taken into account because of the large expenses. Machining costs account for set-up time and time spent on the machine. Since the custom parts have never been manufactured before, an estimate of the required machining time and rate per hour for each part are shown in TABLE III. The total machining costs is estimated to be $4,582.50 for individual components is presented in TABLE III.

TABLE III: ESTIMATED MACHINING COSTS

Description	Purpose	Machines Needed	Estimated Machining Time per Unit [hr]	Rate per Hour[$]	Units	Estimated Cost
Gusset Plate	Base Frame	Mill	4.5	50	4	$900.00
Corner Gusset Plate	Main Frame	Drill Press, Bandsaw	1	35	4	$140.00
Stiffener	Main Frame	Bandsaw	0.25	35	2	$17.50
Internal Cross Plate	Main Frame	Mill	8	50	1	$400.00
External Cross Plate	Main Frame	Mill	8	50	1	$400.00
Gear Mounting Plate	Main Frame	Drill Press, Mill	5	50	1	$250.00
Bearing Mounting Block	Main Frame	Drill Press, Bandsaw	0.5	35	6	$105.00
Cross Mounting Plate	Central Axle Assembly	Brake, MIG weld, Bandsaw, Drill Press	3	65	1	$195.00

Description	Purpose	Machines Needed	Estimated Machining Time per Unit [hr]	Rate per Hour[$]	Units	Estimated Cost
Base Mounting Plate	Central Axle Assembly	Brake, MIG weld, Bandsaw, Drill Press	5	65	1	$325.00
Base Spacer Plate	Plug Actuation Mechanism	Mill, Bandsaw	2	50	4	$400.00
Slider Plate	Plug Actuation Mechanism	Mill, Bandsaw	2	50	4	$400.00
Inner Safety Shield	Plug Actuation Mechanism	Drill, Bandsaw	0.5	35	4	$70.00
Outer Safety Shield	Plug Actuation Mechanism	Drill, Bandsaw	0.5	35	4	$70.00
Tapered Plug	Plug Actuation Mechanism	Lathe, Bandsaw	3.5	65	4	$910.00
					Total	$4,582.50

D.3 References

[1] "McMaster-Carr," [Online]. Available: www.mcmaster.com. [Accessed 12 November 2014].

[2] "Rush Gears," [Online]. Available: www.rushgears.com. [Accessed 25 October 2014].