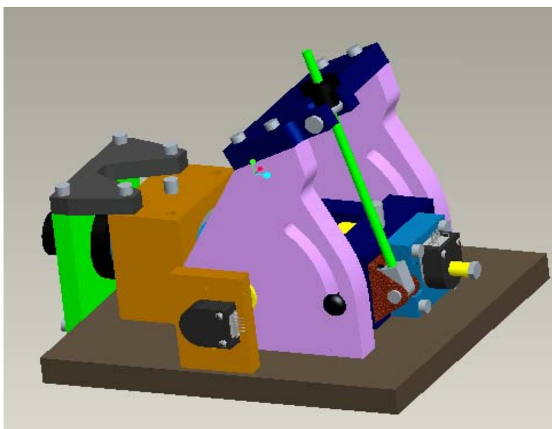
UNIVERSITY OF MICHIGAN

ME450 WINTER 2005

CONSTANT VELOCITY JOINT FIXTURE




GROUP 9

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Executive Summary

The hydraulic pump and motor group of the EPA at the National Vehicle Fuel Emissions Laboratory in Ann Arbor has been doing research and design of hydraulic hybrid vehicles using hydraulic pistons pumps, particularly bent axis pumps, to assist in the propulsion of automobiles. The pump consists of two halves which are rotating and at angles to each other, causing the pump to require the use of a CV Joint. Due to durability issues encountered during testing, the EPA has asked us to create a fixture that will measure the lash in the CV joint throughout its angular operating range. The key requirements of this project are the precise alignment of the joint, as well as the accuracy of the measurements. The EPA requires us to have measurement accuracies of up to 0.1 degrees in some of our measurements and to align certain joint surfaces to within .010 in. The customer also requires us to measure the frictional torque that occurs in the joint and to be able to do this throughout the entire rotation of the joint to note if there are any areas of particularly high resistance.

Each of these customer requirements were taken into account as our team developed several ideas from which to form our concept. These ideas were generated by looking a specific part of the problem and deciding how to accomplish each individually, while being careful to make sure the design would work with the system as a whole. Through this method we came up with at least 5 different ideas for each major task. We then created a scoring matrix, and weighting different attributes to be in line with the customer's wishes we evaluated each concept and used the best pieces to form our fixture design. The net result of this is a fixture which will hold the part accurately, be accurate in its measurements of both lash and frictional torque, and be as easy as possible for the operator.

Once the complete concept was generated, the design was modeled in CAD and engineering drawings were produced. Our team then hit the machine shop over the next 3 weeks and was able to fabricate a near-complete working prototype of the design. Unfortunately we did not have sufficient time to make the stabilizer and friction plate needed for torque measurement, however, appropriate drawings and material are being provided to the EPA for future completion. Our team is confident that our prototype will meet the immediate needs of the EPA and is made to very adaptable to any future expansion or evolution of the design.

While our team cannot be certain, we are reasonably confident that the alignment of the part came out as needed. We do, however, recommend that the EPA look in to having the fixture checked on a CMM machine, and if it fails, to have the design re-fabricated at a professional shop. We also believe that the addition of torque transducers would make the frictional torque measurement both easier and more accurate.

TABLE OF CONTENTS

1. INTRODUCTION

The hydraulic pump and motor group at the EPA National Vehicle Fuel Emissions Laboratory in Ann Arbor has asked us to design a fixture to measure lash and frictional torque of constant velocity joints used in high-efficiency bent axis hydraulic pumps. The joint is shown both in a horizontal and articulated position in Figures 1 and 2. These pumps are currently being researched at the EPA for use in high efficiency hybrid vehicle powertrains. The CV joints are currently being supplied by an outside contractor and have varying amounts of lash and frictional torque. CV lash has been shown to significantly affect pump performance and in a worst case scenario can cause catastrophic pump failures. Frictional torque also detracts from pump efficiency. The current methods for measuring lash and frictional torque are inaccurate and somewhat awkward. The fixture being proposed would take lash and friction measurements of a given CV joint quickly and accurately through the angular operating range of the pump. Additionally the fixture should be easily adaptable to electromechanical actuators, motors, and dynamometers used in the EPA laboratory. With this fixture the EPA will be able to quickly and accurately check the lash and friction parameters of prototype CV joints prior to installation and also measure the effects of wear on these parameters.

Figure 1 - Constant Velocity Joint

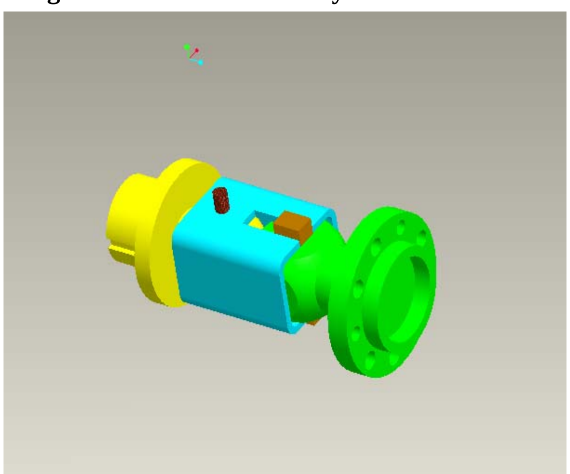
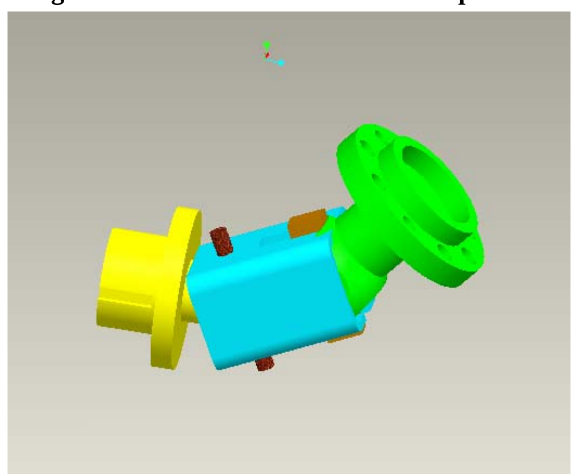


Figure 2 – Joint Shown in articulated position



2. ENGINEERING SPECIFICATIONS

Our customer wants us to design a fixture that will accept a constant velocity joint and measure its lash. The fixture must be able to measure the lash at varying yoke angles and at varying angular positions of the shaft. We must also be able to apply a constant resistance and measure the torque throughout the rotation. A secondary optional task is to design the fixture to be compatible with in-house measurement devices. The fixture must be able to measure the lash angle of the joint to within 0.1 degree. It must also be able to align the joint within the provided engineering tolerances, cover articulation angles between 0 and 54 degrees, and measure the joint rotation for a full 360 degrees. It must also measure the frictional torque over the full range of joint rotation and articulation. These specifications have all been provided by the sponsor along with the governing dimensions and tolerances and easily translate into engineering specifications. There are no current competitive products for this design because our fixture is being developed for a product that is used in research. The relative importance of the following customer requirements was indicated to us by the customer.

Table 1: Conversion of customer requirements to engineering specifications

Customer Requirement	Engineering Requirements
Add minimal friction to the rotation of the joint	Minimize friction
Measure lash angle	Measurements accurate $\pm$ 0.1 deg
Align joint with allowable tolerances	Fit within tolerances provided in engineering drawings
Cover full range of articulation angles	Articulate to angles ranging from 0-54 deg
Cover entire rotation of joint	Rotate 360 deg
Measure articulation angle	Measure within $\pm$ 0.5 deg
Measure joint rotation	Measure within $\pm$ 5 deg
Measure frictional torque over full range of joint rotation and articulation	Measure torque over range of 0-10 Nm and accurate within 1 in-lb

In order to turn this data into a set of design guidelines our team created a QFD matrix. Two additional attributes, "standardized nuts and bolts" and "low weight" were added to the matrix as additional requirements our team brainstormed. The customer requirements were then given weights and quantified. Most of them were in terms of (+) increasing the value or (-) decreasing the value. There were two categories which were determined by a simple "yes" or "no" for whether or not the criteria were met. The correlation was then determined between the various customer attributes and engineering characteristics, with 9 being a strong correlation and 1 being a weak correlation. If there was no relationship then the boxes were left blank. After this, the relationship among the engineering characteristics themselves was determined using the scale shown on the QFD. Finally, the units of all of the engineering characteristics were listed and then the totals for each were calculated, which helped to rank their importance. The important factor was that the design fit the tolerances on the engineering drawings, which comes as no surprise because if it doesn't then the fixture will not give accurate measurements. The rank of the rest of the characteristics can be seen on the QFD. It should be noted that the ability of the design to rotate continuously was increased in importance because it was a very important customer requirement, but did not necessarily correlate with other customer requirements. It should also be noted that the nine engineering requirements listed above must be met in order for our design to be successful. A layout of our QFD matrix can be found in Appendix E at the end of this report.

3. CONCEPT GENERATION

The development of a concept for our fixture required, the brainstorming of different methods by which the engineering specifications could be completed. Instead of developing concepts for 5 different fixtures we tried to conceive and evaluate several different ways of accomplishing each of the primary engineering requirements. We did this by looking at each task the fixture must accomplish individually and developing methods to achieve each. The main objectives we focused on were: i) allowing for complete rotation of the joint while providing a means of locking one end, ii) articulating the joint to a prescribed angle within the given accuracy requirements, iii) providing constant resistance during torque measurement, iv) measuring lash to within 0.1 degrees, v) measuring torque to within 1 in-lb.

3.1 – Allowing complete rotation of joint with means for fixing one end

To provide the rotation our team looked at several different methods. First was a basic design consisting of a collar that would attach to the joint and ride in a slightly oversized hole in a carrier. We then looked to improve upon this design and add bushings to protect against metal to metal contact that could cause wear and reduced accuracy. Next, we looked at bearings, which, although expensive, provided great accuracy and the least resistance and wear and tear. Along with this our team looked at different ways of fixing one end. We looked at the possibility of using set screws, a clamp device similar to a tire quick release on a bike, a key of sorts, and a pair of thread holes through which a bolt could be run to lock the two pieces together. Different combinations of these were devised and then evaluated.

3.2 - Articulating the joint

This objective required a way the joint could be rotated both quickly and accurately, as well as held firmly while testing took place. Our team decided to use a mock yoke that would align the joint accurately, and then looked to investigate ways to adjust it. We looked a ball screw similar to that found in the car jack, a simple support that could be adjusted to hold the yoke in place once it was moved to the proper angle, and a piece of threaded rod that would allow for both gross and fine adjustments.

3.3 - Application of constant resistance for torque measurement

The EPA asked us to be able to apply a constant resistance so that the frictional torque within the joint can be measured. To do this our group looked at using a band brake, a set of friction discs, an electric motor, or a friction-limiting clutch.

3.4 - Measuring lash to within 0.1 degrees

This was perhaps the hardest requirement to develop ideas for. The incredible accuracy required essentially ruled out any mechanical means of measurement. First our team looked at mechanical means. One idea consisted of attaching a lever to the joint that would rotate with it and could be read along a matching gauge or cause translational motion that could be measured. A second idea consisted of using a gear train to amplify the motion to one that could be measured by the human eye. Our team also looked at electromechanical options. We looked at using analog rotational potentiometers, digital encoders, and even a digital protractor.

3.5 - Measuring torque

Our team brainstormed several different ways of measuring this quantity; we looked first at Torque transducers, and conventional torque meters. Next we looked at traditional mechanical torque wrenches and lastly at newer, more accurate digital torque wrenches.

4. CONCEPT SELECTION

In order to select between the different concepts that our team came up with, we created a basic scoring matrix that we applied to each design. We then took the top scorer in each category and combined it to create our team's alpha-concept. The scoring matrix consisted of 8 categories: feasibility, cost, accuracy, ease of manufacturing, ease of implementation, adaptability, ease of use, and simplicity. The ease of implementation category rates how easily the design could be created and implemented with the other parts of the fixture, while the ease of manufacturing category rates how easy it will be to fabricate the parts needed, with purchased products being the highest rated. Adaptability is a measure of how easily the design can be changed to meet any future needs the EPA may have. The remaining categories are self-explanatory. An example of this matrix is found in Table 2. These matrices were then applied to the five major design areas to select the final concept and can be found in Appendix F.

Table 2: Scoring matrix for joint rotation and locking mechanism

Means of Rotating Joint and Locking One End for Lash Measurement	**Category**	**Feasibility**	**Cost**	**Ease of use**	**Ease of implementation**	**Ease of Manufacturing**	**Adaptability**	**Accuracy**	**Simplicity**	**Composite Score**
Concept	**Weight**	**0.25**	**0.125**	**0.188**	**0.063**	**0.031**	**0.031**	**0.25**	**0.0625**	**1.00**
Collar w/ Single Bearing & Set Screw		5	4	5	5	4	4	4	4	4.5
Collar w/ Dual Bearings & Set Screw		**5**	**3**	**5**	**5**	**3**	**4**	**5**	**3**	**4.5313**
Collar w/ Dual Bushings & Clamp		5	4	4	3	4	4	3	3	3.875
Direct mount to Single Bearing		4	5	3	2	3	2	4	4	3.7188
Collar in Machined Hole w/ Pin		5	5	2	2	4	4	5	5	4.1875

The design we settled on is a collar with dual bearing supports on each side and set screws for locking the ends down to hold the joint. This allows us to provide the maximum amount of support with a minimal amount of flexing in the assembly, as well as an easy to apply set screw lock. The yoke will articulate and lock using bushings in the joint, and will be fixed using a threaded rod and knob for fine adjustment, as well as using bolts to clamp the assembly down. The constant resistance for the torque measurement will be applied using a torque-limiting clutch to be purchased at McMaster-Carr. This will apply the needed resistance, as well as be able to be adjusted to vary the amount if the EPA wishes. The measurements will be done using digital encoders and a decoding display. These will get the accuracy needed as well as function by itself with little maintenance needed, and provide a visual output that will be easier to read than other means. The torque measurements will be made by a digital torque wrench. This allows the EPA to measure the torque through all the rotation and is far less complex and cheaper than a torque transducer.

5. PARAMETER ANALYSIS

5.1 - Design for Functional Accuracy

The main premise of this project is to get the most accurate measurement possible, our team kept this in mind during every step of the design process including material selection, the structure design, and tolerance assignment.

5.1.1 - Material Selection

This fixture will not see any real high loads, so we chose to use 6061 Aluminum wherever possible because it is both cheap and easy to machine. There were a few cases, however, where aluminum was to soft to work properly. This usually happened everywhere where a rotating surface would contact a stationary surface, such as the press fits on the yoke, and anywhere a set screw would be used. In these cases we used a low carbon steel (1018) because it would still be easy to machine, and would provide the hardness we were looking for.

5.1.2 - Structure Design

In order to ensure that the framework will not flex, we used relatively thick material everywhere to ensure rigidity. In order to ensure the collars that hold the part are aligned properly, we used collars that ride on 2 bearings with the set screw making contact between the two to ensure minimal deflection. The mock yoke uses a piece of threaded rod and two locking screws to both finely adjust and lock its position.

5.1.3 - Measurement Accuracy

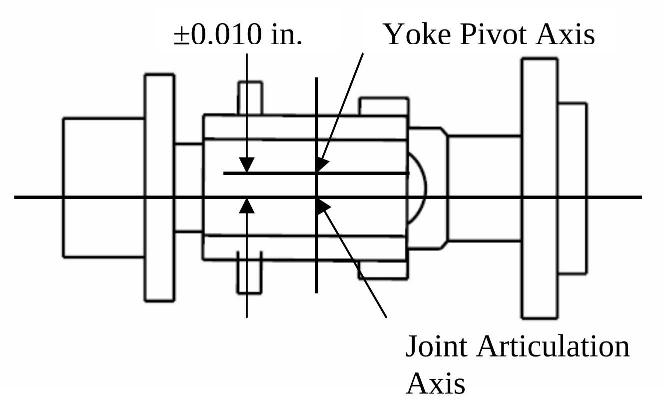
In order to ensure that the measurements were accurate we used digital encoders on each axis to achieve the appropriate resolution. Using encoders with 900 counts per revolution and the displays ability to decode each count into 4 separate counts, we were able to achieve a total of 3600 counts per revolution giving us the 0.1 degree accuracy that we were looking for. Second, our group decided to use a friction torque limiter to provide and adjustable and consistent resistance torque, and combined with a digital torque wrench, an accurate measurement for frictional torque.

5.1.4 - Tolerance Assignments

When developing our final design, our team had to play close attention to the tolerances given to each dimension of each part, in order to make sure that, A) the fixture functioned well, and B) the fixture did not violate any EPA specified tolerances. First our team looked at the major tolerance that was given to us by the EPA. The EPA stated that the pivot axis of the yoke should not be offset vertically from the rotational axis of the non-barrel side collar by any more than 0.010 in. A visual representation of this is displayed below in Figure 3.

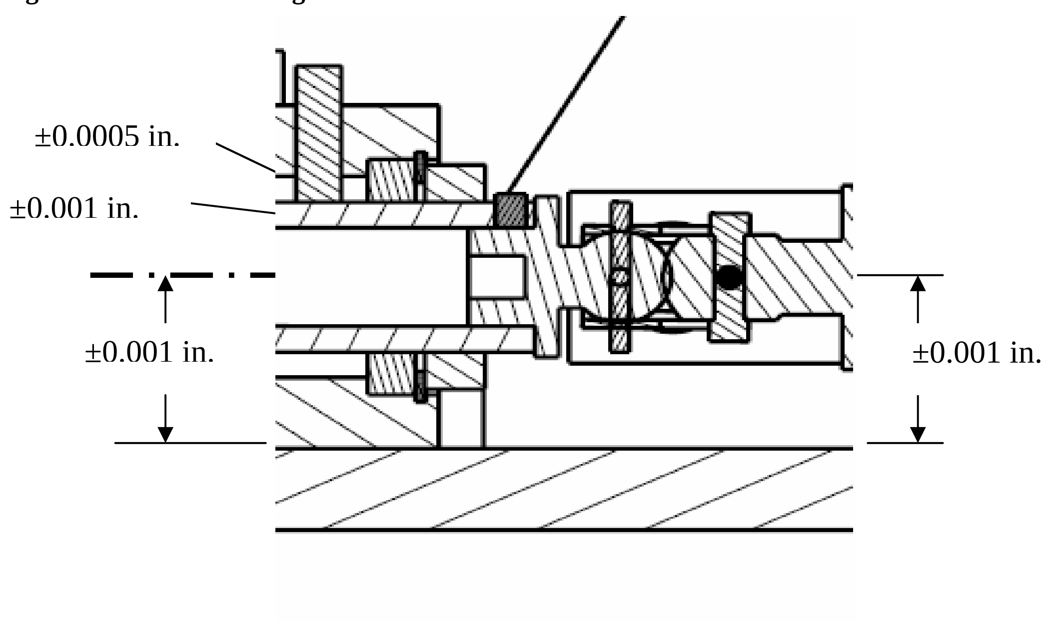
Using this tolerance as a guideline our team allotted tight tolerances to all the parts interfacing between the two axes to make sure they met this requirement. The main goal was to ensure that the sum of all the tolerances in the stack was less than 0.010. Keeping this in mind we assigned the tolerances displayed in Figure 4.

Figure 3 - CV Joint



In addition to these tolerances our team also used common sense to assign others. For example, we needed to have the non-barrel side collar mate with the press fit end of the joint in a manner such that it was able to hold it accurately and precisely, while still being able to take it out. So for this particular task we chose a sliding press fit, and in order to achieve that press fit, we assigned a tolerance of ±0.001 in. to the inner diameter of the collar. Other such applications of common sense, such as along surfaces that will contact bushings, are present throughout the rest of the fixture.

Figure 4 – Tolerance Assignments



5.2 - Design for Assembly/Manufacturing

From the start our group had to consider the fact that the EPA will want to test multiple joints in multiple situations. Because of this we had to make the design easy to assemble and disassemble in order for them to load and unload the joints easily. For this reason we used hardware that took basic tools, and used very few permanent joints. With the exception a few press fits, the entire fixture can easily be taken apart with simple hand tools.

Our group also had extensive manufacturing experience and used it to create parts that were easy to machine, or could be done so in a cost-effective way given modern manufacturing processes.

5.3 - Design for Safety/Failure

Our team used the DesignSafe software to assess any possible safety risks that could come from the use of our design. From this we deduced that the two biggest risks were possible exposure of electronics to moisture, or improper wiring, and cutting caused by burrs on machined edges. We fixed these issues by using electrical connectors that can only be connected one way, and using cables, rather than exposed wire, although we could improve this by adding some sort of protective channel for the wires to run through. And in order to prevent cutting our group made sure that all machined edges were filed and all holes deburred. The robust pieces needed for the stiffness required for accurate measurement, combined with the small applied loads, meant that our group did not have to worry about failure modes and could instead concentrate our efforts on other ways of making the design safe.

6. FINAL DESIGN

6.1 - Design Description

After going through our scoring matrices our group developed a concept that will fulfill all of the customers' requirements and do so in an efficient fashion. Our description of the fixture will begin at the joint (shown in Figures 1 & 2) and working our way out. The press fit end will be held by a collar that will have a sliding press-fit cavity that will hold the end of the joint in place and allow for easy removal, the joint will be fastened in by the use of a set screw that will contact a key-slot already existing in the joint. This collar will ride in two deep-groove ball bearings and will be able to be locked by means of a set screw that will contact the collar between the bearings providing minimum bending load on the whole system. The bearings themselves will be in carriers and mounted to the base plate. This entire assembly can be seen in Appendix D.1. We will then attach our friction-limiting clutch that will use pressure

Figure 5 – Friction Torque Limiter

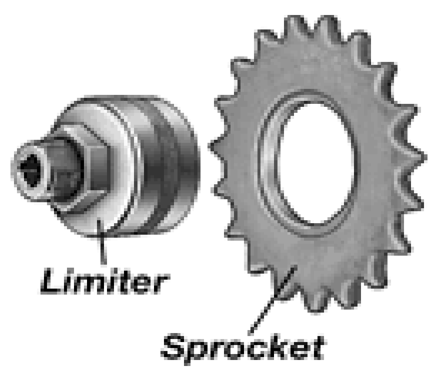
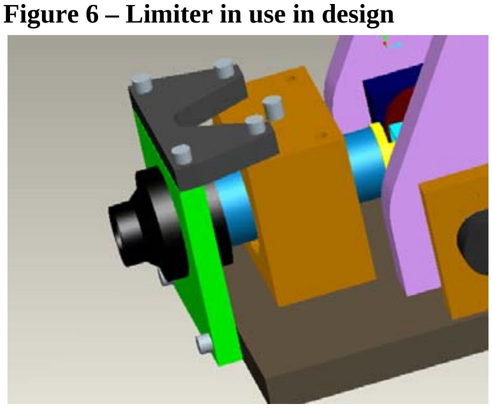


Figure 6 – Limiter in use in design



on a steel plate to apply the resistance for torque measurements. This apparatus can be seen individually and in operation in Figures 5 & 6 respectively. The sprocket seen in Figure 5 is replaced by our own plate in the design.

Moving the other way along the joint, the bolt-circle is placed in a second collar and is aligned using dowel pins and shoulder bolts. This collar is placed in another set of bearings exactly like the other end, again with a set screw. This carrier assembly slides along two supports that mimic the yoke motion, allowing it to be placed at any articulation angle. The use of a threaded rod and a corresponding knob allow for large adjustments as well as small ones to get the accuracy needed. The angular position of this mock yoke is recorded using the first of two digital encoders sending data to one of two LCD displays on the base. The collar continues past the carriers through a second encoder that monitors angular position of the joint and provides the necessary data in measuring lash. On the end of collar is a bolt that is welded, allowing the use of a digital torque wrench to measure frictional torque. To help you better visualize our prototype we have included a complete bill of materials in Appendix A, engineering drawings in Appendix B, and several CAD model pictures in Appendix D.

6.2 - Design operation

6.2.1 – Description of loading/unloading process
Remove stabilizer and friction plate bolts, loosen set screw in bearing carrier (Figure 7) Next, remove the friction plate, stabilizer and torque limiter assembly. Next, undo the bearing nut and set screw and slide the press fit side adapter out. Now simply use an allen key undo the bolts on the barrel side and slide the whole assembly out through the bearing carrier (Figure X)

Figure 7 – Fastener removal

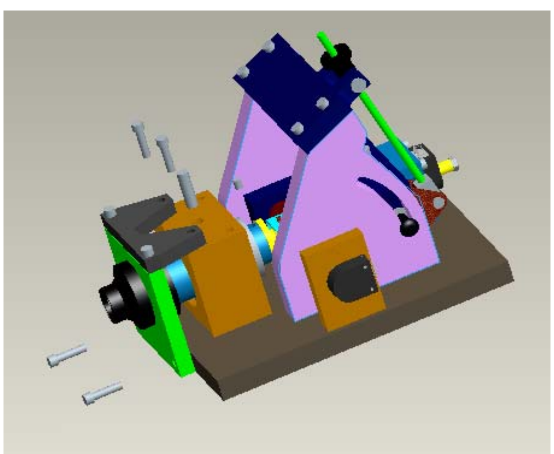
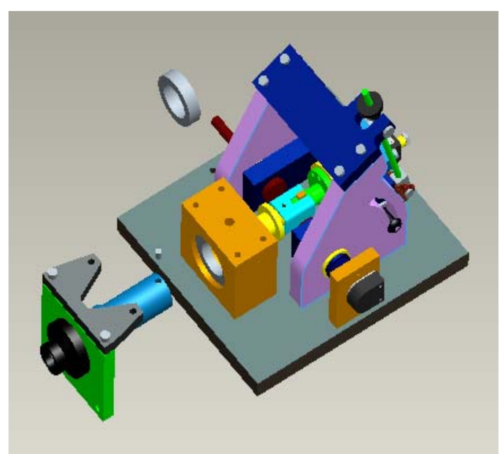


Figure 8 – Friction assembly removal



6.2.2 - Conducting a lash measurement
In order to conduct a lash measurement the joint must first be loaded into the fixture according to the procedure described in the previous section. Once this is done, the set screw (W06P033) on the press fit end bearing carrier (W06P003) must be tightened to

ensure that the one end does not rotate. The user can then set the yoke angle to the appropriate angle, moving it by hand for gross movements, and by using the knob for fine adjustments. Once the desired yoke angle is reached, clamp it in place using the two button head cap screws on each end. Now just simply use a bolt in the threaded end of the collar and a ratchet to rotate the joint to its limits and subtract the two measurement angles to calculate the amount of lash.

6.2.3 - Conducting a frictional torque measurement

In order to conduct a torque measurement, the user must first, using a digital torque wrench, rotate the barrel side adapter (W06P010) to check how much resistance is being applied. The user must then put a bolt into the threaded end of the barrel side adapter use the torque wrench to measure how much torque it takes to spin that collar by itself. Adding these two torques together gives the resistance torque. The user must then load the joint into the fixture using the procedure described in Section 6.2.1. Then again using the digital torque wrench on the barrel side adapter, measure how much torque it takes to spin the joint. Subtracting the resistance torque from this measurement gives the user a measurement of how much frictional torque the joint adds to the system.

6.3 – Prototype Description

A simple proof-of-concept prototype would have been insufficient for our customer requirements and to verify the functionality of the design, for this reason our group opted to build a functional prototype of the complete design. Our team worked diligently in the machine shop and was able to manufacture a fixture that was completely capable of holding the joint appropriately and measuring lash with the prescribed resolution. Unfortunately there was insufficient time to complete the fabrication of the stabilizer (W06P006) and friction plate (W06P004), however, complete engineering drawings and needed materials are being provided to the sponsor for future completion.

The single main design change to our prototype was the addition of a groove in the collars (W06P010 & W06P011) on the bearing surface to prevent any galling caused by the set screws to render the fixture inoperable. By effectively lowering the surface, this allows for some galling, while still maintaining the ability to remove the collar and clean the surface up for more use. While there is no way to completely test this, our team is certain from simple tests that the measurement systems are completely functional and accurate. While we do not have the means to verify the fixture is built to the proper tolerances, we have recommended to the EPA that they have the fixture CMMed in order to verify this.

7. MANUFACTURING PROCESS

7.1 - Fabrication of Individual Parts

The individual custom-made parts for this project were made in the student machine shop using two basic machines, the lathe and the mill, along with one advanced machine, the CNC mill, and a variety of hand tools. Each part was machined, and once everything was completed and purchased, the final product was assembled. Engineering drawings and manufacturing plans for each machined part can be found in Appendices B & C, respectively.

7.2 - Assembly of Final Prototype

7.2.1 - Mock Yoke Assembly

Once all the parts were fabricated our group began the assembly. To begin with the stub shafts (W06P012) were pressed into the yoke arms (W06P013), and the bearings (W06P019)) pressed into the barrel side bearing carrier (W06P002) using an arbor press. The mock yoke was then assembled from these two sub assemblies and the barrel side bearing carrier using dowel pins (W06P039) and appropriate screws. On the left end a clevis for the fine adjustment was installed using the bolts for support. Next, bronze bushings (W06P021) were pressed into each yoke holder and the first yoke holder was bolted to the jig plate using the appropriate shoulder bolts. The second yoke holder was then slid over the other stub shaft and bolted to the jig plate using the same shoulder bolts. The locking screws were then loosely threaded in along with appropriate bushings (W06P022). Next the top plate (W06P007 was bolted on. A bushing (W06P029) was then pressed into the second encoder mount (X), and the sub-assembly was slipped over the stub shaft and bolted to the jig plate using shoulder bolts.

Next, the barrel side adapter (W06P010) was inserted and fastened in using a washer and nut. The lash encoder mount was then installed over this assembly using four ¼" shoulder bolts. The encoders were then mounted according to the instructions provided. Lastly, clevis pins were installed with in each corresponding hole along with the threaded rod and knob to add the fine adjustment mechanism.

7.2.2 - Press Fit End Bearing Carrier and Torque Limiter Assembly

To build the other half of the fixture we began by pressing bearings (W06P020) into the press fit side bearing carrier (W06P003) using an arbor press. This assembly was then bolted to the jig plate using shoulder bolts. The set screw was then installed. Next the first half of the adapter shaft was inserted into the press fit end adapter and tightened down with a set screw. The first half of the friction clutch was then installed. The bearing that came with the torque limiter was pressed into the friction plate and the plate and stabilizer were installed using the appropriate fasteners. Last the second half of the torque limiter was installed and the nut adjusted to the desired resistance.

7.2.3 - Display and Electronics Installation

After the fixture was built, our team fabricated a bracket to hold the two displays out of sheet metal. The bracket was bolted to the jig plate, and the displays were disassembled and re-assembled with the bracket between the two casing pieces to hold them in place. The cables were then hooked up and each display was plugged in and turned on. They were then programmed appropriately.

7.3 - Design Changes During Prototyping and for Mass Production

Our design group only made a few small changes to the design during prototyping. We added a recessed area on both collars where the set screw makes contact to ensure that they will still be able to be removed if any galling occurs on the surface. We also omitted several holes on the encoder mounts that were excessive. In addition to these, we also had to make an adjustment in the first encoder mount, widening the groove to allow the washer and nut on the adapter to rotate freely. None of these design changes have a large impact on the design if it were to be made en masse.

On the whole our design would be relatively easy to put into mass production as the only bits of awkward geometry could be easily fixed with specialized fixtures for holding the parts while machining. The only other changes we would make would be to attempt to standardize the hardware for easier use and quicker assembly.

8. TEST RESULTS

There were several methods that we employed in order to validate our design. Because our design was a fixture, these methods involved making sure it met the original engineering requirements specified in Table 1 and ensuring that all of the parts were manufactured to the dimensions specified in the engineering drawings. Using measuring tools such as rulers, micrometers and protractors, we verified the basic dimensions specified by our engineering drawings were achieved on our prototype. In order to make sure the friction was limited we rotated the shaft going through the position encoder and the mock yoke about there respective axes. We found that the friction was minimal and did not in anyway interfere with the operation of the fixture. The digital encoders we purchased provided us with the accuracy that we needed for the measurements required. In order to test that they could measure the full shaft rotation we marked a point on a dowel pin and rotated it through a full rotation and checked the display to ensure 360 degrees of rotation were measured. We also rotated the mock yoke from its lowest angle to its highest angle to ensure 0-54 degrees of rotation were achievable. We then measured this with a digital protractor to ensure that the digital encoder was giving accurate readings. All of these tests produced results showing that our prototype was manufactured to the specifications outlined on the engineering drawings and achieved the customer requirements

It can be seen that our final design is viable because of the fact that our model is also the prototype that the customers are actually using for their CV joint. It is a fully working prototype that must meet the tolerances outlined by our sponsor in order to function. In order to test the functionality of this prototype we placed a joint inside of the fixture and tested it to make sure that the joint fit and that the fixture could make the joint perform all of tasks required by our sponsor which were outlined in Table X. After completing these tests we were satisfied that our prototype was able to perform the tasks required of it.

9. DESIGN CRITIQUE

Given the money and time constraints on this project, we are very pleased with the way our design and prototype turned out. If we had been given more time and money we would have looked into torque transducers for an accurate torque measurement, as well as collars or other bet forms of clamping other than set screws. This would eliminate the drawbacks of galling at the contact point. Also, in hindsight it may have been better to make the mock yoke wider, to allow slightly more access to bolts and other fasteners while loading and unloading the joint. Even with all these changes in mind, the best way to improve the fixture is to have the machining done by a professional shop that can hit the high tolerances needed better than a team of students. It also would help verify the quality to have the fixture CMMed and checked against the CAD model.

10. RECOMMENDATIONS

Based on our experience during this project we were able to develop several recommendations that could possibly improve on the design we have already presented to our sponsors. The first of these would be to standardize all of the bolt sizes on the design. This would make the prototype easier and possibly cheaper to manufacture. The next proposal would be to attach a torque transducer on the design and use that for torque measurements as opposed to a digital torque wrench. This obviously would cost more money, but it perhaps would make up that cost in its ease of use and time that might possibly be saved. A final proposal for future manufacturing would be to have all the parts of this fixture made in a professional machine shop for improved accuracy and then to test that accuracy using a CMM machine to make sure all the machining was to the specifications. We were unable to implement these recommendations given the budget and time constraints placed on us, but we are confident that following these steps would lead to better overall prototype.

11. CONCLUSIONS

Our team is very pleased with the final outcome of this project. We feel we were able to take the EPA's needs and effectively translate them into engineering targets for us to meet. Using our concept generation and selection processes we were able to settle on a design that would accomplish all the goals in the best way possible. Our design was proven by the construction of a complete working prototype that will give the EPA valuable information regarding lash in their CV joints. Unfortunately, we were not able to complete the fabrication of the friction measurement parts, however we will be providing the EPA with drawings and material from which they should easily be able to manufacture the two remaining parts and acquire another set of valuable data. We submit this fixture to the EPA with the caveat that they understand the limitations of a students machining ability and those of machines that have suffered years of student abuse, and thus if the wish to get a really accurate fixture, it would be best to have a professional machine shop fabricate the parts.

12. ACKNOWLEDGEMENTS

We would like to thank all of our section instructors for a very enjoyable and productive semester. Without the organization they displayed and effort they put forth in presenting quality material, none of this would have been possible. We extend special thanks to Professor Brent Gillespie for his guidance and insight in helping to choose a digital encoder as our measuring device, and Bob Coury and Marv Cressey for their guidance, assistance, and patience in the machine shop. We also do not want to forget to thank Michael Delduca or Andrew Moskalik of the EPA for the cooperation they showed in making sure we had all of the resources and information necessary to complete this project. We especially want to thank Professor Kazuhiro Saitou for the guidance and support as our section instructor. He provided us with countless resources in order to finish the project and helped to make sure that we were organized and headed in the right direction.

13. INFORMATION SOURCES

In an attempt to better understand our design problem, our team conducted a literature search to see if any prior work has been done in this area. After searching the university library, including the catalog of SAE papers, and the U.S. Patent Office we were unable to find any evidence that a fixture of this nature, or one that performs the same task has been designed, made public, and patented in the U.S.

During our search we did however find a book published by the Society of Automotive Engineers that contained a detailed mechanical analysis of the forces our joint experiences in traditional operation[1]. The joint is a double-hook, or Cardan joint that consists of two universal joints connected via a splined sliding shaft. This design allows the joint to transmit torque and adapt to the relative translational motion of the mechanisms it connects. Unfortunately since the purpose of our fixture is to measure quantities that are inherent to the joint itself, rather than those existing in operation, this book will only be of limited use.

Since the beginning of this project, our literature search expanded to include the catalogs of McMaster-Carr, MSC, US Digital, Optrex, and other companies to find the best components for use in our design.

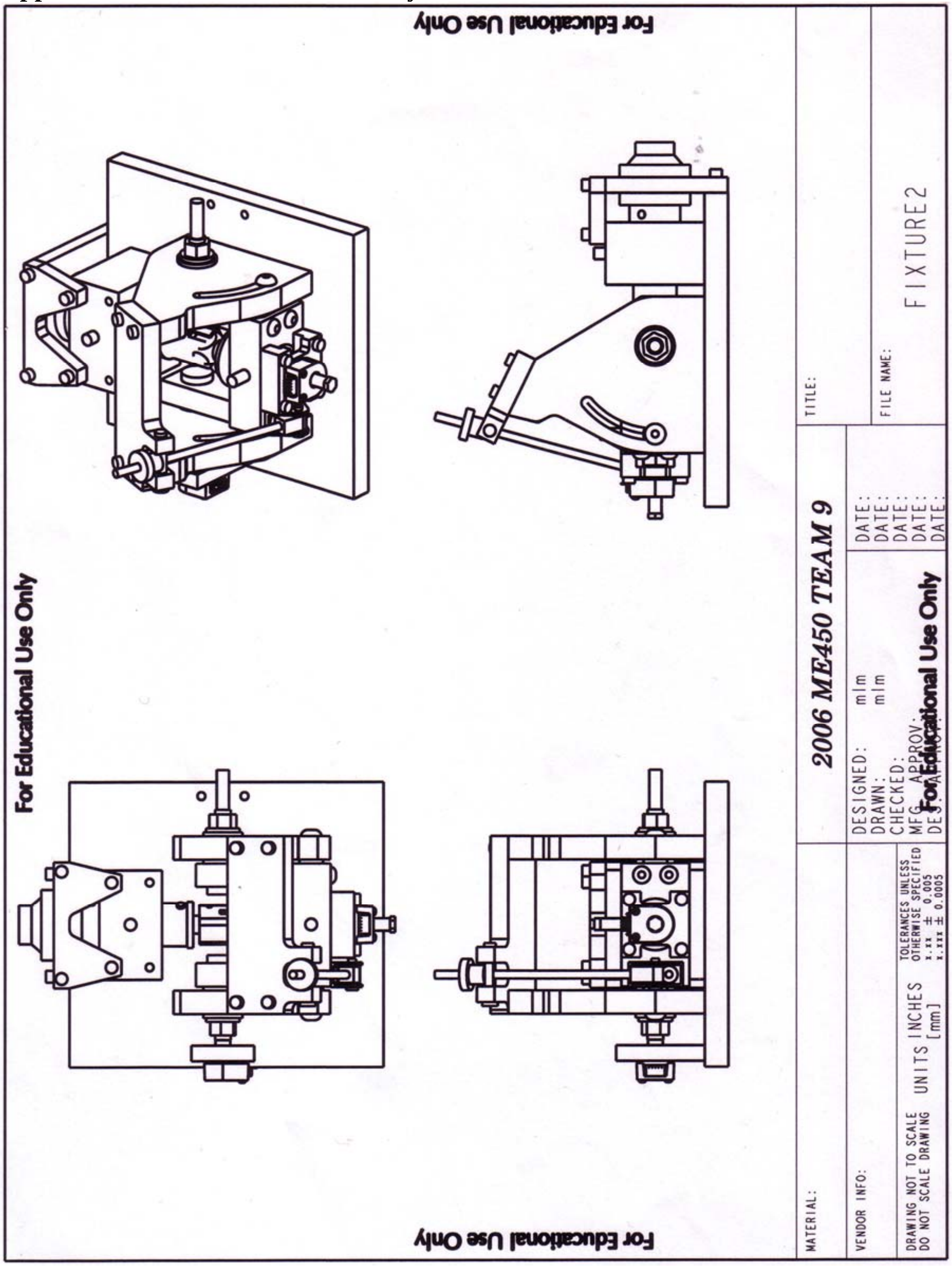
[1] Society Automotive Engineers. Advances in Engineering Series: Universal Joint and Driveshaft Design Manual. Society of Automotive Engineers. Warrendale, PA. 1979.

14. APPENDIX A – BILL OF MATERIALS

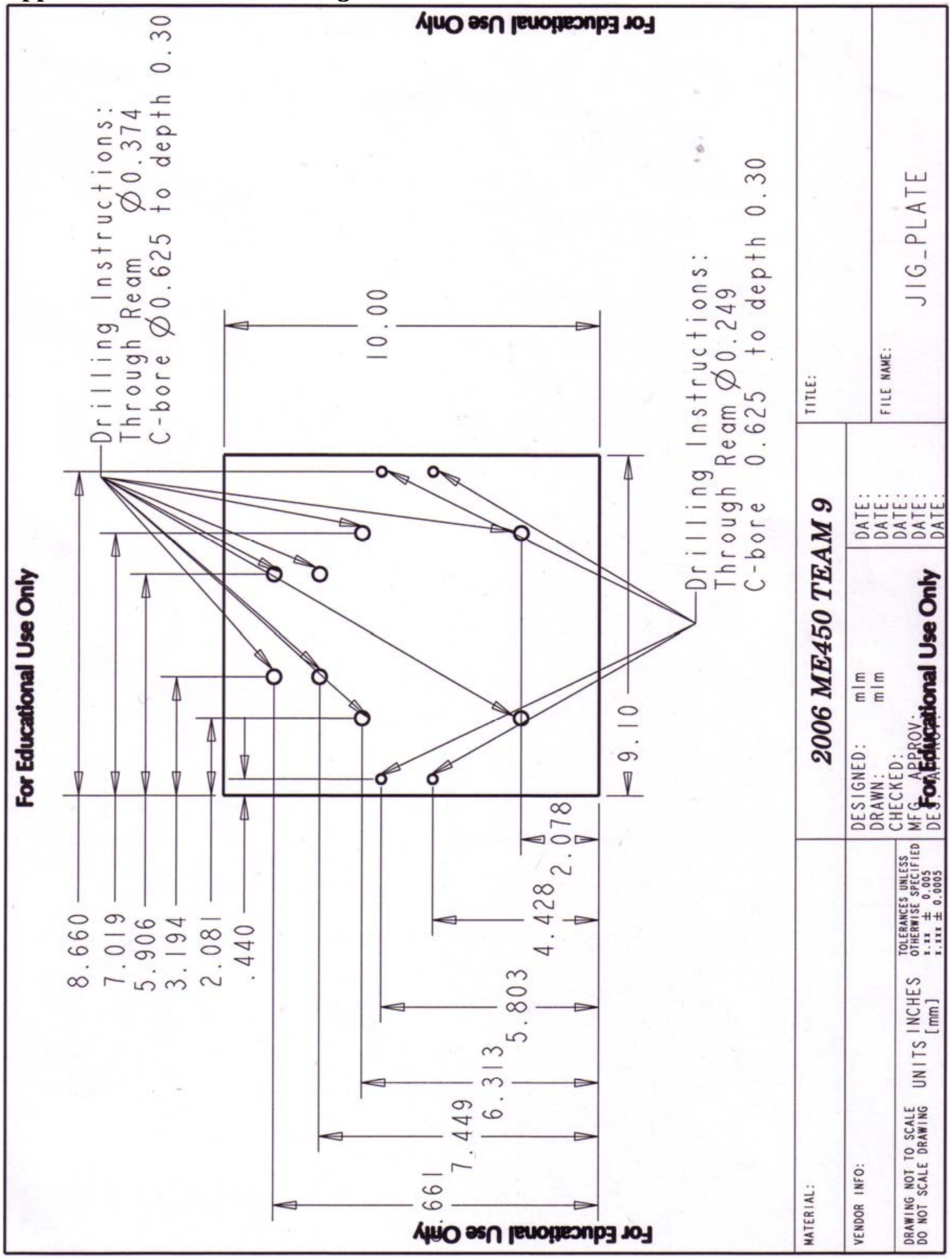
ME450 P/N	Description	Vendor	Vendor P/N	Qty	Price
W06P001	Jig Plate	Metal Xpress	N/A	1	$ 45.20
W06P002	Barrel Side Bearing Carrier	Metal Express	N/A	1	$ 11.84
W06P003	Bearing Carrier	Metal Express	N/A	1	$ 16.26
W06P004	Friction Plate	Metal Express	N/A	1	$ 10.89
W06P005	Lash Encoder Mount	Metal Express	N/A	1	$ 7.57
W06P006	Stabilizer	Metal Express	N/A	1	$ 7.86
W06P007	Top Bracket	Metal Express	N/A	1	$ 10.15
W06P008	Yoke Holder	Metal Express	N/A	2	$ 17.16
W06P009	Adapter Shaft	N/A	N/A	1	Donated
W06P010	Barrel Side Adapter	N/A	N/A	1	Donated
W06P011	Press-Fit Side Adapter	N/A	N/A	1	Donated
W06P012	Stub Shaft	N/A	N/A	2	Donated
W06P013	Yoke Arm	Metal Express	N/A	2	$ 7.06
W06P014	Yoke Encoder Mount	Metal Express	N/A	1	$ 6.37
W06P015	Digital Encoder	US Digital	E2-900-394-A3H-PKG3	1	$ 57.37
W06P016	Digital Encoder	US Digital	E2-900-394-A3H	1	$ 50.37
W06P017	Electronics Cable	US Digital	CA-1394-2FT	2	$ 8.40
W06P018	LCD Display	US Digital	ED3-S	2	$ 103.95
W06P019	Deep Groove Ball Bearing	Bearing Services	6907ZZ	2	$ 62.60
W06P020	Deep Groove Ball Bearing	Bearing Services	6905ZZ	2	$ 40.33
W06P021	Flanged Bronze Bushing - 3/4" OD	McMaster-Carr	7815K46	6	$ 3.34
W06P022	Thrust Bushing - 3/8" ID - 1/8" Thick	McMaster-Carr	2879T3	4	$ 0.65
W06P023	Torque Limiting Clutch	McMaster-Carr	6524K11	1	$ 56.86
W06P024	3/8" Clevis Pin w/ Cotter Pin	McMaster-Carr	97245A688	1	$ 0.84
W06P025	1/4" Clevis Pin w/ Cotter Pin	McMaster-Carr	97245A631	1	$ 0.38
W06P026	Knob	McMaster-Carr	6121K311	1	$ 3.03
W06P027	Thread Rod	McMaster-Carr	91565A567	1	$ 0.56
W06P028	Button Head Cap Screw -5/16"	McMaster-Carr	91255A489	6	$ 0.81
W06P029	Bronze Bushing - 10 mm ID	McMaster-Carr	6679K14	2	$ 2.65
W06P030	Shoulder Bolt - 10-24 Thread - 1/4 Shoulder	McMaster-Carr	91259A544	6	$ 1.02
W06P031	Bearing Washer	McMaster-Carr	94744A289	2	$ 0.93
W06P032	Button Head Cap Screw - 3/8-16 Thread	McMaster-Carr	91255A628	4	$ 0.81
W06P033	Set Screw - 3/8-16 Thread	McMaster-Carr	90289A626	3	$ 0.28
W06P034	Socket Head Cap Screw - 1/4-20 Thread	McMaster-Carr	91251A542	10	$ 0.13
W06P035	Shoulder Bolt - 10-24 Thread - 1/4 Shoulder	McMaster-Carr	91259A541	16	$ 3.18
W06P036	Shoulder Bolt - 5/16-18 Thread - 3/8 Shoulder	McMaster-Carr	91259A623	6	$ 6.07
W06P037	Bearing Lock Nut	McMaster-Carr	6343K19	2	$ 6.70
W06P038	Set Screw - 1/4-20 Thread	McMaster-Carr	90289A534	2	$ 0.12
W06P039	Dowel Pins	McMaster-Carr	97360A110	6	$ 2.18

15. APPENDIX B – ENGINEERING DRAWINGS

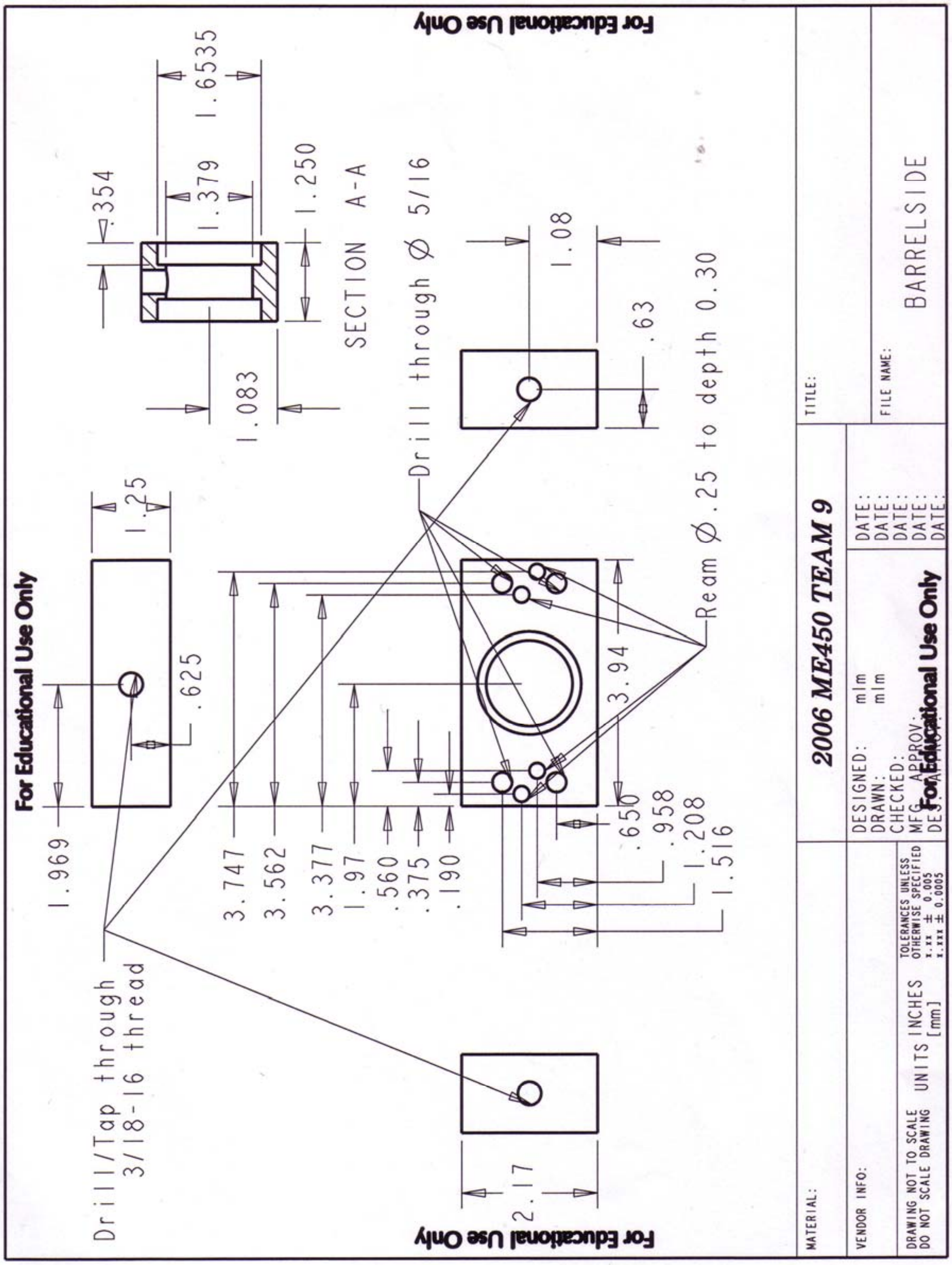
Appendix B.1 – W06P000 - Assembly



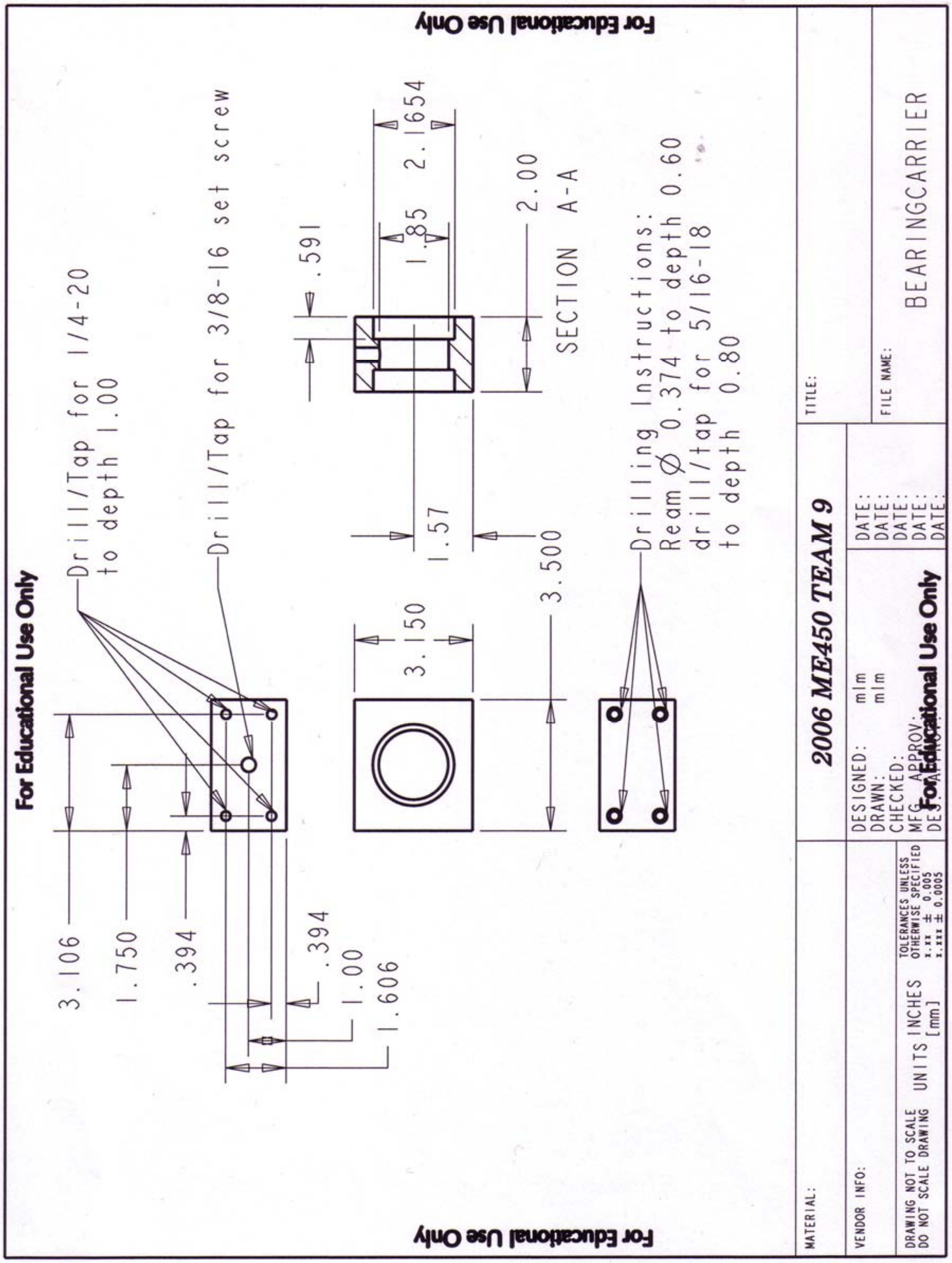
Appendix B.2 – W06P001 – Jig Plate



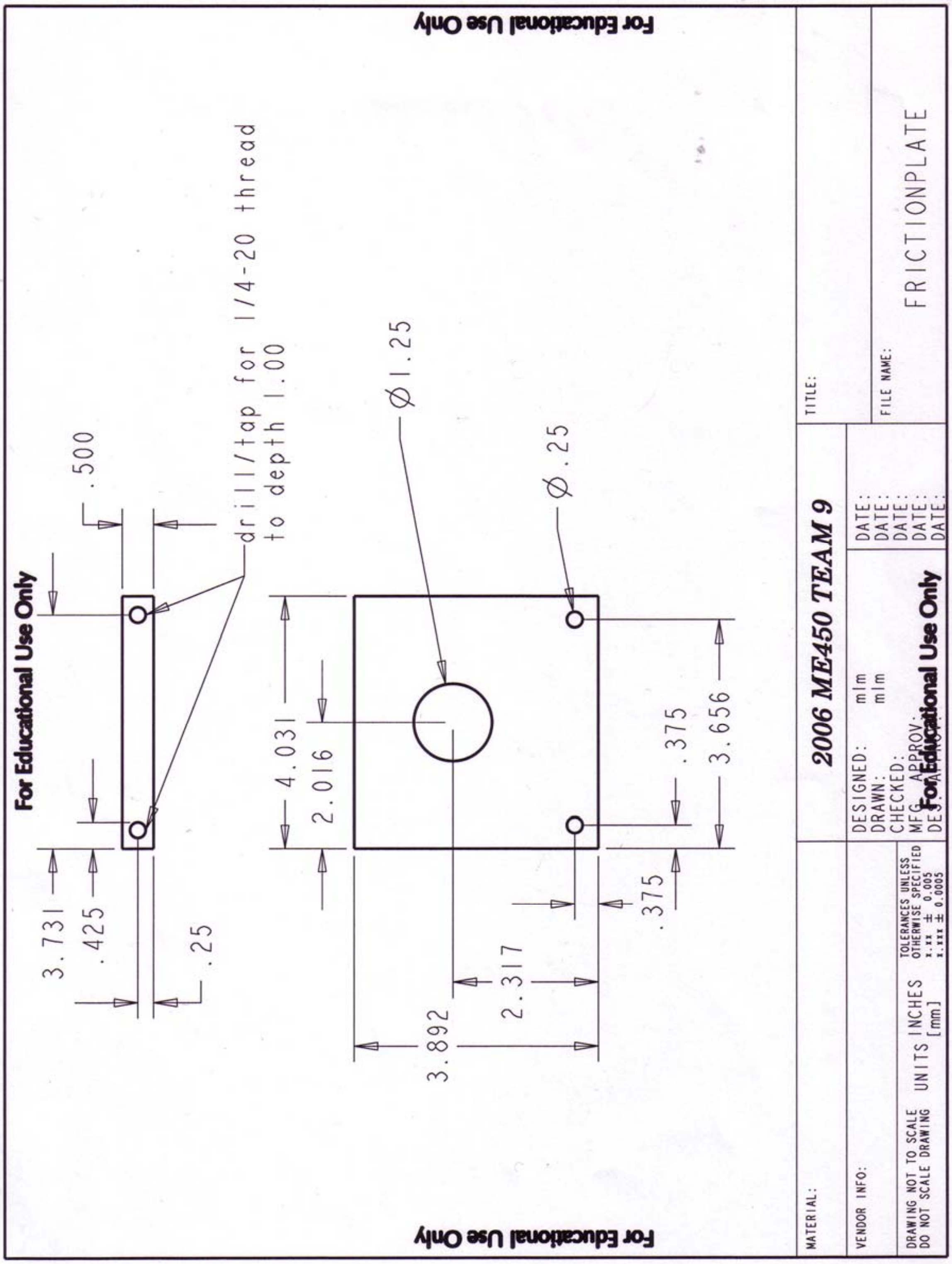
Appendix B.3 – W06P002 – Barrel Side Bearing Carrier



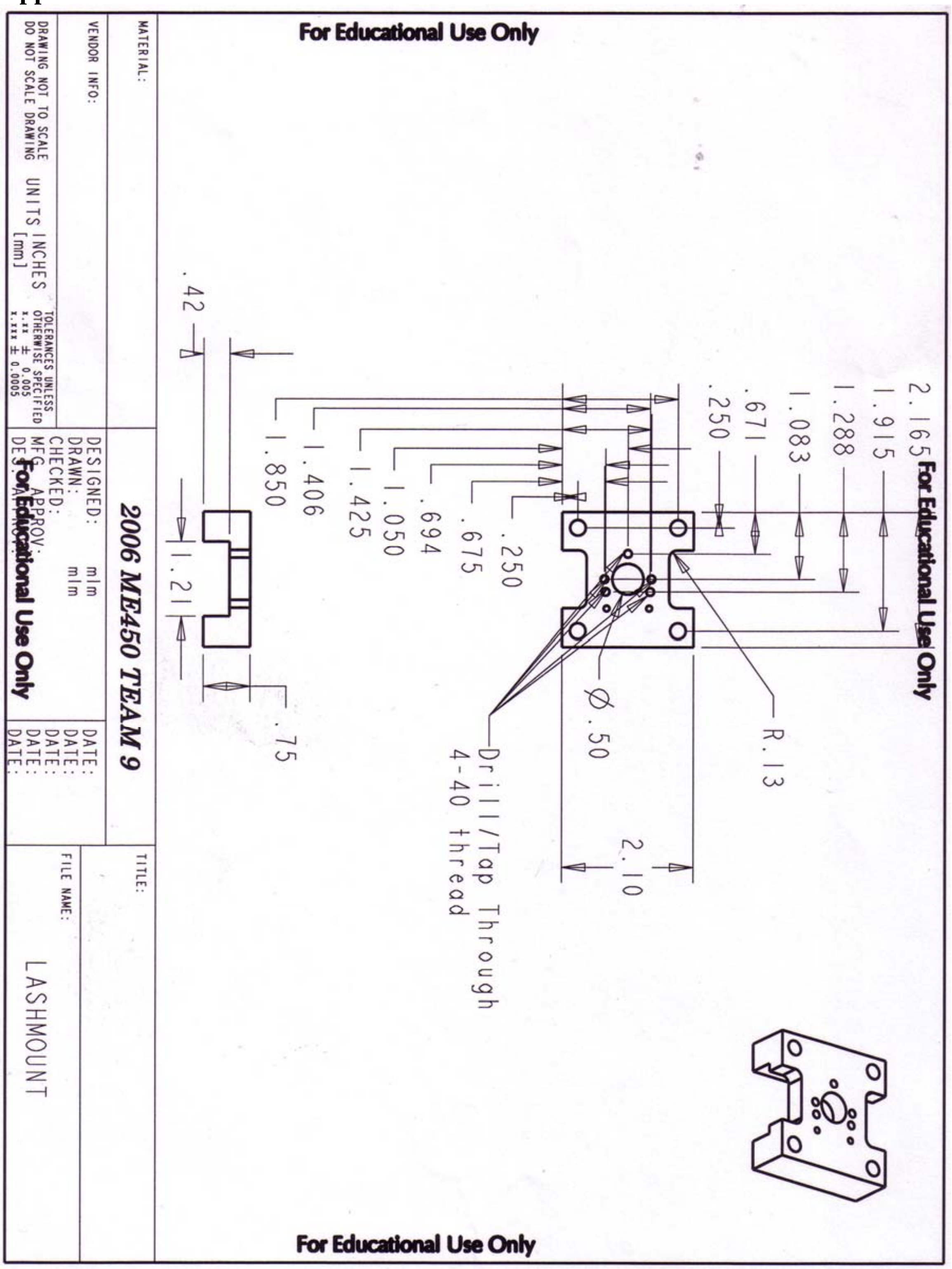
Appendix B.4 – W06P003 – Press Fit Side Bearing Carrier



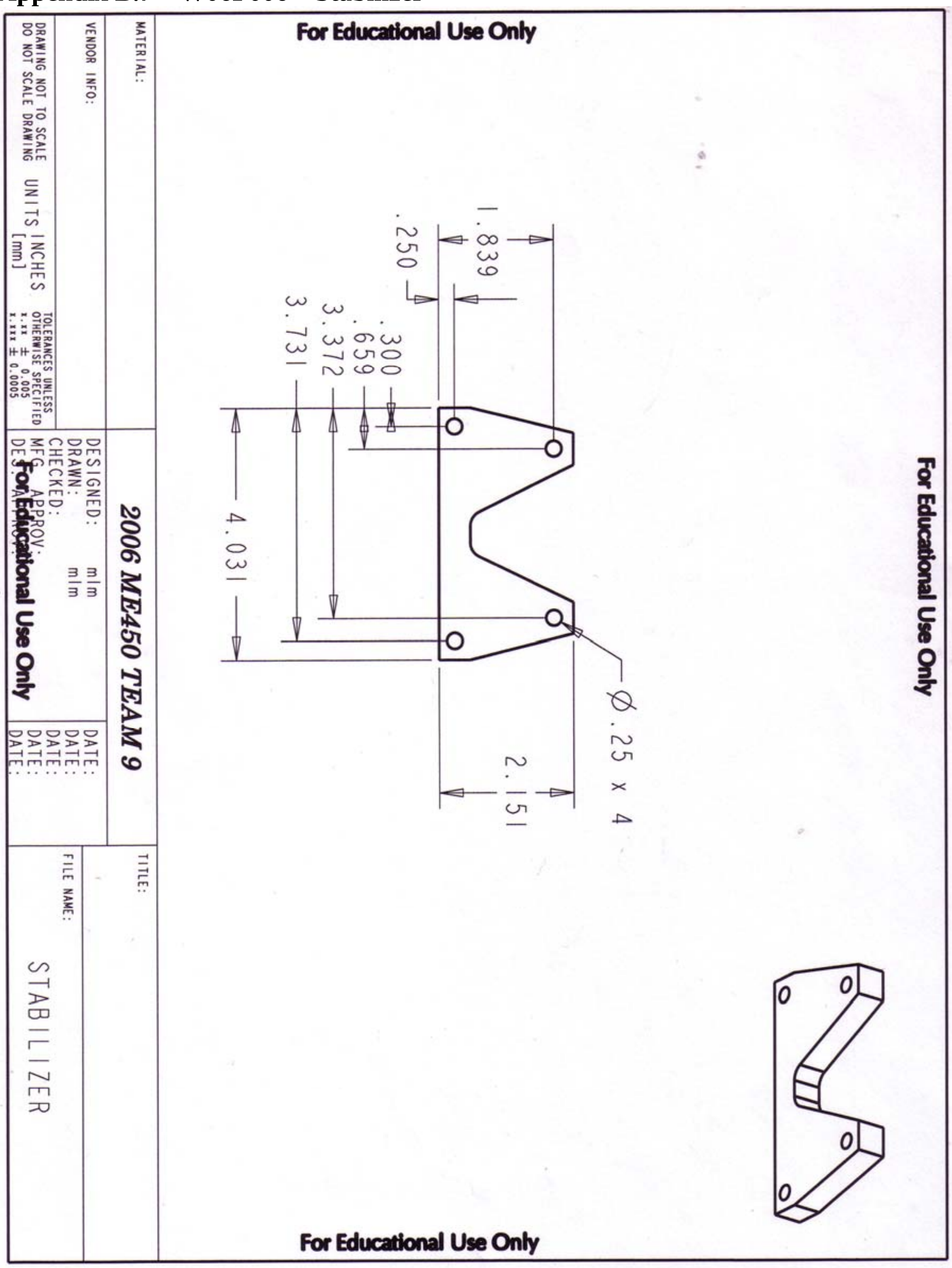
Appendix B.5 – W06P004 – Friction Plate



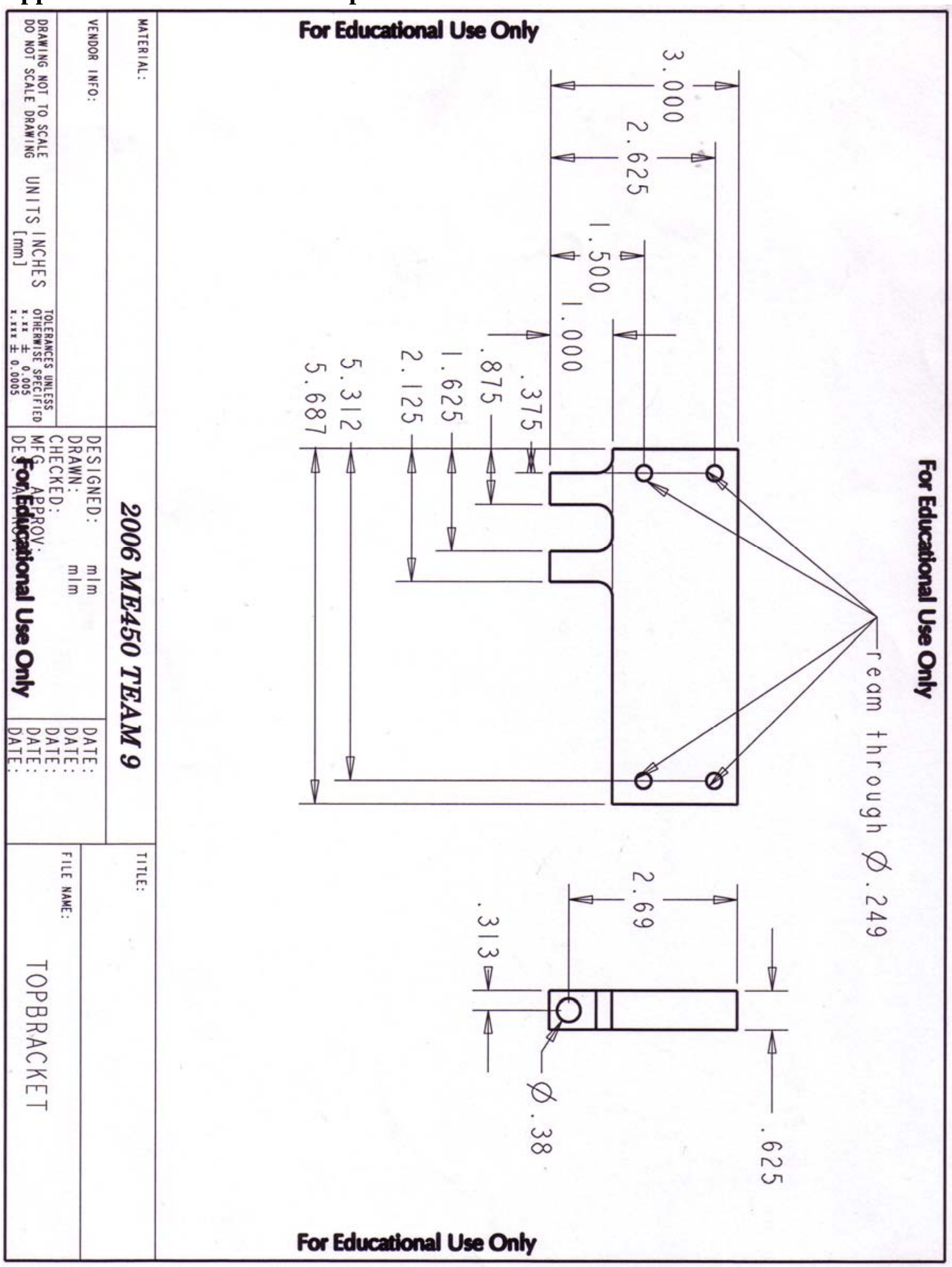
Appendix B.6 – W06P005 – Lash Encoder Mount



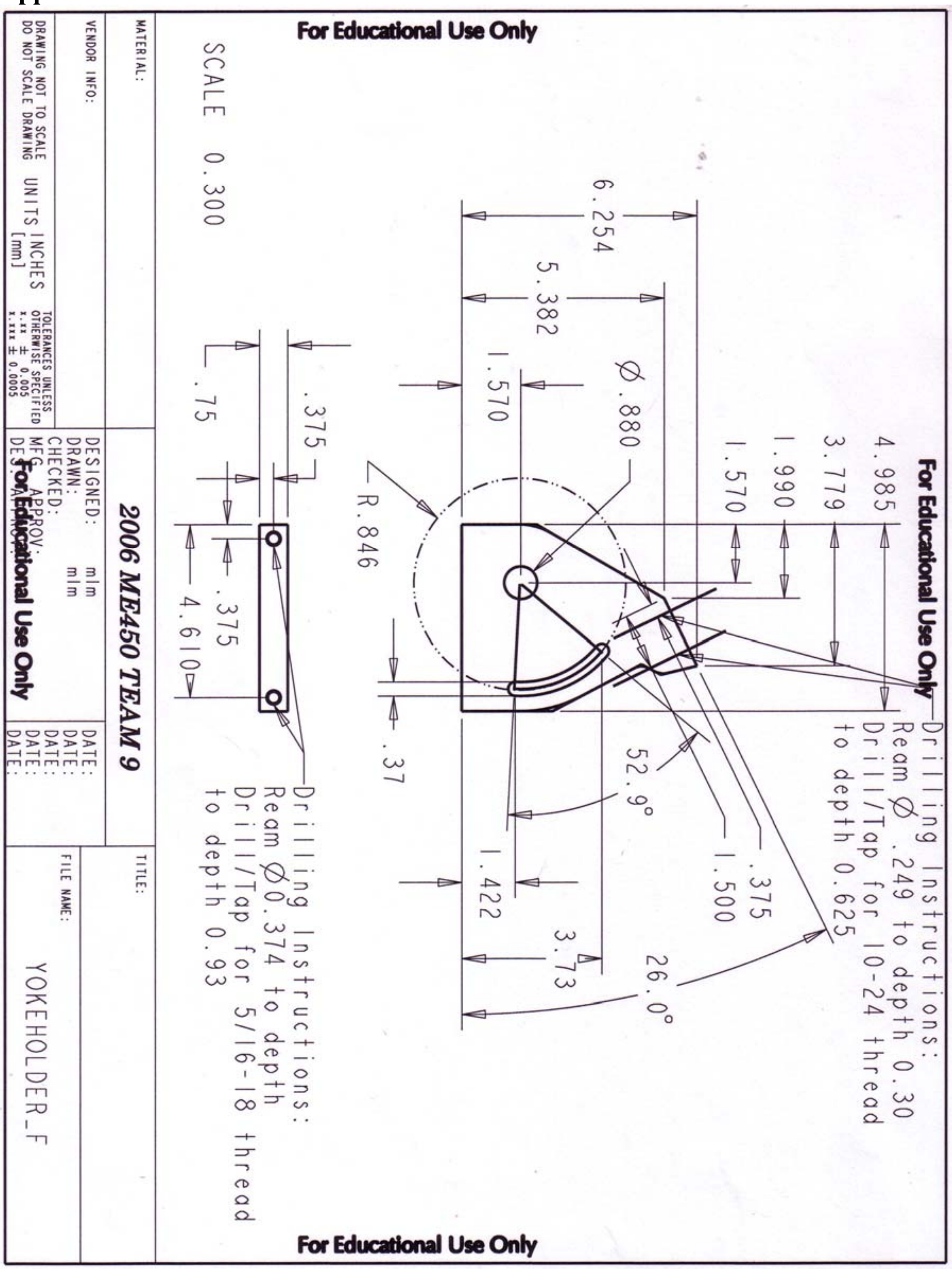
Appendix B.7 – W06P006 – Stabilizer



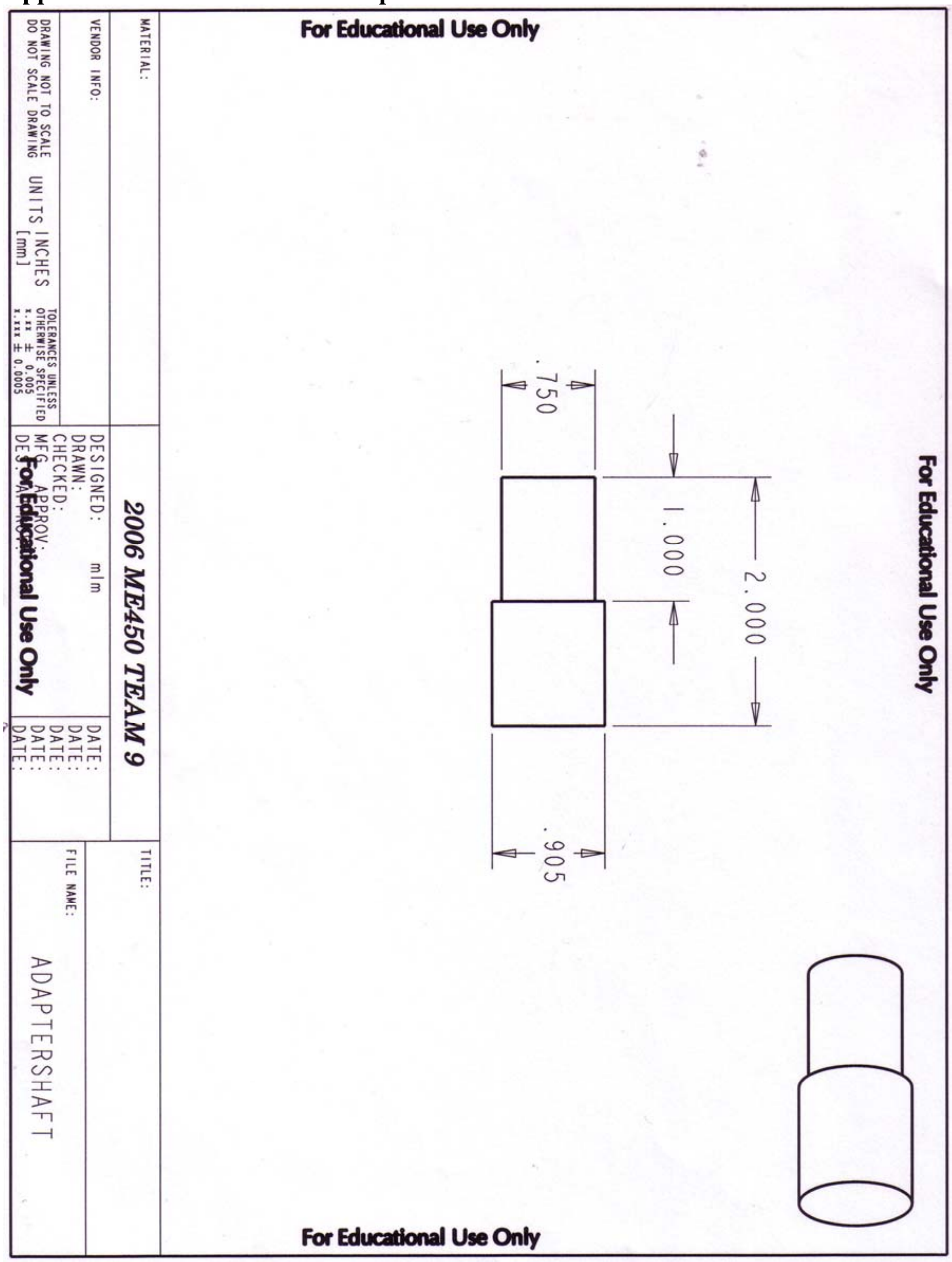
Appendix B.8 – W06P007 – Top Bracket



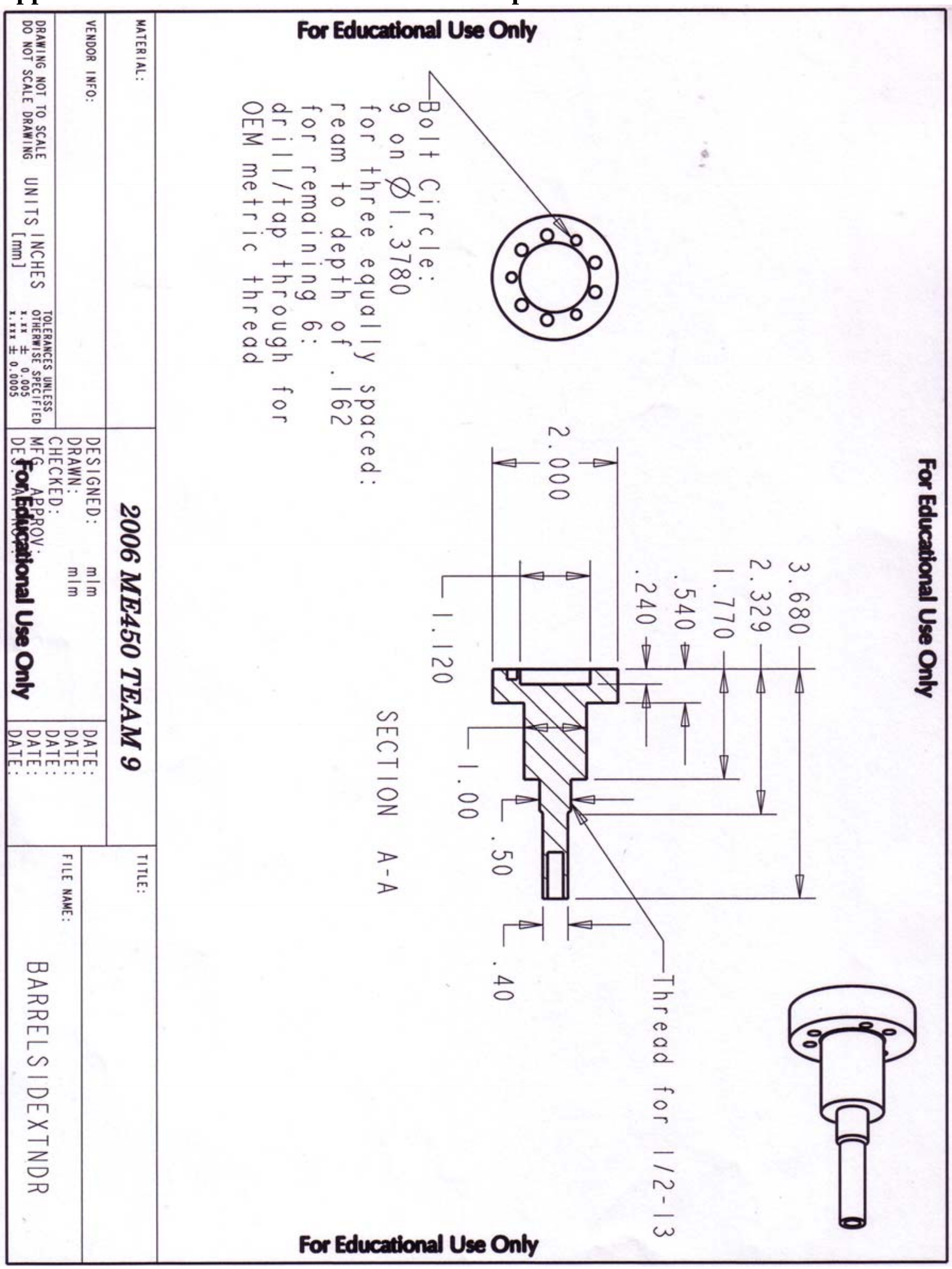
Appendix B.9 – W06P008 – Yoke Holder



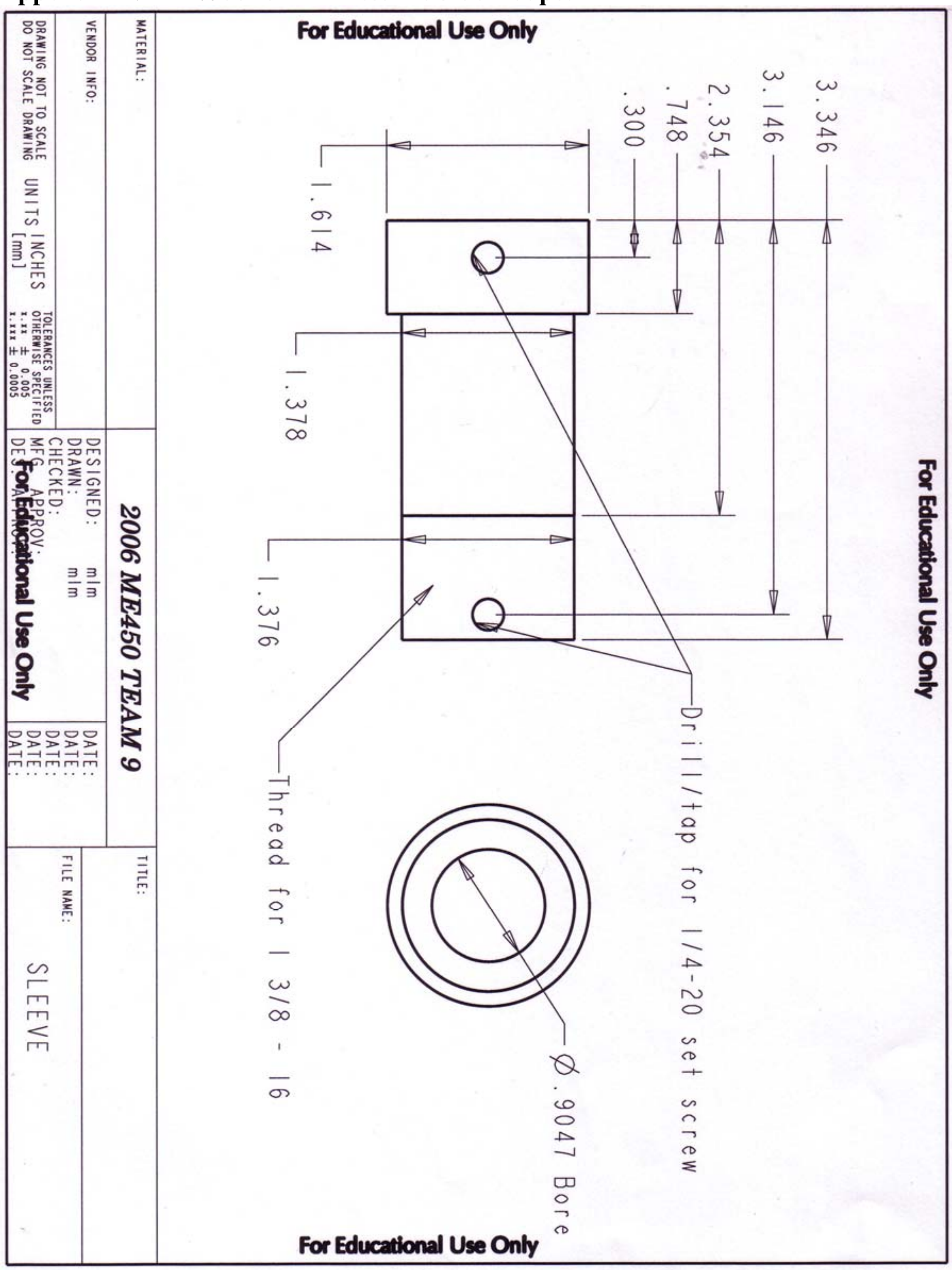
Appendix B.10 – W06P009 – Adapter Shaft



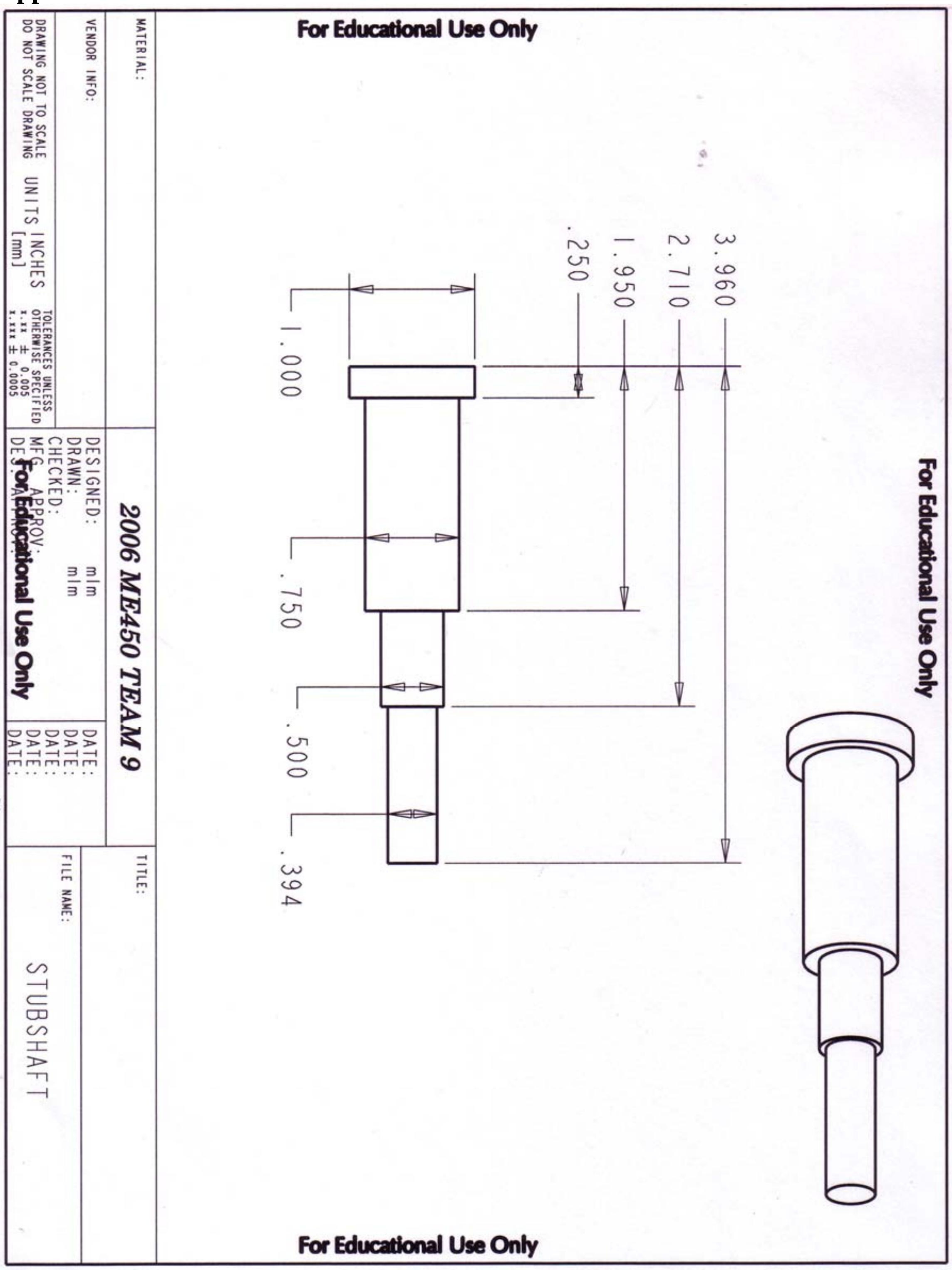
Appendix B.11 – W06P010 – Barrel Side Adapter



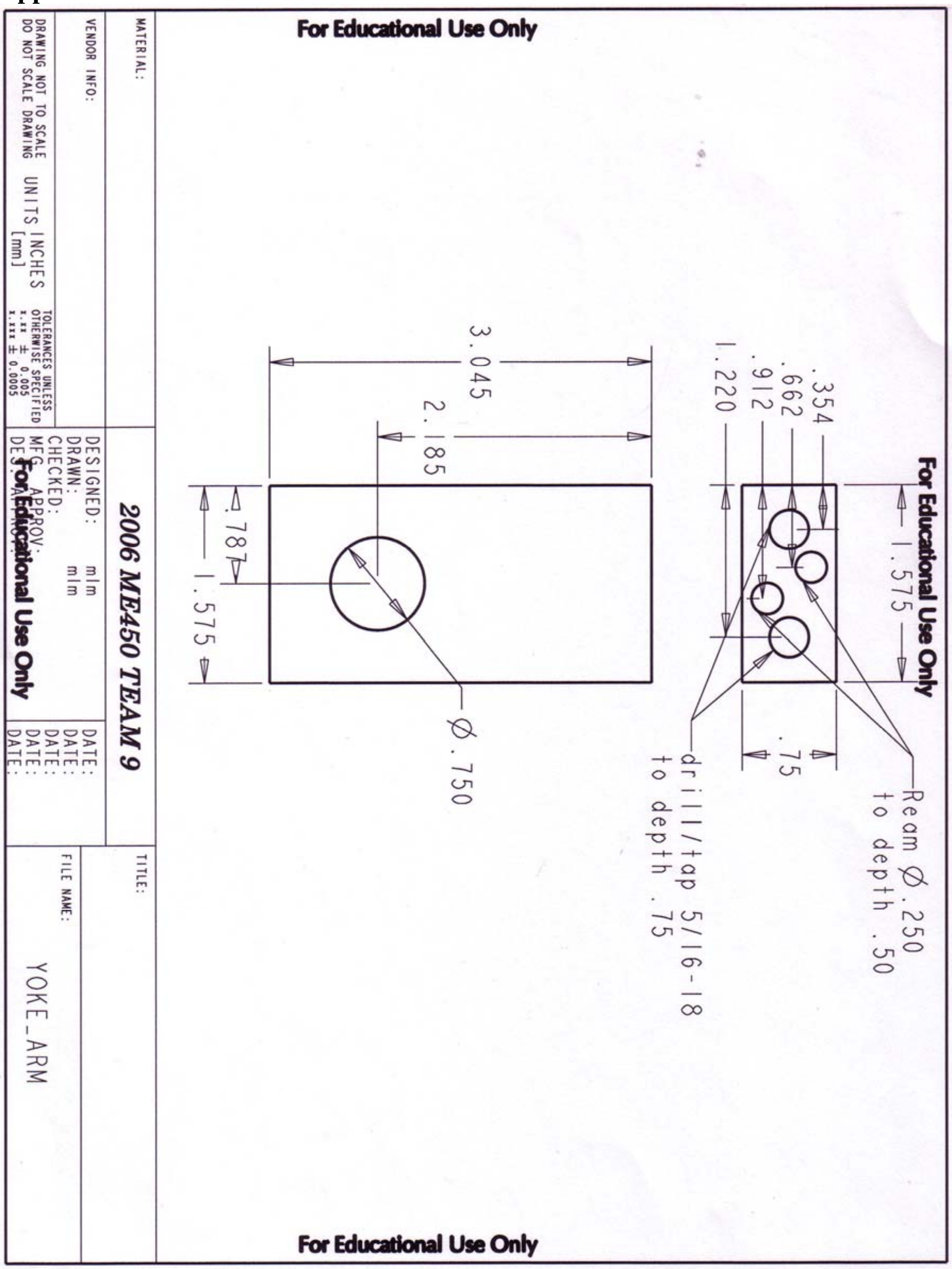
Appendix B.12 – W06P011 – Press Fit Side Adapter



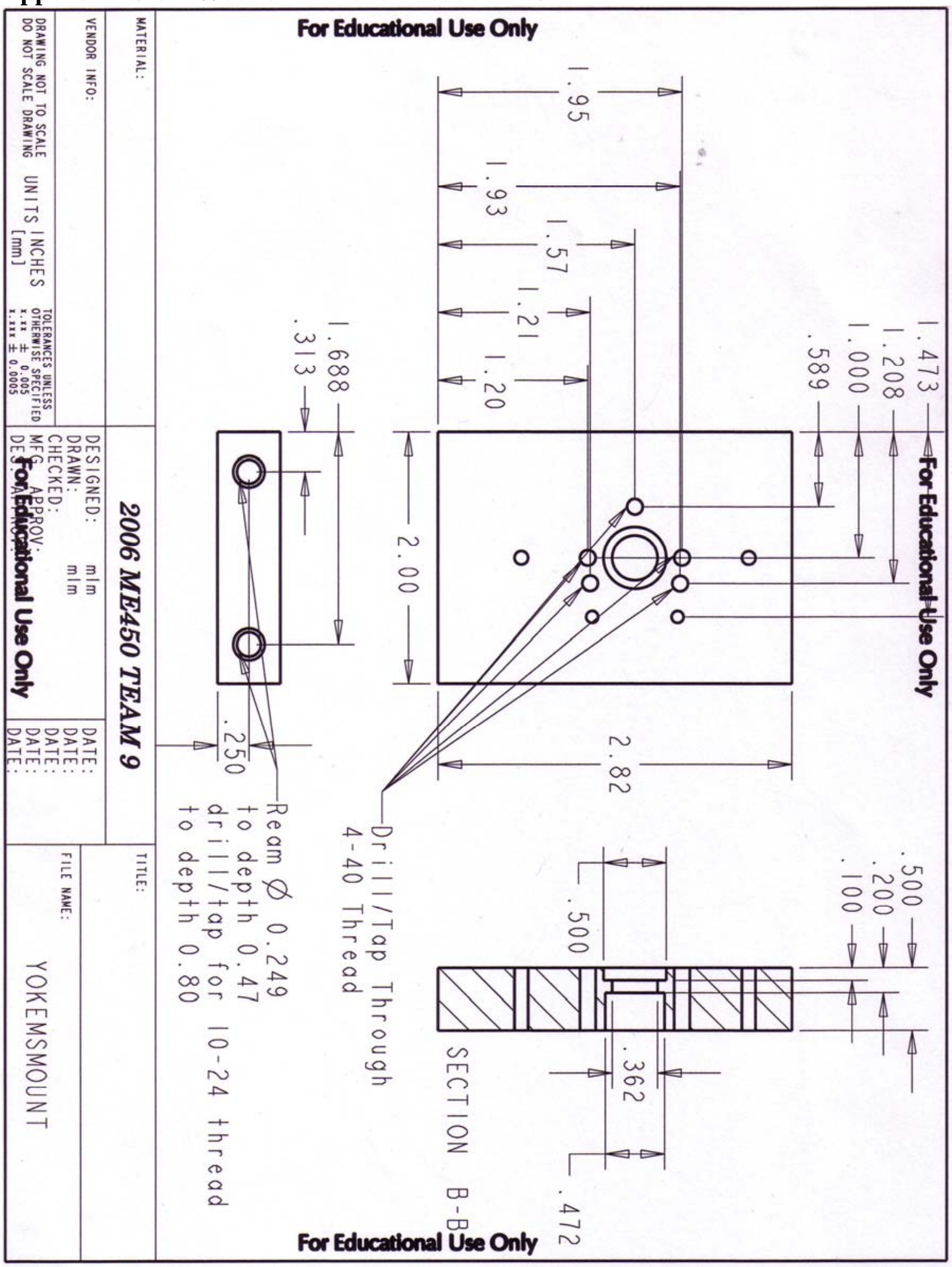
Appendix B.13 – W06P012 – Stub Shaft



Appendix B.14 – W06P013 – Yoke Arm



Appendix B.15 – W06P014 – Yoke Encoder Mount



APPENDIX C – MANUFACTURING PLANS

Appendix C.1 – W06P001 – Jig Plate

Stock: **6061 Aluminum Plate** Qty: **1**

Step	Machine	Description	Tool	Speed (RPM)	Feed (fpm)
1	CNC Mill	Face off edges to outer dimensions	End Mill	1200	2
2	CNC Mill	Center Drill for all holes	Center Drill	1000	0.5
3	CNC Mill	Drill through holes	11/32" Drill Bit	1000	0.5
4	CNC Mill	Ream through holes	3/8" Under Reamer	1000	0.5
5	CNC Mill	Drill through holes	7/32" Drill Bit	1000	0.5
6	CNC Mill	Ream through holes	1/4" Under Reamer	1000	0.5
7	CNC Mill	Mill counter bores 0.30" deep	5/8" End Mill	1200	0.35
8	N/A	Deburr all holes	Deburring Tool	N/A	N/A
9	N/A	File all edges	Flat File	N/A	N/A

Appendix C.2 – W06P002 – Barrel Side Bearing Carrier

Stock: **6061 Aluminum Billet** Qty: **1**

Step	Machine	Description	Tool	Speed (RPM)	Feed (fpm)
1	CNC Mill	Face off edges to outer dimensions	5/8" End Mill	1200	2
2	CNC Mill	Mill Center Pocket - OD 1.379"	5/8" End Mill	1200	0.5
3	CNC Mill	Mill Outer Bearing Press Fit - OD 1.6535"	5/8" End Mill	1200	0.5
4	CNC Mill	Flip over, Mill Inner Bearing Press Fit - OD 1.6535"	5/8" End Mill	1200	0.5
5	CNC Mill	Center drill for dowel pins and through holes	Center Drill	1000	0.5
6	CNC Mill	Drill through holes	1/4" Drill Bit	1000	0.5
7	CNC Mill	Drill Dowel Pin Holes - 0.30" Deep	7/32" Drill Bit	1000	0.5
8	CNC Mill	Ream Dowell Pin Holes	1/4" Reamer	1000	0.5
9	CNC Mill	Reposition, and center drill for set screw hole	Center Drill	1000	0.5
10	CNC Mill	Drill set screw hole - Through	5/16" Drill Bit	1000	0.5
11	CNC Mill	Repositon, center drill for locking screw hole	Center Drill	1000	0.5
12	CNC Mill	Drill locking screw hole - through	5/16" Drill Bit	1000	0.5
13	CNC Mill	Flip over, center drill for locking screw hole	Center Drill	1000	0.5
14	CNC Mill	Drill locking screw hole - through	5/16" Drill Bit	N/A	N/A
15	Tapping Machine	Tap all 5/16" Holes	3/8-16 Tap	N/A	N/A
16	N/A	Deburr all holes	Deburring Tool	N/A	N/A
17	N/A	File all edges	Flat File	N/A	N/a

Appendix C.3 – W06P003 – Press Fit Side Bearing Carrier

Stock: **6061 Aluminum Billet** Qty: **1**

Step	Machine	Description	Tool	Speed (RPM)	Feed (fpm)
1	CNC Mill	Face off stock to outer dimensions	5/8" End Mill	1200	2
2	CNC Mill	Mill Bearing Press Fit #1	5/8" End Mill	1200	0.5
3	CNC Mill	Flip over, Mill center pocker	5/8" End Mill	1200	0.5
4	CNC Mill	Mill Bearing Press Fit #2	5/8" End Mill	1200	0.5
5	CNC Mill	Reposition on long edge, center drill for shoulder bolt holes	Center Drill	1000	0.5
6	CNC Mill	Drill shoulder bolt holes - 0.80" Deep	F Drill Bit	1000	0.5
7	CNC Mill	Drill shoulder bolt holes 0.60" deep	11/32" Drill Bit	1000	0.5
8	CNC Mill	Ream shoulder bolt holes	3/8" Reamer	1000	0.5
9	CNC Mill	Flip over, center drill 4 corner holes and center set screw hole	Center Drill	1000	0.5
10	CNC Mill	Drill corner holes - 1.00" Deep	#7 Drill Bit	1000	0.5
11	CNC Mill	Drill center set screw hole - Through	5/16" Drll Bit	1000	0.5
12	Tapping Machine	Tap all size F holes	5/16-18 Tap	N/A	N/A
13	Tapping Machine	Tap all #7 size holes	1/4-20 Tap	N/A	N/A
14	Tapping Machine	Tap all 5/16" holes	3/18-16 Tap	N/A	N/A
15	N/A	Deburr all holes	Deburring Tool	N/A	N/A
16	N/A	File all edges	Flat File	N/A	N/A

Appendix C.4 – W06P004 – Friction Plate

Stock: **1018 Steel Plate** Qty: **1**

Step	Machine	Description	Tool	Speed (RPM)	Feed (fpm)
1	Mill	Face off all edges	5/8" End Mill	600	0.5
2	Mill	Center Drill for all holes on large face	Center Drill	500	0.25
3	Mill	Drill bottom holes	1/4" Drill Bit	500	0.25
4	Mill	Drill center hole	1" Drill Bit	500	0.2
5	Mill	Bore center hole to 1.25"	Boring Bar	600	0.25
6	Mill	Reposition, center drill for 2 top edge holes	Center Drill	500	0.2
7	Mill	Drill edge holes - 1.00" Deep	#7 Drill Bit	500	0.2
8	Tapping Machine	Tap edge holes	1/4-20 Tap	N/A	N/A
9	N/A	Deburr all holes	Deburring tool	N/A	N/A
10	N/A	File all edges	Flat File	N/A	N/A

Appendix C.5 – W06P005 – Lash Encoder Mount

Stock: **6061 Aluminum Billet** Qty: **1**

Step	Machine	Description	Tool	Speed (RPM)	Feed (fpm)
1	Mill	Face off all edges to outer dimensions	1/2" End Mill	1200	2
2	Mill	Center drill all holes	Center Drill	1000	0.5
3	Mill	Drill 4 corner holes	7/32" Drill Bit	1000	0.5
4	Mill	Ream 4 corner holes	1/4" Reamer	1000	0.5
5	Mill	Drill encoder mounting holes	#43 Drill Bit	1200	0.5
6	Mill	Mill Slot - 0.42" deep, 1.21" wide	1/2" End Mill	1200	1
	Mill	Mill through hole	1/2" End Mill	1200	0.5
7	Mill	Mill cut-outs	1/4" End Mill	1200	0.5
8	N/A	Using tap block, tap encoder mount holes	4-40 Tap	N/A	N/A
9	N/A	Deburr all holes and curved edges	Deburring Tool	N/A	N/A
10	N/A	File all flat edges	Flat File	N/A	N/A

Appendix C.6 – W06P006 – Stabilizer

Stock: **6061 Aluminum Plate** Qty: **1**

Step	Machine	Description	Tool	Speed (RPM)	Feed (fpm)
1	CNC Mill	Face off one long edge	1/2" End Mill	1200	2
2	CNC Milll	Reclamp, mill outer profile	1/2" End Mill	1200	1
3	CNC Mill	Center drill corner holes	Center Drill	1100	0.5
4	CNC Mill	Drill corner holes - Through	1/4" Drill Bit	1100	0.5
5	N/A	Deburr all holes, and curved edges	Deburring Tool	N/A	N/A
6	N/A	File all straight edges	Flat File	N/A	N/A

Appendix C.7 – W06P007 – Top Bracket

Stock: **6061 Aluminum Plate** Qty: **1**

Step	Machine	Description	Tool	Speed (RPM)	Feed (fpm)
1	CNC Mill	Face off one long edge	1/2" End Mill	1200	2
2	CNC Milll	Reclamp, mill outer profile	1/2" End Mill	1200	1
3	CNC Mill	Center drill corner holes	Center Drill	1100	0.5
4	CNC Mill	Drill corner holes - Through	7/32" Drill Bit	1100	0.5
5	CNC Mill	Ream corner holes - Through	1/4" Reamer	1100	0.5
6	CNC Mill	Reposition, center drill for clevis pin hole	Center Drll	1100	0.5
7	CNC Mill	Drill clevis pin hole - Through	3/8" Drill Bit	1100	0.5
8	N/A	Deburr all curved edges and holes	Deburring Tool	N/A	N/A
9	N/A	File all straight edges	Flat File	N/A	N/A

Appendix C.8 – W06P008 – Yoke Holder

Stock: **6061 Aluminum Plate** Qty: **2**

Step	Machine	Description	Tool	Speed (RPM)	Feed (fpm)
1	CNC Mill	Mill bottom edge	5/8" End Mill	1200	2
2	CNC Mill	Mill back edge	5/8" End Mill	1200	2
3	CNC Mill	Mill stub shaft press fit	5/8" End Mill	1200	0.5
4	CNC Mill	Reclamp, mill outer profile	5/8" End Mill	1200	0.5
5	CNC Mill	Mill guidance slot	3/8" End Mill	1200	0.5
6	CNC Mill	Reclamp, center drill for top holes	Center drill	1000	0.5
7	CNC Mill	Drill shoulder bolt holes - 0.625' deep	#25 Drill Bit	1000	0.5
8	CNC Mill	Drill shoulder bolt holes - 0.30" Deep	7/32" Drill Bit	1000	0.5
9	CNC Mill	Ream shoulder bolt holes - 0.30" Deep	1/4" Reamer	1000	0.5
10	CNC Mill	Reposition, center drill for bottom holes	Center Drill	1000	0.5
11	CNC Mill	Drill bottom hole - 0.93" Deep	F Drill Bit	1000	0.5
12	CNC Mill	Drill bottom hole - 0.60" Deep	11/32" Drill Bit	1000	0.5
13	CNC Mill	Ream bottom holes - 0.60" Deep	3/8" Reamer	1000	0.5
14	Tapping Machine	Tap top holes	10-24 Tap	N/A	N/A
15	Tapping Machine	Tap Bottom holes	5/16-18 Tap	N/A	N/A
16	N/A	Deburr all holes and curbed edges	Deburring Tool	N/A	N/A
17	N/A	File all straight edges	Flat File	N/A	N/A

Appendix C.9 – W06P009 – Adapter Shaft

Stock: **1018 Steel - 1" round** Qty: **1**

Step	Machine	Description	Tool	Speed (RPM)	Feed
1	Lathe	Face off part	Cutting Tool	250 RPM	Hand
2	Lathe	Turn to OD 0.905" - 2.2" Long	Cutting Tool	250	.005 in/s
3	Lathe	Turn to OD 0.750" - 1" from faced off end	Cutting Tool	250	.005 in/s
4	Lathe	Part off piece at 2.075"	Parting Tool	75	.003 in/s
5	Lathe	Chuck part on small OD, face off to final length	Cutting Tool	250	Hand

Appendix C.10 – Barrel Side Adapter

Stock: **1018 Steel - 2" round** Qty: **1**

Step	Machine	Description	Tool	Speed (RPM)	Feed
1	Lathe	Face off part	Cutting Tool	200	Hand
2	Lathe	Turn OD til concentric with axis	Cutting Tool	200	.005 in/s
3	Lathe	Turn 1" OD - 3.14" from faced off end	Cutting Tool	200	.005 in/s
4	Lathe	Turn 0.5" OD - 1.91" from faced off end	Cutting Tool	200	.005 in/s
5	Lathe	Turn 0.4" OD - 1.351" from faced off end	Cutting Tool	200	.005 in/s
6	Lathe	Center Drill for end hole	Center Drill	200	.005 in/s
7	Lathe	Drill end hole - 1" Deep	#7 Drill Bit	200	.005 in/s
8	Lathe	Chamfer end hole slightly	Chamfer Bit	200	Hand
9	Lathe	Tap end hole	1/4-20 Tap	N/A	N/A
10	Lathe	Use die and cut exterior threads	1/2-13 Die	N/A	N/A
11	Lathe	Cut groove in bearing surface for set screw - 0.020" Deep	Cutting Tool	N/A	N/A
12	Lathe	File all edges	Flat File	200	N/A
13	Band Saw	Cut part off of stock	N/A	N/A	95 fpm
14	Lathe	Rechuck on 1" OD, face off large face to final length	Cutting Tool	200	Hand
15	Lathe	File edge	Flat File	200	Hand
16	CNC Mill	Mill center pocket - .240" Deep	5/8" End Mill	650	.005 in/s
17	CNC Mill	Center drill bolt circle	Center Drill	650	.005 in/s
18	CNC Mill	Drill dowel pin holes - 0.162" Deep	1/8" Drill Bit	650	.005 in/s
19	CNC Mill	Ream dowel pin holes	5/32" Reamer	650	.005 in/s
20	CNC Mill	Drill remaining six holes - Through	OEM specified	650	.005 in/s
21	N/A	Tap remaing six holes, use tap block	OEM specified	N/A	N/A
22	N/A	Deburr all holes and curved edges	Deburring tool	N/A	N/A

Appendix C.11 – W06P011 – Press Fit Side Adapter

Stock: **1018 Steel - 2" round** Qty: **1**

Step	Machine	Description	Tool	Speed (RPM)	Feed
1	Lathe	Face off stock	Cutting Tool	200	Hand
2	Lathe	Center drill for live center tail stock	Center Drill	200	.005 in/s
3	Lathe	Turn 1.614" OD - 3.5" from faced off end	Cutting Tool	200	.005 in/s
4	Lathe	Turn 1.378" OD - 2.598" from faced off end	Cutting Tool	200	.005 in/s
5	Lathe	Turn 1.376" OD - 0.992" from faced off end	Cutting Tool	200	.005 in/s
6	Lathe	Turn Exterior thread	Single Point Threading	Prescribed by thread	Prescribed by thread
7	Lathe	Drill bore hole - 3.625" Deep	7/8" Drill Bit	200	Hand
8	Lathe	Bore ID to 0.9047"	Boring Bar	200	.005 in/s
9	Lathe	File edge	Flat file	200	N/A
10	Band Saw	Cut off part from stock	N/A	N/A	95 fpm
11	Lathe	Chuck on 1.378" OD, face off to final length	Cutting Tool	200	Hand
12	Lathe	File edges	Flat file	200	N/A
13	Mill	Center drill for both holes	Center Drill	200	Hand
14	Mill	Drill both holes - Through	#7 DrillBit	600	Hand
15	Tapping Machine	Put in vise, tap both holes	1/4-20 Tap	N/A	N/A
16	N/A	Sand inner surface to remove burrs	320 Grit Emrey Tape	N/A	N/A
17	N/A	Deburr holes	Deburring Tool	N/A	N/A

Appendix C.12 – W06P012 – Stub Shaft

Stock: **1018 Steel - 1.125" round** Qty: **2**

Step	Machine	Description	Tool	Speed (RPM)	Feed
1	Lathe	Face off end	Cutting Tool	400	.005 in/s
2	Lathe	Center drill for live center tail stock	Center Drill	400	.005 in/s
3	Lathe	Turn 1" OD - 4.335" from faced off end	Cutting Tool	400	.005 in/s
4	Lathe	Turn 0.75" OD - 3.96" from faced off end	Cutting Tool	400	.005 in/s
5	Lathe	Turn 0.5" OD - 2.35" from faced off end	Cutting Tool	400	.005 in/s
6	Lathe	Turn 0.394" OD - 1.5" from faced off end	Cutting Tool	400	.005 in/s
7	Lathe	Face off to final length	Cutting Tool	400	Hand
8	Lathe	File all edges	Flat File	400	N/A
9	Lathe	Part off machined part from stock	Parting Tool	75	.003 in/s
10	Lathe	Rechuck, face off end til flat	Cutting Tool	400	Hand

Appendix C.13 – W06P013 – Yoke Arm

Stock: **6061 Aluminum Plate** Qty: **2**

Step	Machine	Description	Tool	Speed (RPM)	Feed (fpm)
1	Mill	Face off all edges	5/8" End Mill	1200	2
2	Mill	Mill bushing press fit	5/8" End Mill	1200	0.5
3	Mill	Repositon, center drill for all holes	Center Drill	1000	0.5
4	Mill	Drill screw holes - 0.75" Deep	F Drill Bit	1000	0.5
5	Mill	Drill dowel pin holes - 0.5" Deep	7/32" Drill Bit	1000	0.5
6	Mill	Ream dowel pin holes - 0.5" Deep	1/4" Reamer	1000	0.5
7	Tapping Machine	Tap screw holes	5/16-18 Tap	N/A	N/A
8	N/A	Deburr all holes	Deburring Tool	N/A	N/A
9	N/A	File all edges	Flat File	N/A	N/A

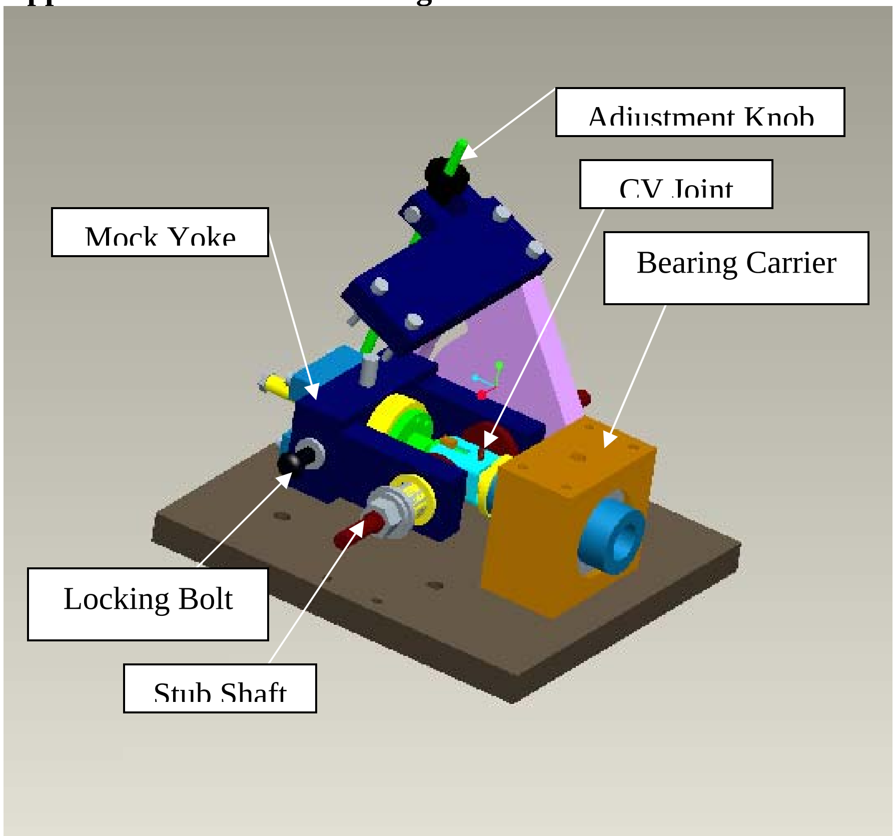
Appendix C.14 – W06P014 – Yoke Encoder Mount

Stock: **6061 Aluminum Plate** Qty: **1**

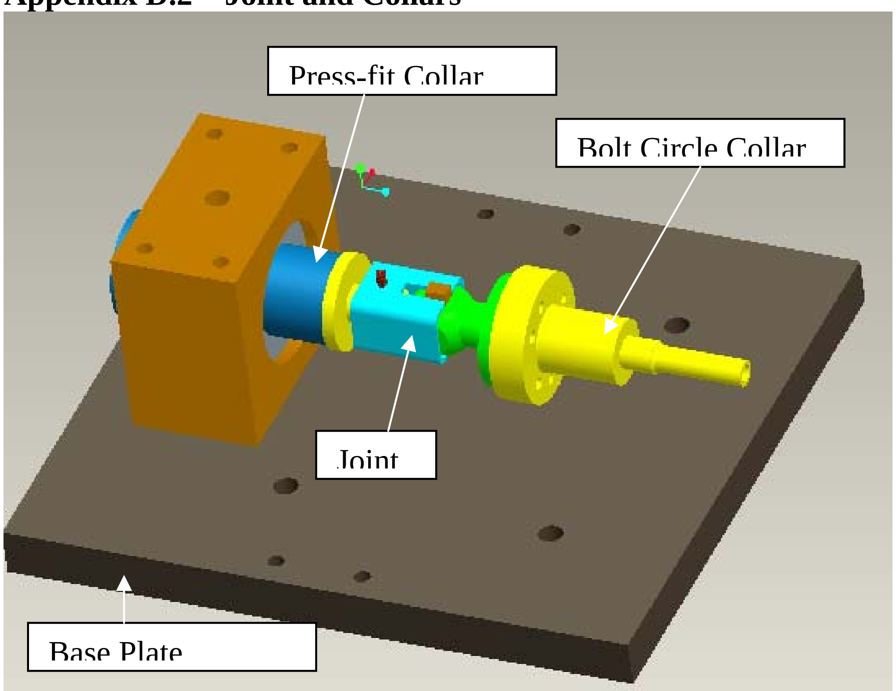
Step	Machine	Description	Tool	Speed (RPM)	Feed (fpm)
1	Mill	Face off all edges	1/2" End Mill	1200	2
2	Mill	Center drill for all holes	Center Drill	1000	0.5
3	Mill	Drill center hole - Through	11/32" Drill Bit	1000	0.5
4	Mill	Bore center hole to 0.362" ID	Boring Head	1000	0.5
5	Mill	Mill 1/2" counter bore	1/2" End Mill	1200	0.5
6	Mill	Drill encoder mounting holes	#43 Drill Bit	1000	0.5
7	Mill	Flip over, machine counter bore - 0.472" OD - 0.3" Deep	Boring Head	1000	0.5
8	Mill	Flip onto top edge, center drill for shoulder bolt holes	Center Drill	1000	0.5
9	Mill	Drill shoulder bolt holes - 0.80" Deep	#25 Drill Bit	1000	0.5
10	Mill	Drll shoulder bolt holes - 0.47" Deep	7/32" Drill Bit	1000	0.5
11	Mill	Ream shoulder bolt holes - 0.47" Deep	1/4" Reamer	1000	0.5
12	Tapping Machine	Tap shoulder bolt holes	10-24 Tap	N/A	N/A
13	N/A	Tap encoder mounting holes	4-40 Tap, Tap Block	N/A	N/A
14	N/A	Deburr all holes	Deburring Tool	N/A	N/A
15	N/A	File all straight edges	Flat File	N/A	N/A

APPENDIX D – FINAL DESIGN - CAD

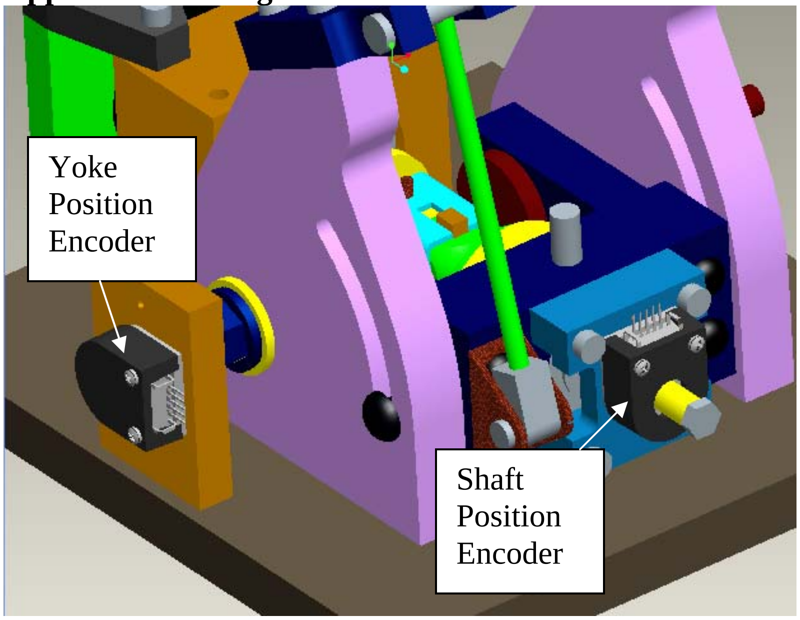
Appendix D.1 – Joint Fixturing



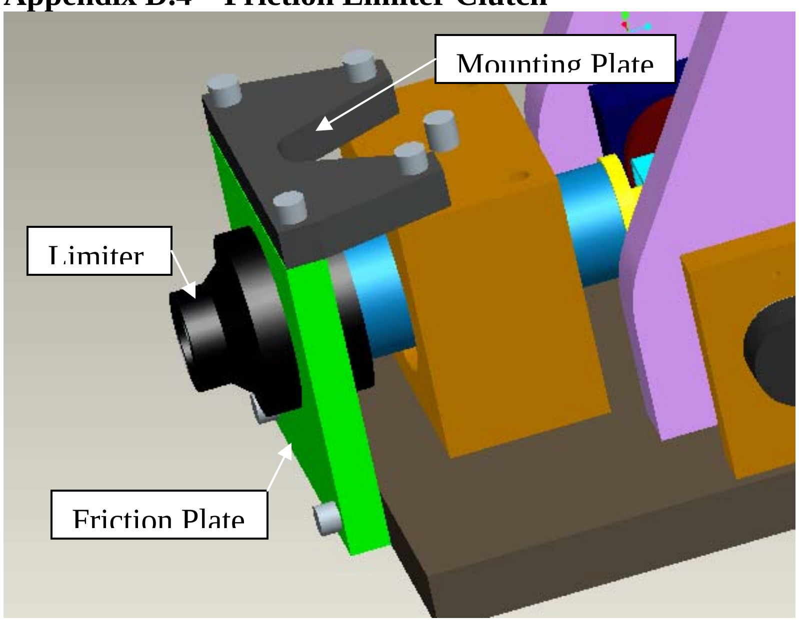
Appendix D.2 – Joint and Collars



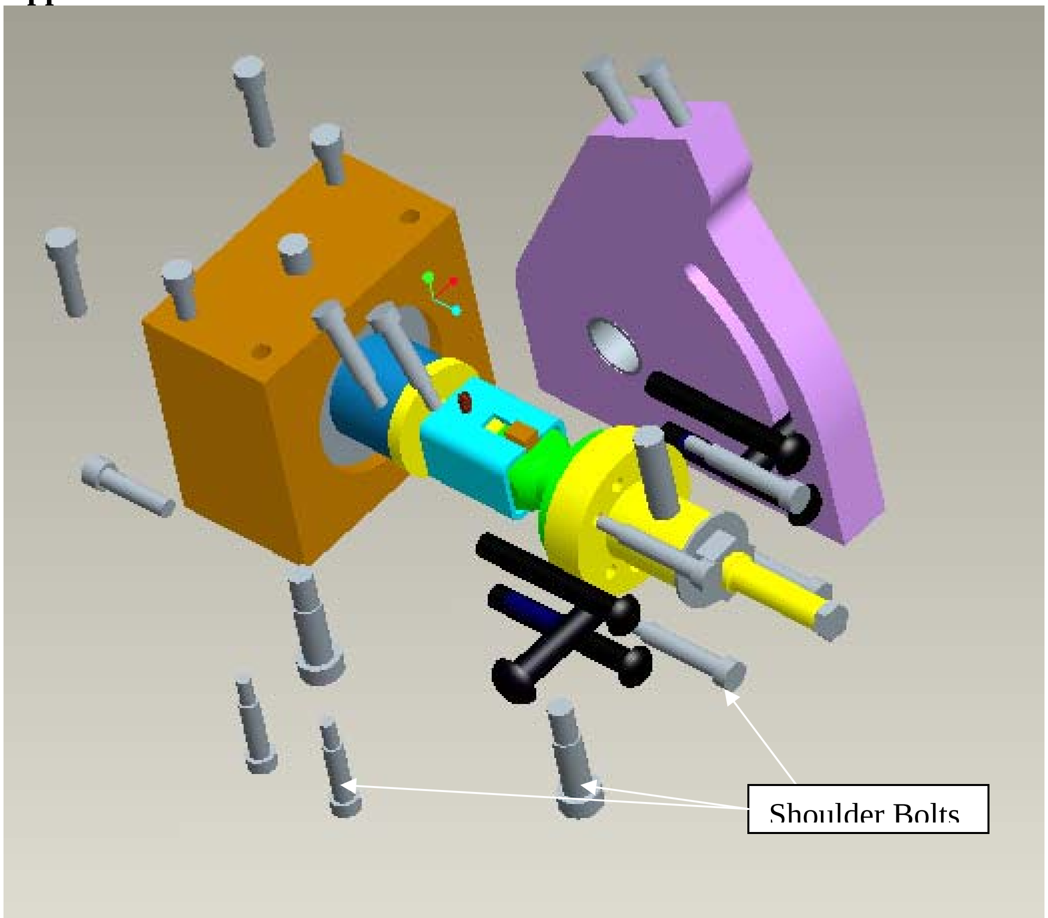
Appendix D.3 – Digital Encoders and Their Placements



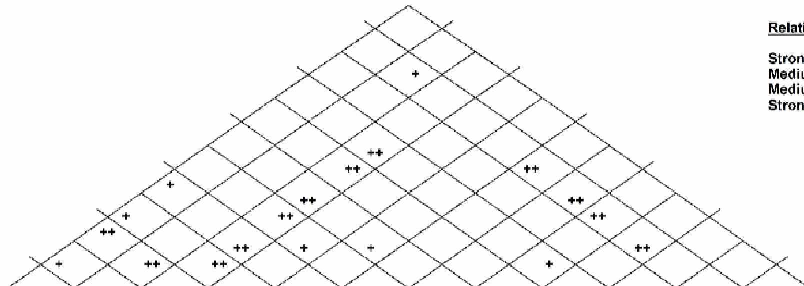
Appendix D.4 – Friction Limiter Clutch



Appendix D.5 – Fasteners



APPENDIX E – QFD MATRIX



Relationships

Strong Positive ++
Medium Positive +
Medium Negative -
Strong Negative --

Customer Attribute	Importance	Rotational friction (-)	Lash measurements accuracy (+)	Fit tolerance on engineering drawings (yes 9 / no 0)	Articulate to angles range (+)	Has continuous rotation capability (yes 9 / no 0)	Articulation measurement accuracy (+)	Joint rotation measurment accuracy (+)	Torque measurement range (+)	Torque accuracy (+)	Material weight (-)	Project hardware specificity (+)	Now
Minimize rotational friction	9	9	5						5	7			9
Accurate lash measurement	9		9	9	7								9
Align joint to tolerances	9		9	9	9		9	9	9	9		9	9
Cover articulation angle range	9		7	9	9		9	3	5	5			9
Cover full joint rotation range	9		7	9	7	9	9	5	5	7			9
Measure articulation angle	9			9	9		9					7	9
Measure joint rotation	9			9		9		9				5	9
Measure frictional torque over full range of joint rotation and articulation	9	5		9	9	9			9	5		9	9
Accurate torque measurement	9	9		9	7	9				9		9	9
Low weight	1										9	5	3
Standardized nuts and bolts	2			9								9	7
	100												
Units		in-lb	deg	yes/no	deg	yes/no	deg	deg	Nm	in-lb	lb	%	
Now													
Competitor													
Target (Plan)													
Total		207	333	729	513	324	324	234	297	378	81	477	
normalized		0.05312	0.08545	0.18707	0.13164	0.08314	0.08314	0.06005	0.07621	0.097	0.02079	0.1224	
Importance rating		7	5	1	2	2	6	6	5	4	8	3	

APPENDIX F – CONCEPT SELECTION SCORING MATRICES

Method of Joint Articulation and Support	**Category**	**Feasiblity**	**Cost**	**Ease of use**	**Ease of implentation**	**Ease of Manufacturing**	**Adaptablitity**	**Accuracy**	**Simplicity**	**Composite Score**
Concept	**Weight**	**0.2500**	**0.1250**	**0.1875**	**0.0625**	**0.0313**	**0.0313**	**0.2500**	**0.0625**	**1.00**
Bushings w/ Clamp		5	5	5	5	5	3	2	5	4.1875
Bushings w/Clamp & Knob		**5**	**4**	**4**	**4**	**4**	**3**	**5**	**4**	**4.4688**
Bearings w/ Clamp & Knob		5	3	3	4	4	3	5	4	4.1563
Bearings w/ Ball Screw Support		3	3	3	3	3	3	4	4	3.3125
Stub Shaft w/ Clamp & Ball Screw		3	4	3	3	3	3	4	3	3.375

Application of Consant Resistance for Torque Measurement	**Category**	**Feasiblity**	**Cost**	**Ease of use**	**Ease of implentation**	**Ease of Manufacturing**	**Adaptablitity**	**Accuracy**	**Simplicity**	**Composite Score**
Concept	**Weight**	**0.2500**	**0.1250**	**0.1875**	**0.0625**	**0.0313**	**0.0313**	**0.2500**	**0.0625**	**1.00**
Friction Discs		5	5	5	3	4	4	3	4	4.25
Band Brake		5	4	5	4	3	3	4	3	4.3125
Friction Limiting Clutch		**5**	**5**	**4**	**5**	**5**	**5**	**5**	**4**	**4.75**
Lifting Weight		5	5	5	4	4	2	5	5	4.8125
Electric Motor		4	2	3	4	4	2	3	2	3.125

Measurement of Lash	Category	Feasiblity	Cost	Ease of use	Ease of implentation	Ease of Manufacturing	Adaptablitity	Accuracy	Simplicity	Composite Score
Concept	**Weight**	**0.2500**	**0.1250**	**0.1875**	**0.0625**	**0.0313**	**0.0313**	**0.2500**	**0.0625**	**1.00**
Analog Potentiometer		5	2	5	4	5	3	5	3	4.375
Digital Encoder		**5**	**4**	**5**	**4**	**5**	**3**	**5**	**3**	**4.625**
Digital Protractor		3	3	5	3	5	3	5	4	4
Lever Arm w/ Gauge		2	5	5	2	3	4	3	5	3.4688
Lever Arm w/ Dial Gauge		4	5	3	4	3	4	4	4	3.9063

Measurement of Torque	Category	Feasiblity	Cost	Ease of use	Ease of implentation	Ease of Manufacturing	Adaptablitity	Accuracy	Simplicity	Composite Score
Concept	**Weight**	**0.2500**	**0.1250**	**0.1875**	**0.0625**	**0.0313**	**0.0313**	**0.2500**	**0.0625**	**1.00**
Force Transducer w/ Lever Arm		3	3	4	4	3	3	5	3	3.75
Conventional Torque Meter		4	3	5	4	5	4	5	3	4.2813
Torque Transducer		5	2	5	3	4	4	5	3	4.3125
Torque Wrench		4	4	4	5	5	5	4	5	4.1875
Digital Torque Wrench		**5**	**3**	**4**	**5**	**5**	**5**	**4**	**5**	**4.3125**