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GENERAL AVIATION MODULAR ELECTRIC TOW BAR

2019-2020 Mechanical Engineering Technology Senior Project

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Abstract

In general aviation, pilots use either a tow bar or a tug to maneuver their planes to and from its parking place. A tow bar is a lightweight human powered device that allows a pilot to push and pull his/her pane by themselves using human power. A tug is a similar device, except much bigger and heavier, and is electrically powered, allowing for an easier time maneuvering a plane. The downside to a tug is since they are bigger and heaver, they cannot be taken with a pilot on a trip. The goal of this project was to combine the best parts of both devices, making something that is electrically powered and able to maneuver a Cessna 175 on its own, but is small and light weight enough to be taken with on a trip. The device is made from a 20:1 worm gear set, powered by a 20V DeWalt cordless drill. The drill power is transferred through the gearbox to a set of 8-in pneumatic wheel that will push and pull the aircraft. All these parts are connected to a frame made of 1"x1" T Slot extrusions. The frame can be taken apart into smaller pieces to allow for storage inside a Cessna 175. This project was tested on four areas; ability of device, weight, storage, and usability. The device was successfully able to maneuver a plane on its own, as well as able to be stored in a Cessna 175. Unfortunately, the device's weight is 100 percent over target, and it takes too long to assemble and disassemble.

Keywords: Tow Bar, Tug, Airplane

Introduction

Description

In general aviation, tow bars are a necessity for every pilot and every plane. The ability for a pilot to maneuver their aircraft much easier on the ground either prior to starting the engine, or after engine shutdown, allows for a plane to be in the correct and safest position both for the plane, the pilot, people, buildings, and other objects in the vicinity of the area.

Tow bars in aviation come in two main designs. The main design is a piece of metal with an attachment side that connects to a plane, and a handle side that allows a pilot to push, pull, and turn and airplane using one's own strength. This design is nice because these designs are small and lightweight, and thus can be stored in the plane and taken with the pilot on trips. The second design is something called a tug, which is a much larger, electrically powered version of a tow bar. This design allows the user to have a much easier time maneuvering their airplane because all the work is down through a motor instead of the pilot doing all the work. However, these designs are big and heavy, and thus can't be taken with the pilot on trips, it can only be stored elsewhere and used only in that location. They are also exceptionally expensive, making them much less common in general aviation.

The goal of this project is to find a way to combine these two designs. To create a device that is light weight and can be stored in an aircraft, but still electrically powered so the pilot has a much easier time maneuvering the aircraft as well.

Motivation

This project was motivated by a passion for aviation. The Tandberg Family has been a family of aviators for the past two decades and have always wanted a fancy new tug. Unfortunately, they've never had the money for one. The tow bar their Cessna 175 is an old and bent up piece of metal that is bent up, and it could stand to be upgraded. This stood as the perfect opportunity to both design and build something that is completely new and upgrade the Tandberg family's current device for cheaper than buying a brand-new aviation tug, and be more useful to the entire family.

Function Statement

A device is needed to maneuver small aircraft on the ground.

Requirements

This device's requirements are:

- Must be able to attach/detach from a tricycle gear aircraft
- Must be powered by a drill
- Must weigh less than 15 lbs.
- Must be able to take apart and put together in 2 minutes for storage
- Must fit in the storage compartment of Cessna 175 N7154M

Engineering Merit

This project involves a large amount of engineering in many different areas. These areas include statics, dynamics, and mechanics of materials just to name a few. An engineer must be adept in these areas in order to make a product that will both work and be safe. This does not mean just knowing the formulas of these areas, but knowing how to use them in designing and analyzing the different requirements the device will have. For this project to be a successful engineering project, a RADD process will be used ensuring that the merit of this project will be accurate, and allowing for everything to be kept track of by correct analysis and documentation.

Scope of Effort

The scope of this effort is going to involve starting the entire project from scratch. This is a project that is going to involve creating a frame, a gear box, a drive train, and more. With having all these different areas of creation and analysis, it will be important for everything to be designed to fit together well. There are basic functions that are already known for a tow bar needs to work and how people are used to using one, but that will not make the effort for this project any smaller. However, since this is not a large project, the amount of effort needed will not be enough to keep the student, the only person working on the project, from finishing the device in the time allotted.

Success Criteria

The success of this project depends on how the device works. There are a few success requirements:

- The device works with drill on low power mode
- The device can maneuver an aircraft
- The device weighs less than 15 lbs.
- The device able to be put together and taken apart in less than 2 minutes

Design and Analysis

Approach / Design Description

The basic approach that is going to be taken with this project is iterative design. There are many basic requirements in this project such as needing to be powered by a cordless hand drill, size requirements, etc. For everything to work correctly, it is important to start with the most important step and work forward from there. In this project, the first step is going to be designing how the device will transfer power from the input (cordless drill) to the output (wheels). In order to keep the design simple enough to manufacture and make, a worm gear system is going to be used to connect the input and output. This will require a couple different analysis's such as speed ratios, stress, shaft size, etc. With this being the most important portion of the design, it is important that this be the first thing designed, and everything else will work around it.

The next most important question that needs to be answered is how will the worm gear system and drive train be mounted? The most obvious answer is creating a frame that holds not just the worm gear system and drive train, but allows for everything else to be connected to it. This would include the handle arm for connecting the cordless drill, and the portion of the project that will connect to the plane. These are going to be the last portion of the design process.

Once both the power system and the frame are designed, the final design process can take place. Way the connection point to the plane must not impede either the frame or the gear system, and must be able to connect and disconnect with ease. This will allow for the device to be easily stored. The handle must to the same thing. If this process as done out of order, most of the device has a large chance of not working, or even being able to be put together. It is important that all of the project, especially the design and analysis portion be planned out accordingly.

Along with this planning, a R.A.D.D. process will be used. For each step of the project, it is important to find the Requirements for what is being designed, Analyzing the requirement, Designing what will be used from the analysis's performed, and Documenting the process. This will ensure that each step is done correctly and safely, allowing for the creation of something that is safe and will work.

Benchmark

The closest device in terms of design for this project is the AircraftCaddy 4K Jr from DJProducts. The goal of this project is to create a device with similar performance that is cheaper, lighter, and able to be stored in an aircraft. The AircraftCaddy 4K Jr. is sold for approx. $2,000.00, and can push and pull a plane at 0-2 MPH. The goal is for this new device to cost much less than that Price, but have similar speed capability, and be able to push and pull that same amount of weight which is around 3,000 lbs. Below, the AircraftCaddy 4K Jr in Figure: 2a below, and the project will have a similar shape and look to it.

Figure: 2a
AircraftCaddy 4K Jr

https://www.teamcartcaddy.com/products/aircraftcaddy/item/271-aircraftcaddy-4k-jr-airplane-ug?keyword=&gclid=Cj0KCQiAn8nuBRCzARIsAJcdIfPOn3_IJlnnNBQshFfv1TwNFi2-uIyGFjien9g4uNvalcVK2gBlSHAaAgq7EALw_wcB

Performance Predictions

This device is being designed to have certain performance capabilities. The first is it is being designed to push and pull a Cessna 175 at its max weight (max fuel and baggage) at around 1 MPH. The max weight of the plane is approx. 1826 lb. It is also being designed to have a weight of less than 15 lb. It also should be able to be taken apart, and the tow bar section of the design should be able to be used by itself, in case the person is on a grass area and needs to still maneuver his/her airplane.

Description of Analysis

This project involves many different areas of engineering. Physics, dynamics, and materials are just a few examples. Because of this, it is important that every area of the project be analyzed so the minimum requirements for designing the product can be found. The first analysis that needed to be done was finding the force required to move the fully loaded Cessna 175. The analysis showed that a force of approximately 100 lb. is required to move the fully loaded plane. Once this analysis and values were found, the rest of the analyses will use the same values to ensure that the product will work as designed. These same values were used in the analysis done for gear ratios, shaft design, and tow bar design. Below, the basic outline of how R.A.D.D can be found, and how is was used to help design this project. All the analysis's required for this project can also be found in Appendix A.

Analysis (RADD)

Area of Analysis Part 1 (RADD): Basic Requirements

Requirements: This portion of the project will be the base that the rest of the project is based on. The important sections that need to be figured out include determining what speeds are wanted for the product to work at, and what forces are required to make it happen.

Analysis: The analyses for this area of the project can be found in Appendix A. Analysis 1 – Total Force Required, and Analysis 7 – Gear Ratio Required gives the basic values the rest of the project will use.

Design: While this section does not specifically detail any of the design, it is the portion of the project that will determine what the design looks like and how it is designed.

Documentation: All analysis's and drawings can be found in Appendix A and Appendix B.

Area of Analysis Part 2 (RADD): Design Specifications

Requirements: This area of analysis is the next step of the project. It involves using the values from Area 1 to find minimum design specifications such as size, material, etc. to make the project safe. Examples of this area would be finding minimum sizes for the gears, so they don't break, minimum shaft sizes to support the forces from the gears chosen, and minimum sizes of material to withstand the forces applied to them from pulling a fully loaded plane.

Analysis: All analysis's can be found in Appendix A. Each of the Analysis's, except 1 and 7, gives the specifics of this project, and allows for the choosing of products such as gears (Analysis 8), and Shafts (Analysis 12) that will meet the needs of the project.

Design: Each of these analysis's allows for the development of individual parts that will meet the specifications found in the Analysis.

Documentation: Drawings of each part, both manufactured and bought can be found in Appendix B along with Assembly Drawings showing how parts are put together to create the entire project.

The previous 2 R.A.D.D.'s is overarching areas of the entire project. R.A.D.D.'s can also be used for singular portions of the project. The following is an example of another way it was used in the development of this project.

Area of Analysis (RADD): Shaft Design

Requirements: The device requires a shaft that is strong enough to handle the forces put upon it from a worm gear system used to transfer torque from an input device (cordless drill) to an output shaft connected to 2 wheels that will be pulling the plane. The shaft must be large enough to handle the stresses involved.

Analysis: Analysis 12 in Appendix A shows how the requirement of the shaft was analyzed, and how the minimum Dia. of 0.75 inches was found. This size gives a safety factor of over 2, and will create a product that is safe and will work.

Design: Based on the Analysis, the Shaft size chosen allows the ability to choose what size of bearings and keyways are needed, and allows for the drive train shaft to be designed.

Documentation: The analysis can be found in Appendix A, as well as all drawings of each part and assembly in Appendix B. The specific drawings attached to this analysis are Figures B14, 16, 22, 23, 25, and 38.

Scope of Testing and Evaluation

Testing will consist of a few of criteria. The first one is that the device works and can maneuver a Cessna 175 within the design specifications. The second success criteria is whether it can fit within the plan in storage. The third is if the device fits within design weight specifications. The overall success can be evaluated by the final and overall performance of the Modular Electric Tow Bar. More details can be found in the Testing Methods Section of this report.

Device: Parts, Shapes, and Device Assembly

This device consists of 2 major assemblies that all connect to form the Modular Electric Tow Bar. The first is the actual tow bar itself that will be what connects to and from the plane. The second is the frame that includes the gear box, drive train, and connection points for the cordless drill and tow bar.

Most of the manufacturing for this project involves cutting multiple pieces of stock T Slot framing to specific lengths. These parts are 20-0001 – 20-0009. They are what will make up the majority of the tow bar section of the project, as well as the frame. Everything will be attached to this material in some fashion, so it is important that these be carefully measured and cut so that it will be easy to assemble all the pieces.

Parts 20-0010 is the part of the device that will attach and detach from the plane, and will be made using a milling machine. Part 20-0011 is a wheel hub that will be manufactured using a CNC. It will allow for torque to be transferred from the driven shaft directly to the wheels using a keyway. It is important to keep the holes concentric to the center to keep the rotation of the part from wobbling. Part 20-0012 and 20-0013 are both pieces of keyed shaft material that will be cut to length, with one having a machined end to allow for torque transfer from the drill directly to the shaft. The final manufactured part is the worm gear that will have a keyway broached into it.

The rest of the parts required for this project will be bought online and will not be modified. These will be parts 50-0001 – 50-0017. T slotted framing uses special brackets that allow for easy assembly, and that is most of the parts that will be bought. Assembly and part drawings can be found in Appendix B.

Tolerances

The overall Tolerance for each piece of this project is +- 0.06 inches as noted on relevant drawings. This project does not need precise dimensioning, and this Tolerance will allow for measurements to be done by a measuring tape.

Safety Factor

For this project, the goal is for nothing on the device to break in the given design use. With that, the safety factor for this project is SF=2. Nothing in the analysis portion of the project has shown any stresses being close to failure, however, devices always get used differently than how it is designed to be, so making the Safety Factor of 2 used throughout the design process will make the product safer overall.

Methods, Manufacturing, and Construction

Basic Approach

After researching information about the different designs of general aviation tow bars and tugs, the design choice became apparent. The goal of this project is to combine the best aspects of both designs, that being electrically powered, and small and light enough to fit inside a Cessna 175. The easiest way to do this is to take the same shape of the Tandberg's current tow bar and make a similarly shaped device that can attach and detach from a drill powered drive train. The drill will need to be at a comfortable height for the user and must power a worm gear system that will distribute the drills power to wheels that are attached to the frame. The frame must be small enough to fit in the plane by itself, and light enough to not overweigh the airplane, but strong enough to handle the forces being exerted on it by the plane being maneuvered. It was also decided that the frame, handle, and tow bar must be different pieces that are able to be attached and detached with ease for easier storage inside the plane, and the device is designed as such.

Methods

Throughout the design process of this project, there have been a few different methods taken into consideration on how to manufacture and build this device. Each of these ideas had merit, and allowed for even greater ideas to come forth because of them.

The first idea that came up during the design process was taking aluminum rectangular tubing, and welding them together to create a frame and tow bar strong enough to handle the forces that will be put upon it. The upside to this design is that it would be very light weight and strong at the joints. This would also not require any brackets to be either purchased or manufactured, and would keep any manufacturing of the aluminum to a minimum for attachment points to and from the frame. The downside to this however is that the amount of welding, especially for someone who does not have any welding experience at all, would be a huge undertaking to learn the basics of. This would also run into the risk of making welds that are not correct or strong enough. Because of this, price would go up, and it would be very slow. This idea was set aside for creating a better version of this product later down the road.

The second idea was manufacturing everything that would be included in the product. That would include manufacturing fastener holes and brackets out of aluminum and the aluminum tubing. This would allow for greater control of where everything would be and help create an even small design. The downside to this was that manufacturing every piece would take a considerable amount of time. Making each bracket and framing piece to spec, and from scratch, would take a lot of time away from the build schedule, where many problems tend to arise. This idea would still allow for a lightweight product that was strong, but it was the time consideration that showed that it was not conceivable. However, it did point down the correct path.

The idea/method that was decided upon came after discarding the previous idea. In order to keep the easiness of building that the previous idea had, but cut down heavily on the manufacturing time therefore saving money, it was decided to use 1"x1" T Slot framing extrusion. Mr. Tandberg has experience in using this material from his high school FIRST Robotics team. It is light weight, and the only manufacturing involved will be using cutting the pieces to length. Fastening together this material is easy because it is built directly into the design. A special nut fits into the grooves of the material, and allows brackets to be fastened to it very easily. The material is also not expensive, and overall, the cost of the project will be only a small amount more than the previous idea, but will save time in both the manufacturing portion of the project, as well as in the building of this project.

Frame Construction:

The frame of this project is the backbone of the device. It is where the gearbox, drive train, handle, and tow bar will all be attached too. Because of this, the frame must be strong enough to handle all of the forces that it will be subjected to. Therefore, the entire frame will be made out of 1”x1” T Slot Framing Extrusion, and will be bracketed together using different kinds of brackets bought from online. The gear box will be made using a worm and worm gear system, and will be attached to the frame using more of the framing material, bearings, and keyed shafts. The worm will be set at a 45-degree angle to the worm gear, and will allow for a drill to give power from an appropriate location in regard to the plane and handle. This design of the gear box also will be strong and keep the forces from the gear box as low as possible. Manufacturing and building this frame will be easy as the only manufacturing part of this is cutting the frame pieces to length.

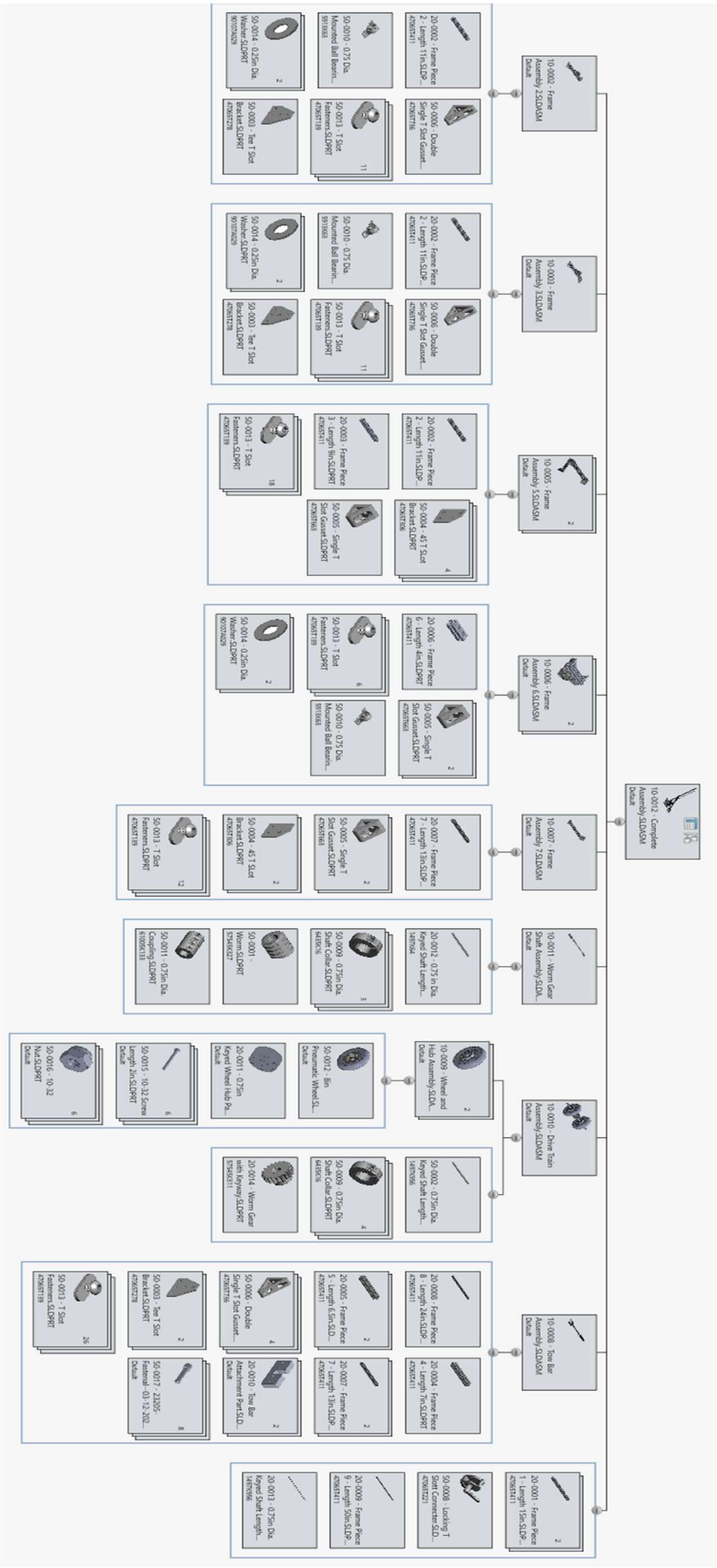
Tow Bar Construction:

The tow bar portion of this project will be similar to the construction of the frame. It will be made with 1”x1” T Slot Framing Extrusion, and be bracketed together with brackets bought online. The only manufacturing involved in this part of the project will be cutting the framing down to the correct lengths, and developing a strong attachment point for the tow bar to connect to the aircraft.

Complete Construction:

In order to build this project, the frame and tow bar must fit together easily to also ensure an easy separation. The use of T Slot Framing allows for products to be bought that will allow for an easy connection of the two assemblies, and disconnection. The connection products are light weight and will allow keeping unneeded weight off the product. The Drawing Tree for this project can be found on the next page, as well as in the Appendix portion of this report.

Drawing Tree Diagram



Parts List and Budget:

The budget and parts list of this project is an important consideration. The Budget for this project is $1000.00. Most of the budget for this project comes from the many different brackets that are necessary for building the device, along with the few raw materials such as the aluminum bar needed for the attachment point, and the 1”x1” T Slot Framing Extrusion. The budget of this project can be found in Appendix C of this report, as well as a parts list in Appendix D. The part lists come from available materials from the budget and allows the student to create the different parts of the frame and other portions of the project. It can also be seen where each part comes into play in the Drawing tree.

Possible Manufacture Issues:

There are a couple manufacturing issues that can come up during this project. The first is making sure that when parts are cut, nothing is wasted. If a part is cut wrong, or a mistake is made during the manufacturing phase, more budget money will need to be allocated, and this project is already expensive as it is. The project is being funded by the Tandberg family, and asking for more money from them because of a mistake would be unfortunate. Along with the manufacturing issues are the risks of hurting oneself from manufacturing machines such as either saws or drills must also be taken into consideration. Proper use of these machines must be used to keep accidents from happening.

T Slot Manufacturing Discussion:

The actual manufacturing of the T Slot framing has gone easier than anticipated. The use of an electric band saw made the cutting of multiple pieces of raw material into many different length parts much easier and faster than expected. The entirety of framing required for the frame assembly was cut in less than half an hour. The expected way of cutting this material was one by one using a miter saw, measuring and cutting using a tape measure and a sharpie. In reality, a special band saw allowed for multiple pieces to be cut at the same time, and allowed for an easier time measuring the lengths. The only thing not expected during the cutting was the need to finish some of the cuts with a file as sharp edges were found on the parts, and were able to create minor cuts on a person’s hand. This was handled easily, but took some time with the amount of pieces that were cut.

Tow Bar Attachment Manufacturing Discussion:

Overall, the manufacturing of the tow bar attachment point went as expected, other than taking a little longer than planned. Using the milling machine, the holes required for the part were able to be accuracy milled with no issues. The center cutout was easy to mill as well. By making multiple passes each at a larger depth, the finish on the cutout can be fine as well as the accuracy. Doing this also keeps the milling tool from getting hot and failing.

The only issue that came up was a mistake in the measuring before drilling 2 holes. This mistake however does not affect the ability of the part to work. The parts came out very well overall.

Wheel Hub Manufacturing:

The wheel hub was a part that had some problems with knowing how to get the part made. Because this part requires much more accuracy than the rest of the parts, because the holes need to line up with the holes on the Pneumatic Wheels, an accurate method of manufacturing was needed. At first, it was going to be milled using a milling machine, but none of the methods thought up during this time were going to be accurate enough to create the part. Because of this, Dustin Braun was reached out to because of his knowledge with advanced machining practices, specifically in with the CNC, and he was happy to lend his help to get this part manufactured properly. He helped set up a program in the CNC machine that would allow for an accurate part to be made. One the right, a picture of the process can be seen.

Worm Gear / Wheel Hub Keyway Manufacturing Discussion:

To create the needed keyways that allow for torque to be transferred from input to output, a keyway was needed to be manufactured in both wheel hubs and worm gear. This was done using a broach and hand press. This process went very smoothly with no issues.

Device Construction Discussion:

Overall, the construction of this device has gone smoothly. Using the .06” tolerance allowed for easy manufacturing, and that easiness has carried over to the construction. The parts have been easy to put together, and there have not been many snags along the way. The few things that have caused some trouble is the fasteners that come with the brackets and were not able to be modelled in the Solidworks files. This in turn, didn’t allow knowledge on where some of the fasteners would stick out and get in the way of putting sub-assemblies together. Luckily, an easy work around was found in grinding down the metal sticking out. This would not take away from the strength of the material, and allow for the assemblies to be put together completely.

Another problem that arose was that fastening the mounted ball bearings to the proper locations would require some more thought. It was believed that there would be extra fasteners in all the kits that the student received, and that they would fit right, and secure the bearings well. Unfortunately, the heads of the fasteners were not big enough to hold the bearings down, they slid through the openings. To fix this problem, washers were used. This allowed for the fasteners already in stock to be used, and not have to use more of the budget.

Here are a few pictures of the Construction phase of the project. See the next page.

DAKE
ARBOR
PRESS

Testing Method

Introduction (What will be tested)

The tow bar will be tested in two main areas. The first will be the size and weight of the device. It must be able to be taken apart and fit inside of the Tandberg families Cessna 175. It must also weigh less than 20 pounds. The second area of testing will be its usefulness. Does the device work as intended? Is the device capable of push and pulling the aircraft? Is the device easy to use? Is it easy to take apart and put back together? If these areas of testing are passed, the project will be a success and does not require more redesign.

Method/Approach (How will the testing be conducted?)

In order to test these two areas, how the device will be tested must be decided upon. For the first area, the device will be weighed to determine if it fits in the weight restriction. After this is done, it will be taken apart and stored in the plane to see if it fits the size restriction.

The second area of testing will involve using the device to maneuver the Tandberg's plane around. Pushing, pulling, turning, etc. This will be both using the tow bar portion with the drive train, and without, as the device is intended to be used separately from the drive train when the time calls for it. Below is the general timeline of the testing required for this project.

The following is the method of testing for the size and weight restrictions:

- Weighing of the device.
- Storing the device in the plane.

The following is the method of testing that will be used for this device will be a practical use test. For the tow bar portion of the test, the testing will include the following:

- Pushing and Pulling of the airplane through the power of the device alone and calculating max velocity. Goal is 0.5 m/s, or approximately 1mph.

The following is the method of testing for the practicality of the device's use portion of the test.

- It can be taken apart and stored in less than 2 minutes.

Testing Expected Results

The expected results are that every test should be successful. Much of the design and analysis is over engineered in certain ways to make sure of this. The goal is for the Tandberg Family to be able to use this device as soon as it is done, and the way that everything has been designed should allow for that to be a reality.

Testing Results

The results of the testing are split. In the first test. overall, the device works as expected. It can push and pull the plane at a comfortable walking speed. However, the speed does not quite match the design requirement/goal. In the two tests the results were;

Pushing: 0.285 m/s

Pulling: 0.415 m/s.

As can be seen, the results are below the goal of 0.5m/s. However, during actual testing, the speeds were found to be quite nice on the user and allowed for an easier time seeing what was behind the plane being pushed. So, while the device was not as fast as the goal set in the beginning of the project, still did 2 things. First, it was able to successfully push and pull a plane with only the power of a drill. And Second, was able to push and pull the plane at a comfortable walking speed. Overall, this test is a success.

In the second test, the size of the device was tested. For this test, the device was taken apart into its storage size, and attempted to be place into the plane's storage area. With the device taken apart, it was able to easily fit into the plane's storage area with not size issues.

Going along with the devices size, the weight of the device was of importance as well. For this test, the device was placed on a scale and weighted. The goal for this project was to have the device weight less than 15 pounds. Unfortunately, due to some design choices, many parts brought the weight much higher than expected. Overall, the weight of the device is 31.5 lbs. Much too heavy for normal everyday use. However, this device has gone though many different versions of its design, and just from the testing, many ideas have been brought up to take much of the excess weight away making it much closer to the original goal. In future iterations of this project, these ideas will be explored.

The final test that was performed was the practicality test, where the user was timed taking the device apart, and putting the device together. This is important because when the device is together, it is much to big and be stored in the plane. The user much be able to get all the parts out of the plane should be able to put it together in less than 2 minutes. During the testing, it was found the device's design was not as practical being taken apart and put together as it seemed when the parts were chosen. In the testing, the time taken to take the device apart was 4 minutes and 41 seconds. Along with that high time, it was found to be much easier taking the device apart than putting it back together. The time it took to put the device together was 9 minutes and 18 seconds.

Overall, these test results show a device that works as designed. It is able to push and pull a plane by its own power, and is able to fit in the plane. It just is much more difficult to put together and take apart than was originally expected, and the device is very heavy overall. In future designs, these 2 areas must be addressed.

Testing Issues

There were a few issues that came up during the testing of this project. Many of which came from the device. Many areas of the device were found to be weak at the forces being applied by the device. Because brackets were being used to attach every part together, if a bracket was not strong enough to hold the forces, the parts would bend out of place. This was found mostly on the actual tow bar portion. Because of this, more parts needed to be bought to strengthen this portion of the device. Once the parts were bought and assembled, the device worked much better.

Another issue that came up was the gear box grinding. This was taken apart and put back together many times trying to find where the problem was hiding, and whether the gears were meshing correctly. Finally, it was found that a shaft coupling was grinding on one of the bearings, and once that was taken off, the whole device worked much smoother and normally.

The final issue that was found was the connection point of the device to the plane was not fitting correctly. On the nose wheel of the plane, there is a screw that sticks out about an inch behind the attachment point. Because of this, the tow bar attachment point parts needed to be modified to be shorter on one end. Once these parts were modified, they fit perfectly on the attachment point and worked normally.

Budget

Part suppliers, substantive costs and sequence or buying issues

The majority of parts for this project are going to be bought from McMaster-Carr, Amazon, Andy Mark, and Fastenal. The availability of parts from these websites, stores, and the speed of shipping, make them the best options for parts and raw materials for this project. These websites also go into detail about all the specifications of each part and raw material, making it easy to make sure the right parts are being bought and shipped. They also allow for download of 3D models used to create the assembly drawings in Appendix B. This made creating the drawings especially easy for all the different brackets needed for the frame of this project which only needed to be downloaded. McMaster-Carr was the main website used because of its easy access to all needed parts, and the speed of its delivery. The other websites were used for access to parts not available on McMaster-Carr.

The sequence of buying for this project was getting the frame parts first, then raw materials for other manufacturing, then buying wheels and shafts. This makes it easy to change things if problems arise during the build and makes it so that money isn't wasted because a problem wasn't known, and the parts were already bought.

There have been a couple buying issues in this project. It was thought that the parts would come with enough fasteners that extra ones not used would be enough for the entire project. This turned out to be false and more needed to be bought. This was a small price to pay, but was something that was unforeseen. Another problem was when attempting to buy T Slot framing the first time from McMaster-Carr, the shipping costs were astronomical, which is why it was decided to use Amazon for their free shipping.

Outsourcing rates and estimate cost

There are no outsourcing labor costs for this project. All labor will be done either in house or at Central Washington University.

Labor

At the beginning of the project, when most of the processes were planned out, it was believed that all labor for this project was going to be done by the student. Since most of the labor for this project is going to be done with basic machining processes, it is going to be done mostly either at the Tandberg's workshop or in the Machine Shop at Central Washington University. This ended up being true for all parts except one.

The wheel hubs ended up being outsourced to have help getting the accuracy involved. While normally outsourcing involves price, the person reached out to for this process did not require for any funds to get this done. A special thanks to Dustin Braun for this.

Estimate total project cost

The total estimated project cost for this project is $1250.00. The budget can be found in Appendix C, and it breaks down all the raw materials and parts that the project will require. All the raw materials that need to be processed into workable parts can be seen in Appendix B, and part lists of each sub assembly in Appendix D.

Funding sources

The funding for this project is being paid out of pocket by the Tandberg Family. They have been wanting a new tow bar for their Cessna 175 for years as their current one is old and falling apart. They are happy for the opportunity for a new tow bar. Since aircraft tugs in general aviation are very expensive, it is a great opportunity both for their son in his senior project to create something new, but also for the entire family of pilots to be able to get a new Aircraft Tug for a significantly cheaper price than if it was to be bought regularly online.

Budget Discussion

Overall the budget for this project has stayed on track. After the Re-design as seen in the Schedule / Gantt Chart, there was a large budget need increase, however this is cancelled out in the ease of manufacturing and building. There have also been more Analysis's done and that has changed some of the required parts, mostly needing to get bigger parts instead of smaller, which usually requires more money to buy instead of the smaller parts. From the original design to the finalized design, the budget increased from $850.00 to $1250.00, which is an increase of $400.00.

The only thing that was not taken into consideration during the design portion of this project was that shipping costs and tax costs exist. This has been a surprisingly large amount that was the student did not realize would be there. So, the actual price spent to get all the parts has been about an extra 10% increase on the subtotal of $1250.00. Luckily, the after talking to the Tandberg Family, they were expecting something like this to happen as the project is tough, and they want a product that will work, so the extra funding will not be a problem.

There have been many edits to the project in order to save money with the new design, such as taking out unneeded brackets, or searching the internet for different products or cheaper versions. Unfortunately, this hasn't produced the results that the student was hoping for, but some of the original budget has been reduced. The goal in future versions of this project is to come up with an even cheaper, and better solution.

The final amount spent over this entire process is $1280.00. That is $30 dollars over budget, and this comes from a couple sources. Mainly from having to get more fastener than what was originally thought would be needed. Also, from shipping prices being higher than expected. Overall however, the budget for this project has remained on track while still being very high. Hopefully in future iterations the budget can be significantly cut so that manufacturing costs will be lower.

The testing portion of this project has no cost associated with it, as all the testing materials were supplied for free from the Tandberg Family. Their aircraft, hangar, and workshop were all in the same location, making it an easy decision to do all the testing there. All of the testing was also done for free, as all tools for assembly, disassembly, storage, etc. were all located in the workshop.

If someone was to do this on their own, and not have access to the student's family resources, they would need to find access to a small tricycle gear aircraft of some sort. This could be done by going to a local small airport and seeing if they would allow access to one of their planes. This would also probably give access to an open large area for testing the speed of the device. Also, some cost might come from the need to be able to test the assembling and disassembling of the device. However, if the device is already built, chances are access to the tools required is already available. This would be the only cost associated with testing the device if the resources were not already available.

Schedule

Gantt Chart Outline

The schedule for this project has been organized using an Excel Spread Sheet. This can be found in Appendix E. This project schedule is divided into three sections. Fall quarter includes “Design and Analysis”. Winter Quarter includes “Methods, Manufacturing, and Construction”. And Spring quarter includes “Testing”. During the fall, the proposal of this project was created. This Report is the embodiment of the entire project from start to finish including changes, modifications, manufacturing, construction, and testing.

The Gantt Chart outlines the entire schedule from start to finish and allows for documentation on the time spent on the scheduled activities. This could mean something could have taken longer or shorter, and that time can be kept track of. There are a few things that could go over time. While the student is confident in his machining skills, the amount of parts that need to be made could become an issue. Another issue is how long it could take for raw materials to be delivered to the student. Another thing that could take longer than what the schedule allots for is the amount of time it is going to take for the device to be assembled. The student has a lot of FIRST Robotics experience and fastening things together should not take longer than what is allotted on the schedule. There could also be a lot of documentation changes during the construction phase of this project because things might not work as originally planned in the beginning of the project.

Milestones

There are a few milestones for this project. The first milestone is to have a completed proposal for this project finished and submitted for approval by the end of CWU’s Fall 2019 quarter (December 5th, 2019). The second milestone is to have a completed project construction and working device by the end of CWU’s Winter Quarter. The final milestone for this project is to complete and present a presentation on the device engineered by end of CWU’s Spring Quarter. If all these milestones are hit successfully, the project will stay on track.

Proposal Discussion

During the fall quarter 2019 at CWU, the proposal of this project was created. The entire project was planned out along with part drawings, assembly drawings, schedule, budget, etc. This part of the schedule remained on track during the entire portion of the fall quarter.

Project Modification Schedule Discussion

This portion of the schedule is what set the student behind the most. The entire project modifications and changes took much longer than the student expected, and because of winter break, was started much later than expected as well. Because of this, the manufacturing and construction portion of the schedule was started late, and will cause a big time crunch near the end of Winter quarter 2020 at CWU.

Manufacturing/Construction Schedule Discussion

Other than starting late because of the project modification portion of the project, the amount of time being spent is on each portion of the project has been accurate, if not ahead of schedule.

Overall Schedule Discussion:

This second section of this project has been behind schedule since the beginning of the Winter 2020 quarter. The project modifications to make everything easier to manufacture and save time, while successful, ended up with the entire project being behind schedule for the entire quarter. It also created a time crunch near the end when everything became due. However, the modifications were a success in that it saved so much difficulty with manufacturing the project. T slot framing made assembly very easy once the order of construction was figured out. It also made it so a smaller amount of parts needed to be manufactured and could be bought instead. It added on price, but overall made everything much easier.

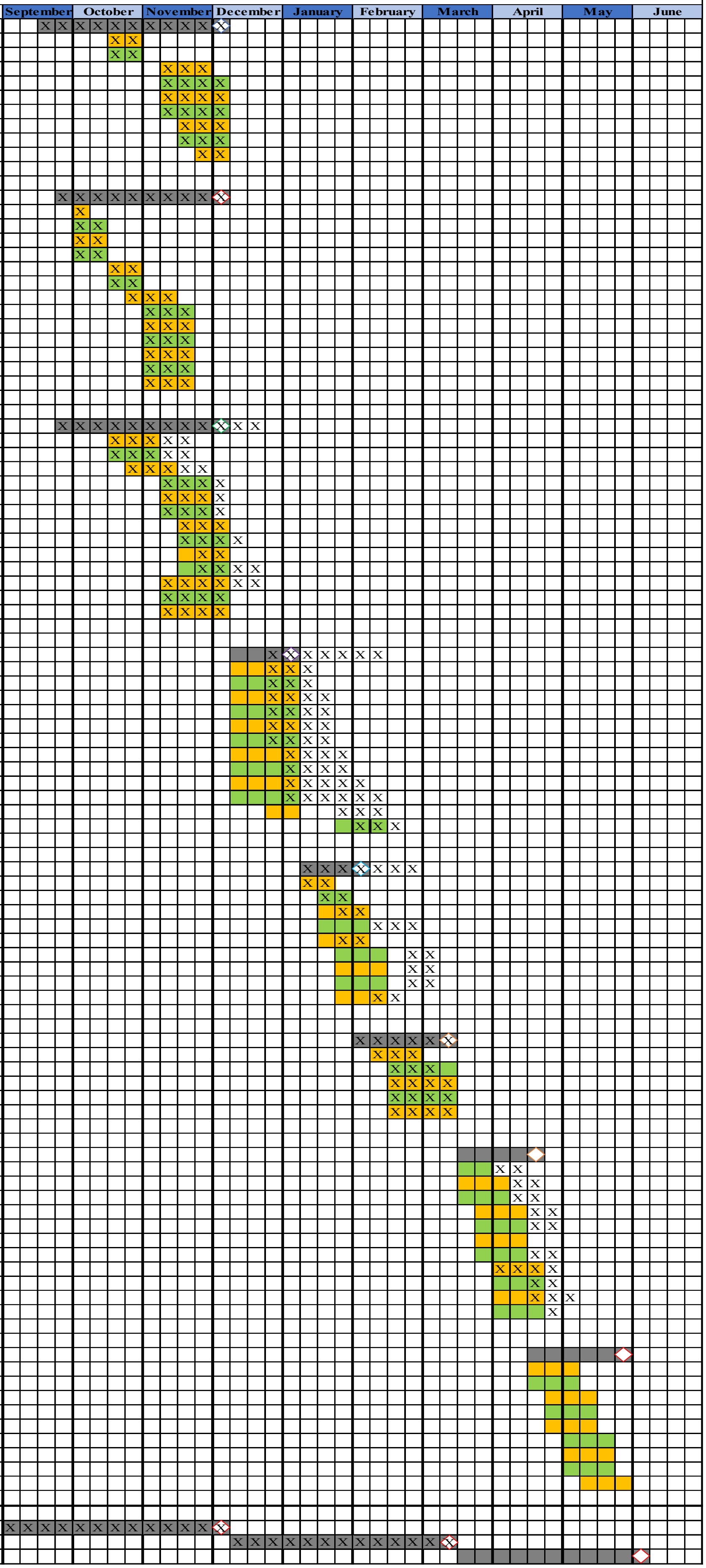
Testing Schedule Discussion:

The beginning of the quarter started a week behind because of Covid-19. Because of this, the entire portion of the schedule started a week behind. Other than that, the amount of time required for everything was either spot on the expected, or slightly above. When obtaining resources for the testing of the project, time needed to be scheduled with the Tandberg family in their hangar, and access to their Cessna 175. Once this was scheduled, all of the resources were obtained. The entire testing of the project, once the scheduled day arrived, the testing went smoothly and on schedule. A few modifications to the device were needed, and they were found because of the testing. Once these were resolved (these issues were mainly gears/bearings rubbing too much, not allowing the device to spin), the testing became much more successful. These weren't huge time consumers during the testing, and issues like these were planned into the amount of testing time.

Once the testing was finished, the testing report was started. It was believed that writing the testing report would not take a lot of time, however, it ended up taking much longer than expected. However, getting it done correctly was important. It allowed for all the results to be shown clearly, and a discussion about them much more detailed.

Project: Modular Electric General Aviation Tow Bar
Project Lead: Devon Tandberg
Schedule/Gantt Chart

TASK ID:	Description:	Est.	Actual:	% Comp.
1	**Proposal**			
a	Outline	2	2	
b	Intro	2	2	
c	Methods	2	2	
d	Analysis	2	2	
e	Discussion	2	2	
f	Parts and Budget	2	2	
g	Drawings	2	2	
h	Schedule	2	2	
i	Summary and Appendix	2	2	
	Subtotal:	18	18	
2	**Analysis**			
a	Force Required To Move Plane	1	1	
b	Tow Bar Minimum Area Req'd.	2	2	
c	Tow Bar Main Stress	2	2	
d	Tow Bar Internal Stress	2	2	
e	RPM of wheel	2	2	
f	Needed Gear Ratio	1	1	
g	Gear Analysis	3	3	
h	Base Frame Size Sketch	3	3	
i	Gear Box Sketch	3	3	
j	Tow Bar Attachment Sketch	3	3	
k	Handle Arm Bending Stress	3	3	
l	Tow Bar Arm Length	1	1	
m	Drill Power Axle Stress	2	2	
	Subtotal:	28	28	
3	**Documentation**			
a	Tow Bar 3D Models	5	8	
b	Frame Base 3D Models	6	9	
c	Handle 3D Models	3	6	
d	Tow Bar Drawings	5	6	
e	Frame Base Drawings	7	8	
f	Handle Drawings	4	5	
g	Tow Bar Assembly Drawing	4	4	
h	Frame Assembly Drawing	5	6	
i	Handle Assembly Drawing	4	4	
j	Complete Assembly Drawing	2	2	
k	Parts List	5	7	
l	Budget	3	5	
m	Schedule/Gantt Chart	5	5	
	Subtotal:	58	75	
4	**Project Modifications**			
a	Re-Do Analysis for Re Design	5	5	
b	Frame Re-Design	5	10	
c	Tow Bar-Redesign	5	10	
d	Handle Re-Design	5	8	
e	Re-Do Part Drawings	6	10	
f	Re-Do Assembly Drawings	4	10	
g	Re-Do Part Lists	4	8	
h	Re-Do Budget	4	6	
i	Re-Make Schedule Gantt Chart	4	5	
j	Re-Write Proposal/Report	6	6	
k	Update Website	3	3	
l	Redesign Wheel Attachment	4	4	
	Subtotal:	55	85	
5	**Manufacturing**			
a	Buy Raw Material T Slott Framing	1	1	
b	Cut All T Slott Framing to Length	2	2	
c	Buy Raw Aluminum Bar	1	1	
d	Manufacturing Tow Bar Attatchment	3	4	
e	Buy All Other Needed Bought Materials	2	2	
f	Manufacture Wheel Hub	3	3	
g	Broach Keyways	1	1	
h	Cut Shaft Lengths	1	1	
i	Update Report	4	5	
	Subtotal:	18	20	
6	**Construction**			
a	Assemble Tow Bar	3	3	
b	Assemble Frame	5	9	
c	Assemble Handle	2	2	
d	Assemble Complete Device	3	3	
e	Update Report	6	9	
	Subtotal:	19	26	
7	**Device Evaluation**			
a	Report Abstract	3	3	
b	List Parameters	4	4	
c	Design Test and Scope	4	4	
d	Obtain Resources	2	2	
e	Make Test Sheets	2	3	
f	Plan Analysis	4	5	
g	Instrument Robot	4	0	
h	Test Plan	5	7	
i	Perform Evaluation	5	8	
j	Test ing Report	6	9	
k	Update Website	4		
	Subtotal:	43	45	
8	**495 Deliverables**			
a	Get Report Guide	4		
b	Make Rep Outline	4		
c	Write Report	4		
d	Make Slide Outline	4		
e	Create Presentation	4		
f	Make CD Deliv. List	4		
g	Write 495 CD Parts	4		
h	Update Webside	4		
i	Project CD	4		
	Subtotal:	36		
	Project Milestones			
	Milestone 1 - Complete Proposal	104	121	
	Milestone 2 - Complete Device Construction	92	131	
	Milestone 3 - Present Completed Project	79	45	



Project Management

Human Recourses

- CWU Dr. Craig Johnson: Provided guidance throughout the design phase of this project
- CWU Charles Pringle- Provided guidance throughout the design phase of this project.
- CWU Jeunghwan Choi – Provided guidance throughout the design phase of this project.
- CWU Tedman Bramble – Will provide access to the Hogue Machine Shop.
- Dustin Braun – Helped with his abilities with the CNC creating the Wheel Hub.

Physical Resources

- CWU Hogue Machine Shop
- Tandberg Family Workshop
- Tandberg Family Cessna 175 N7154M
- CWU Hogue Materials Lab
- CWU Hogue CAD Lab

Soft Resources

- Dassault Systems Solidworks
- Microsoft Excel
- Microsoft Word

Financial Resources

The tow bar project is being funded by the Tandberg family. The project has no external funding as of this time.

Discussion

Design Evolution

This project has gone through a few different iterations over the past “fall quarter”. At the beginning of the process, the goal of the project was to not have any power device, and for the tow bar to be a new manual towing device. After a few days of designing, it was determined that this was not going to be very efficient to go this route, as it would only be a more expensive device on par with a normal general aviation tow bar. Because of this, it was decided that a tow bar should be designed in a way that only a cordless drill is required to power the device. Another initial goal of this project was to lift the nose wheel. Again, after some design and thought, it was decided that this was unnecessary as the nose wheel is what is going to be used to steer the plane on the ground. It was also decided that the tow bar should be designed in a way that it could be used in conjunction with the wheel frame and handle, as well as on its own as planes sometimes land on soft field airports like grass, dirt, etc. This allows the device to be used in many ways and opens its usefulness up more than the original design.

The final design iteration that has been developed was due to the amount of time that would have been required to manufacture all the parts in the original design. In the original design, almost every single part was going to be either manufactured from raw materials or edited in some form. This would have taken many more hours than what was available. Because of that, the project was redesigned so that ease of manufacturing and construction would cut as much time as possible away from the project. This was done by using a material called T-Slot Framing extrusion. This product uses special brackets and fasteners that allow for multiple pieces of the frame to be bracketed together without having to mill or drill holes. The only manufacturing required of the raw material is to cut the pieces to the required frame lengths. Making this design change also made it so that frame brackets could be bought instead of made, again cutting the required manufacturing time down.

This change cut most of the required time away from the project schedule, however it added cost. The original design had a budget of approximately $850.00. This final design has a budget of approximately $1250.00. While the price increase is not ideal, buying many more premade parts gives much more confidence in the final product. The original design has the risk of making parts wrong and wasting material. This would have then caused the required time for manufacturing to rise, and possible not being able to finish the project in general. With this new design, buying parts from trusted companies such as AndyMark and McMaster-Carr, it is known the quality of the parts that are being bought, thus more confidence in the final product as well.

Project Risk Analysis

This project has risk involved in the construction of the device. A mill, drill press, miter saw, and a host of other small tools will be used in the manufacturing of this project. It is important that proper safe practices be used during all manufacturing process. There is also risk during the planned testing and use of the device, it is important to know that there are hazards as well. A collision hazard to the aircraft is always present when the plane is in motion from the device, and it is important to avoid damage. To se a full detailed description of all the risk involved in this project, please see the Job Hazard Analysis in Appendix J.

Manufacturing Issues/Modifications

One of the main issues during the manufacturing portion of this project was time. Because of experience within the machine shop, it was expected to not take more than the planned number of hours to manufacture each part for the project. Unfortunately, because of the amount of time between the last time the machine shop was used, the skills needed were not as sharp as they were thought to be. So, the amount of time that was taken to make each part was much higher than the projected number.

Along with time taking much longer than expected, the project modifications kept adding more and more parts that needed to be produced. This continued to add time to the overall production side of the project. The details of this are in the Gantt Chart and can be found in the Appendix of this report.

In order to keep the number of hours as low as possible, each new part that needed to be manufactured was planned out. What the raw material was, and how the part will best be manufactured was planned such as what tool to use, and how the tool will affect the part. More details can be found in the Method's and Construction portion of this report.

Construction Issues

Overall, the construction of this project has gone smoothly. Using T Slot framing has allowed for each part to be fastened on smoothly with no issues. The issue has come in the order that parts have been put together. Because the slot has a nut that slides into it, if there are two nuts on the ends, nothing else can be attached to that side of the framing until it is taken apart and the correct number of nuts are put into the slot. This has added a few hours to the total time taken to construct because parts kept getting forgotten to be attached. However, this only affected a few sub-assemblies, and once this problem showed itself and was attended to by putting every sub assembly together correctly before attaching it elsewhere, everything went much smoother. Many more details can be found in the method's and construction portion of this report on this problem and solution.

Project Documentation

All drawings and assemblies can be found in Appendix B of this report. These drawings include full detail specification on all parts for the device as well as how they will be put together. Appendix A has all analyses required for the device, and the design of the project is based off these analysis's. The budget can be found in Appendix C along with all purchases and total spent. A parts lists can be found Appendix D. The schedule/Gantt Chart can be found in Appendix E.

Testing:

The testing for this project seemed to go very smoothly, and all of it was able to be done in a day. There was a total of four tests; Weight, Size, Speed, and Usability. The weight test was used to determine how much weight the device would take up, and if it would take up a significant portion of the luggage capacity a Cessna 175 has. Similar to this idea, the Size test was used to determine if the device would fit inside of Cessna 175. The speed test determined two things. The first was if the device worked as intended, and the second was how fast the device worked. The final test was Usability, in which it was determined how easy and quickly the device was able to be taken apart, and put back together.

For the first test, a distance of 10 yards was measured out. The device was connected to the connection point on the plane, and pushed and pulled the plane the 10 yard distance. The time it took for the plane to travel the 10 yards was recorded, and the average speed was taken from the time. The predicted speed for this test is around 0.5 m/s, or around 1 mph. This is the speed that the gear box was designed to. For the second test, the devices weight was recorded. For the third test, the device was disassembled into its storage parts, and attempted to be put into the storage compartment of the plane. The final test determined the overall usability of the device. The time required to assemble and disassemble the device was recorded.

Once these tests are complete, whether the device passes or fails the test will be recorded, and it will be determined which portions of the device will need more work/redesign in the future.

Project Success

Overall from the testing, this project came out as a success. The device passed 2 of the tests easily, with the other 2 coming out with issues. The two passed tests were its speed and its size. The device worked with a decent useful walking speed, and it also was able to fit into the plane easily. So, it worked as designed. However, the devices weight was much heavier than the goal of the project, and it was much more difficult to take apart and put together than originally thought. These 2 issues will need to be addressed in future iteration of the device. However, even with these 2 problems, the device works, and believed to be a success, and great step forward to General Aviation Tow bars and tugs.

Project Modification:

During the testing portion of the project, there were a few areas of modification needed. The tow bar portion of the device was starting to bend at the joints where the brackets are, since they were not strong enough to handle the load by themselves, so more brackets needed to be added. Along with that, the support holding up the tow bar needed a second support, just to help solidify the whole frame. Also, the long arm was getting in the way of the user holding the drill causing some pinching in the hand. Because of this, the long arm was shortened to just a short support arm for the tow bar to be attached to.

Based on the results of the project, there are a few areas that need to be redesigned. Overall, the device is far too heavy. The number of brackets and framing that was used needs to be cut back. The framing material of the device can be changed to something that uses less brackets (therefore having less material), perhaps using a welded framing instead of bracketed. Also, the use of bearings was overkill for this project. They were chosen for their price instead of their weight, and overall, it is far to heavy for the use they are designed for. Along with the redesigns, the attachment point works, but could stand to changed. Overall, the device can push and pull with ease, however, the connection to the nosewheel is not up to standard when compared to the original tow bar. Coming up with a design similar to original tow bar would make the device much more secure as a connection, both making it easier to push and pull a plane.

Conclusion

This project was a journey, taking many different shapes and evolving as it went along. Overall, it can be seen as a success because the majority of the requirements set out at the beginning were met. A device was created that is electrically powered and allows a pilot to maneuver their aircraft with just the power of the device. The device is also able to be disassembled and stored in an aircraft so the pilot can take the device with them on their trips. The device has the best aspects of both a normal tow bar, and a tug. Unfortunately, the device is difficult to assemble and disassemble, making it not very usable. The device is also much heavier than the requirement. However, even with these two areas not meeting the requirement, this project is a success. This was the first version of a device like this, and with changes and future modifications to materials, design, etc., it is believed that this project will become a complete success.

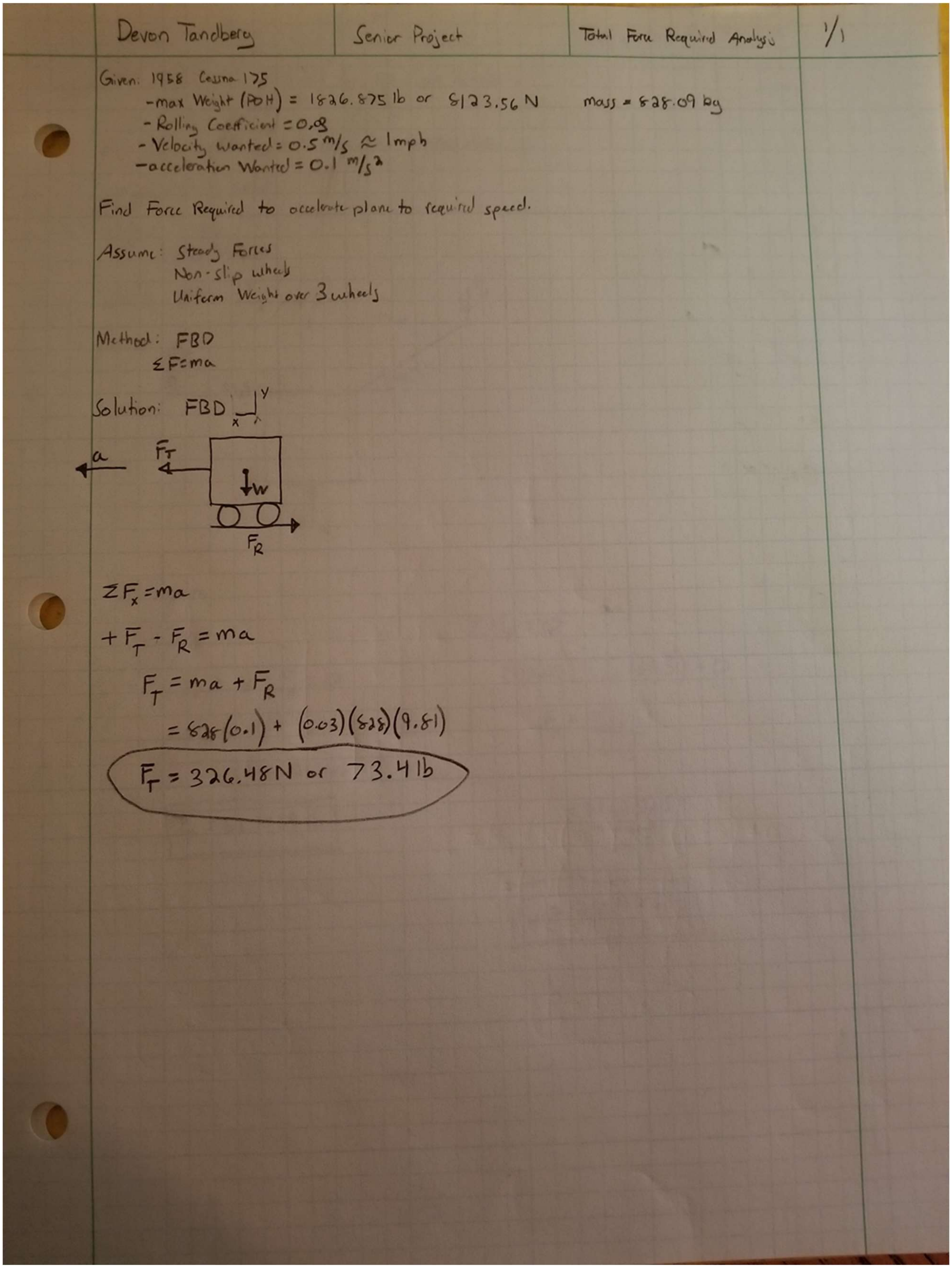
The budget for this project was steep, but the project remained very close to the overall budget, being just slightly over. As stated, the changes made to the design during the design phase made it so that time would be saved during the manufacturing portion of the project, as the first version just was not viable. It seems as if both options considered were both extremes of the overall possible solutions. One taking up too much time, and the other being way too expensive. The future versions of this project will need to find a solution that is in the middle, allowing the budget of the project to be smaller, but not allowing the amount of work required to become too high.

The overall schedule for this project stayed on schedule for most of the project. Items either took the planned amount of time or were over. However, there was one portion of the project that took everything off schedule for a while, and that was the redesign during the winter 2020 quarter at CWU. This redesign pushed back the overall manufacturing dates for the project, however, by the end of the quarter, everything was back on schedule, and allowed testing to go smoothly without any issues.

Overall, most of this project was a success. Most of the requirements for the device were met, and the project remained mostly on schedule and on budget. This project has allowed for many lessons to be learned, and those lessons will allow for more engineering projects in the future to run much smoother, and hopefully, create great project in the future. Thank you.

Appendix A – Analysis

Analysis 1: Total Force Required to Push/Pull Airplane



Devon Tandberg | Senior Project | Total Force Required Analysis | 1/1

Given: 1958 Cessna 175

- max Weight (POH) = 1826.875 lb or 8123.56 N   mass = 828.09 kg
- Rolling Coefficient = 0.03
- Velocity wanted = 0.5 m/s ≈ 1mph
- acceleration Wanted = 0.1 m/s^2

Find Force Required to accelerate plane to required speed.

Assume: Steady Forces
Non-slip wheels
Uniform Weight over 3 wheels

Method: FBD
$\Sigma F = ma$

Solution: FBD

$$\Sigma F_x = ma$$

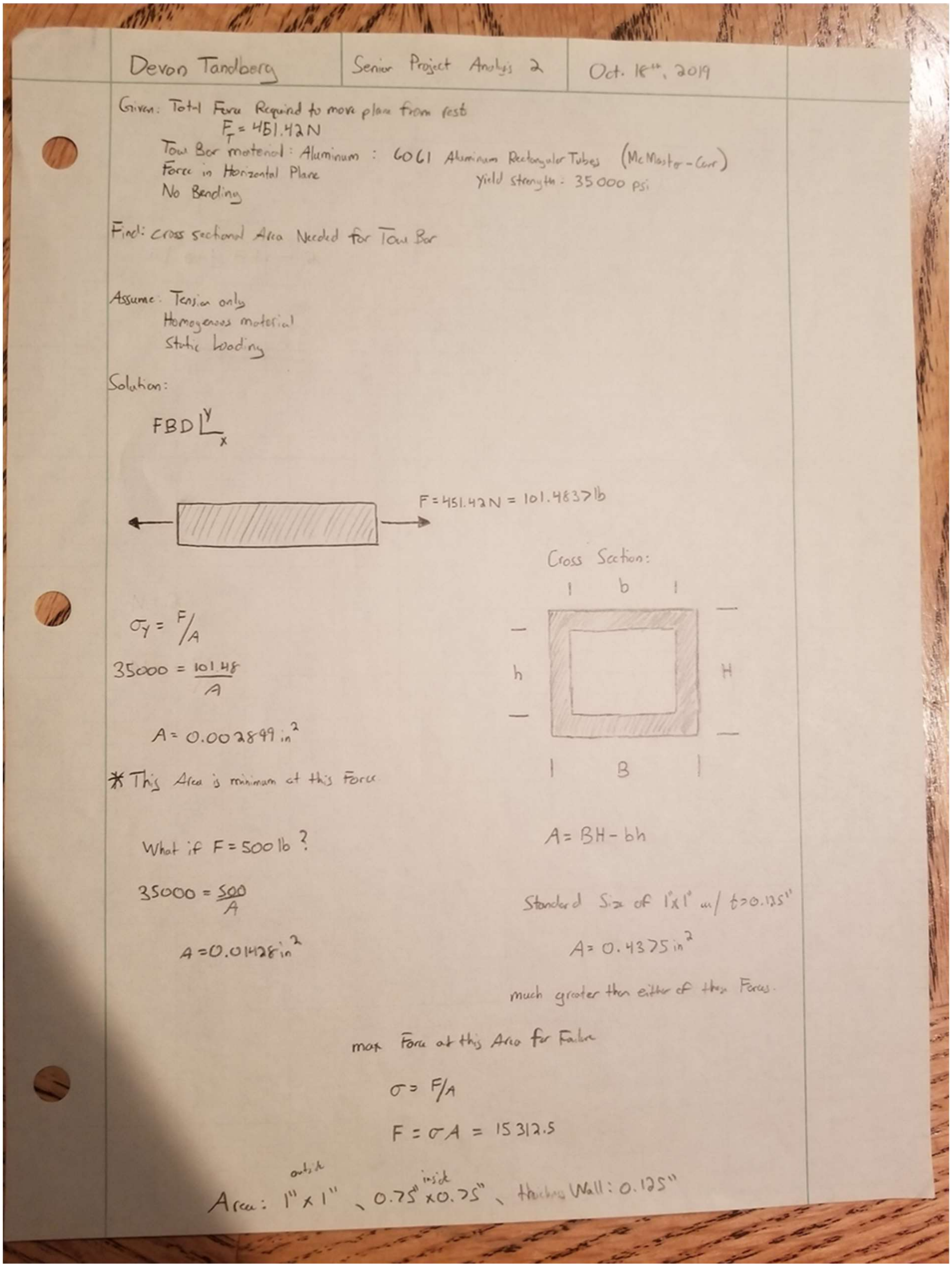
$$+F_T - F_R = ma$$

$$F_T = ma + F_R$$

$$= 828(0.1) + (0.03)(828)(9.81)$$

$$\boxed{F_T = 326.48N \text{ or } 73.4 lb}$$

Analysis 2: Minimum Tow Bar Cross Section Required



Devon Tandberg | Senior Project Analysis 2 | Oct. 18th, 2019

Given: Total Force Required to move plane from rest
$F_T = 451.42N$
Tow Bar material: Aluminum : 6061 Aluminum Rectangular Tubes (McMaster-Carr)
Yield strength: 35000 psi
Force in Horizontal Plane
No Bending

Find: cross sectional Area Needed for Tow Bar

Assume: Tension only
Homogenous material
Static loading

Solution:

FBD

$F = 451.42N = 101.48371b$

$\sigma_Y = F/A$

$35000 = \frac{101.48}{A}$

$A = 0.002899 \text{ in}^2$

* This Area is minimum at this Force

What if F = 500 lb ?

$35000 = \frac{500}{A}$

$A = 0.01428 \text{ in}^2$

Cross Section:

$A = BH - bh$

Standard Size of 1"x1" w/ t=0.125"

$A = 0.4375 \text{ in}^2$

much greater than either of these Forces.

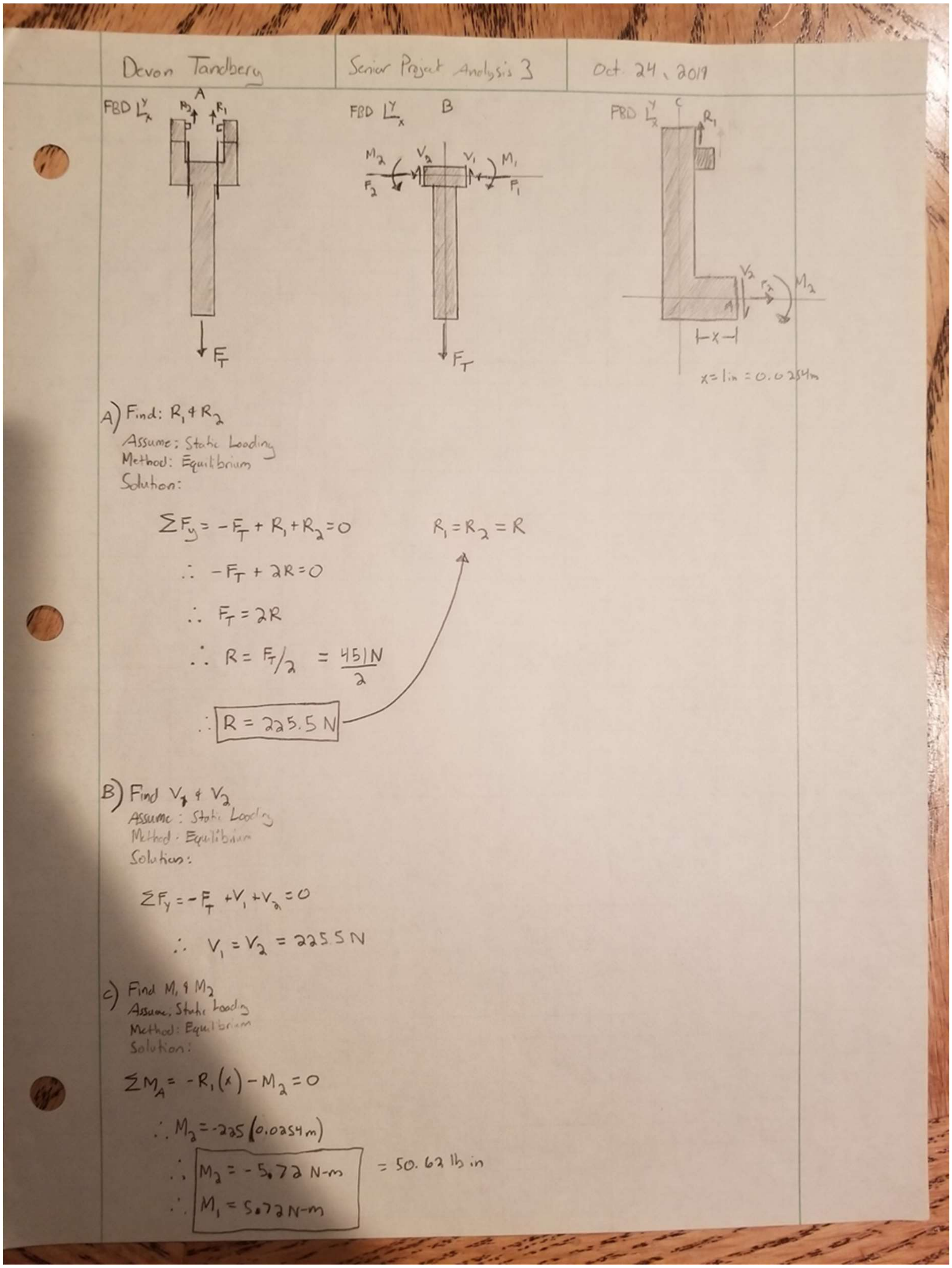
max Force at this Area for Failure

$\sigma = F/A$

$F = \sigma A = 15312.5$

Area: $\overset{\text{outside}}{1" \times 1"}$, $\overset{\text{inside}}{0.75" \times 0.75"}$, thickness Wall: 0.125"

Analysis 3: Internal Forces on Tow Bar



Devon Tandberg | Senior Project Analysis 3 | Oct. 24, 2019

$x = 1\text{in} = 0.0254\text{m}$

A) Find: R_1 & R_2
Assume: Static Loading
Method: Equilibrium
Solution:

$$\Sigma F_y = -F_T + R_1 + R_2 = 0 \qquad R_1 = R_2 = R$$

$$\therefore -F_T + 2R = 0$$

$$\therefore F_T = 2R$$

$$\therefore R = F_T/2 = \frac{451\text{N}}{2}$$

$$\therefore \boxed{R = 225.5\text{ N}}$$

B) Find V_1 & V_2
Assume: Static Loading
Method: Equilibrium
Solution:

$$\Sigma F_y = -F_T + V_1 + V_2 = 0$$

$$\therefore V_1 = V_2 = 225.5\text{ N}$$

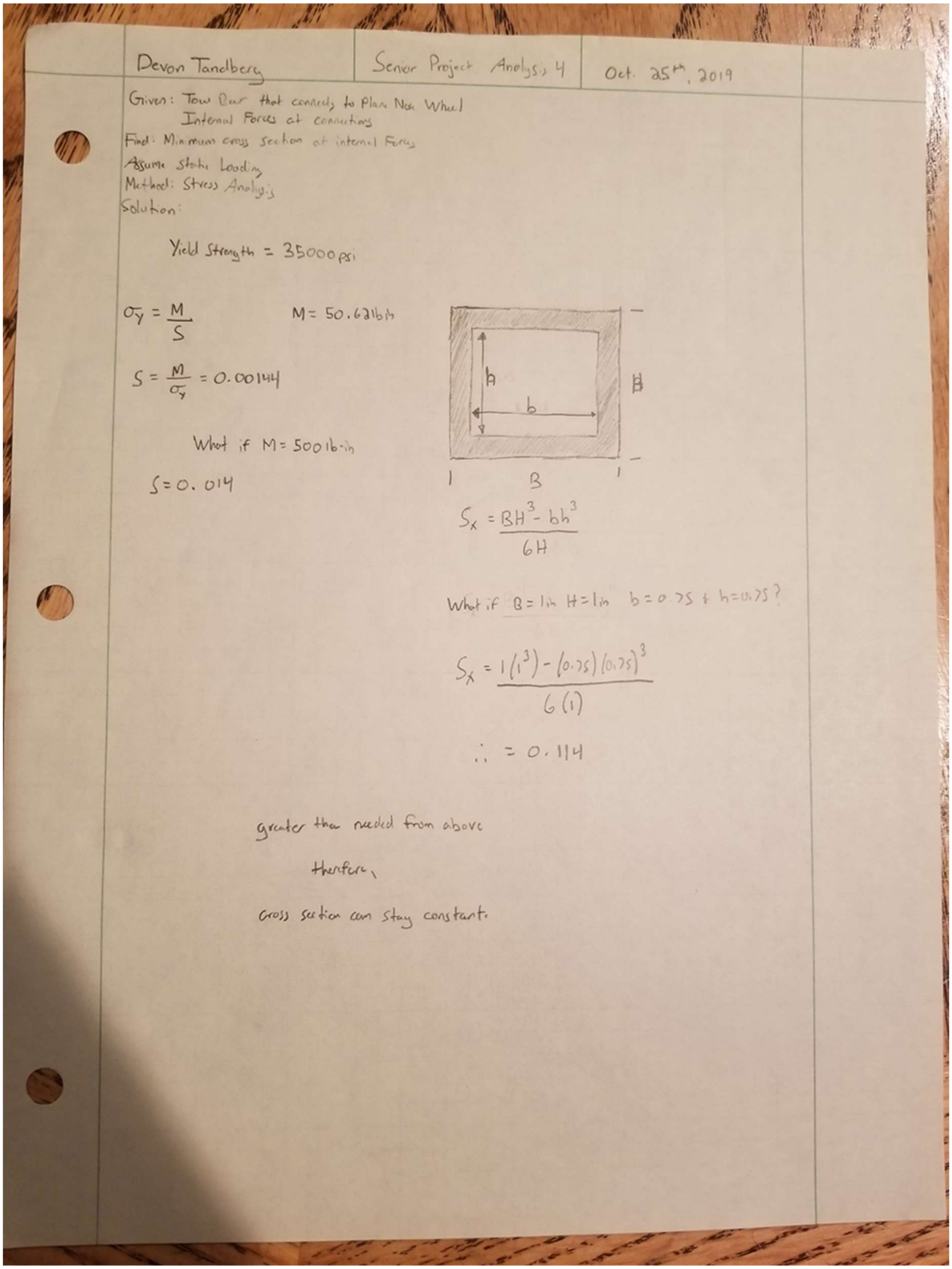
C) Find M_1 & M_2
Assume: Static Loading
Method: Equilibrium
Solution:

$$\Sigma M_A = -R_1(x) - M_2 = 0$$

$$\therefore M_2 = -225(0.0254\text{m})$$

$$\boxed{\begin{array}{l} \therefore M_2 = -5.72\text{ N-m} \\ \therefore M_1 = 5.72\text{ N-m} \end{array}} = 50.62\text{ lb in}$$

Analysis 4: Minimum Cross Section from internal Forces



Devon Tandberg | Senior Project Analysis 4 | Oct. 25th, 2019

Given: Tow Bar that connects to Plane Nose Wheel
Internal Forces at connections

Find: Minimum cross section at internal Forces

Assume Static Loading

Method: Stress Analysis

Solution:

Yield Strength = 35000 psi

$$\sigma_y = \frac{M}{S} \qquad M = 50.62 \text{lbin}$$

$$S = \frac{M}{\sigma_y} = 0.00144$$

What if M = 500 lb-in

$$S = 0.014$$

$$S_x = \frac{BH^3 - bh^3}{6H}$$

What if B = 1in H = 1in b = 0.75 + h = 0.75?

$$S_x = \frac{1(1^3) - (0.75)(0.75)^3}{6(1)}$$

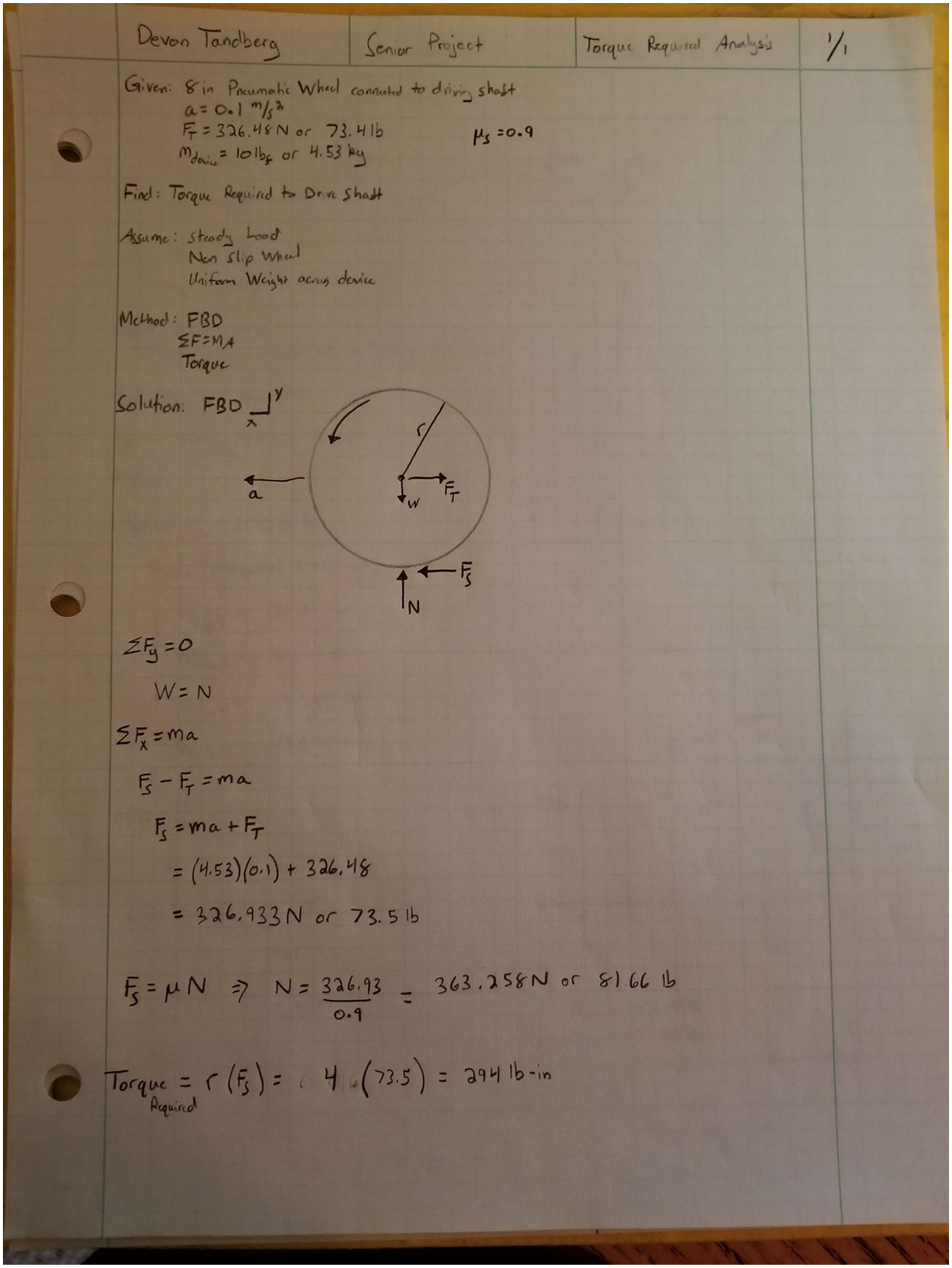
$$\therefore = 0.114$$

greater than needed from above

therefore,

Cross section can stay constant.

Analysis 5: Torque Required



Devon Tandberg
Senior Project
Torque Required Analysis
1/1

Given: 8 in Pneumatic Wheel connected to driving shaft
$a = 0.1 \; m/s^2$
$F_T = 326.48 \, N$ or $73.4 \, lb$
$m_{device} = 10 \, lb_f$ or $4.53 \, kg$
$\mu_s = 0.9$

Find: Torque Required to Drive Shaft

Assume: Steady Load
Non Slip Wheel
Uniform Weight across device

Method: FBD
$\Sigma F = MA$
Torque

Solution: FBD

$$\Sigma F_y = 0$$

$$W = N$$

$$\Sigma F_x = ma$$

$$F_s - F_T = ma$$

$$F_s = ma + F_T$$

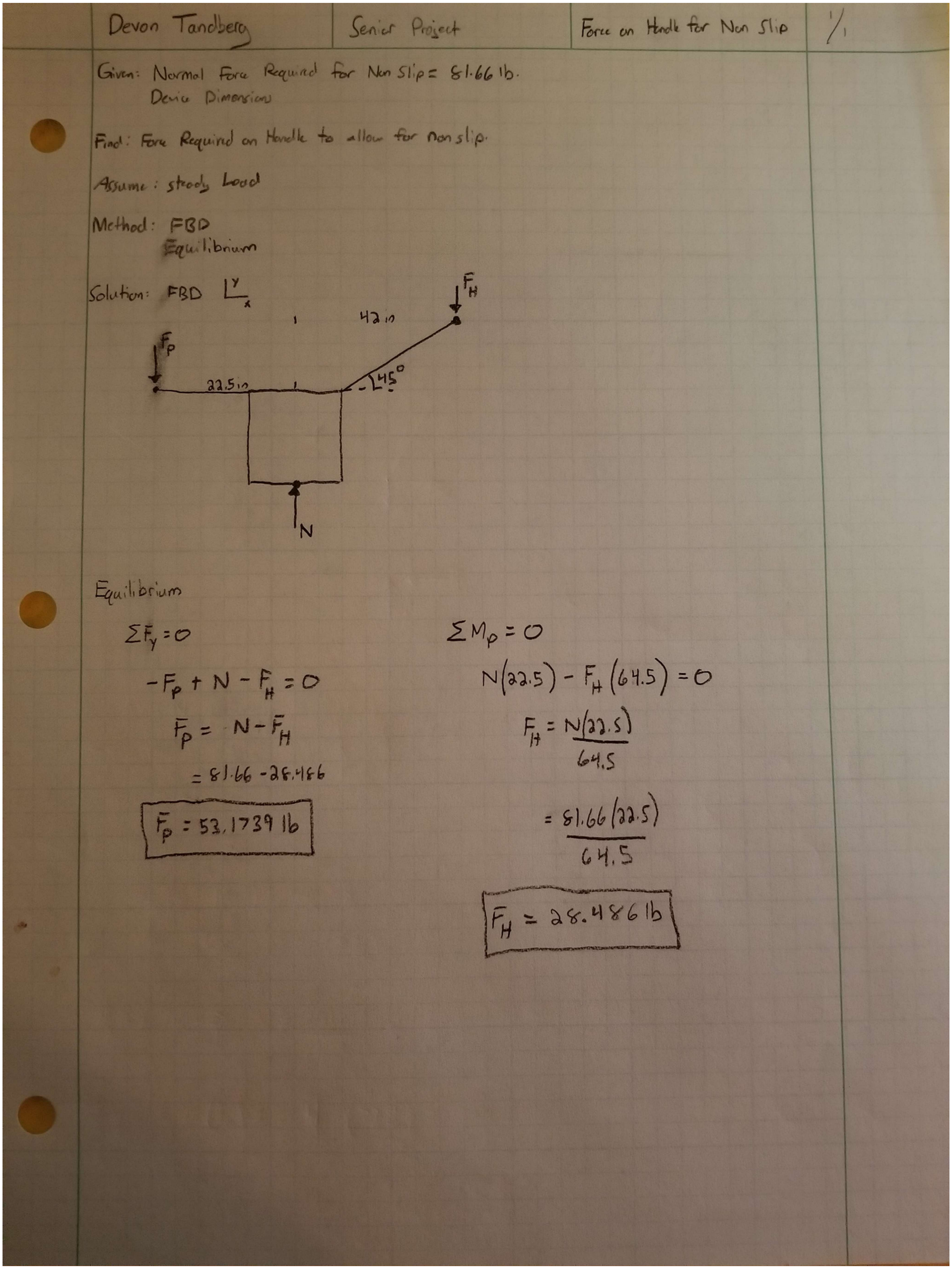
$$= (4.53)(0.1) + 326.48$$

$$= 326.933 N \text{ or } 73.5 \text{ lb}$$

$$F_s = \mu N \Rightarrow N = \frac{326.93}{0.9} = 363.258 N \text{ or } 81.66 \text{ lb}$$

$$\text{Torque}_{\text{Required}} = r(F_s) = 4(73.5) = 294 \text{ lb-in}$$

Analysis 6: Force on Handle For Non-Slip Wheels



Devon Tandberg	Senior Project	Force on Handle for Non Slip	1/1

Given: Normal Force Required for Non Slip = 81.66 lb.
Device Dimensions

Find: Force Required on Handle to allow for non slip.

Assume: steady Load

Method: FBD
Equilibrium

Solution: FBD

Equilibrium

$$\Sigma F_y = 0$$

$$-F_P + N - F_H = 0$$

$$F_P = N - F_H$$

$$= 81.66 - 28.486$$

$$\boxed{F_P = 53.1739 \text{ lb}}$$

$$\Sigma M_P = 0$$

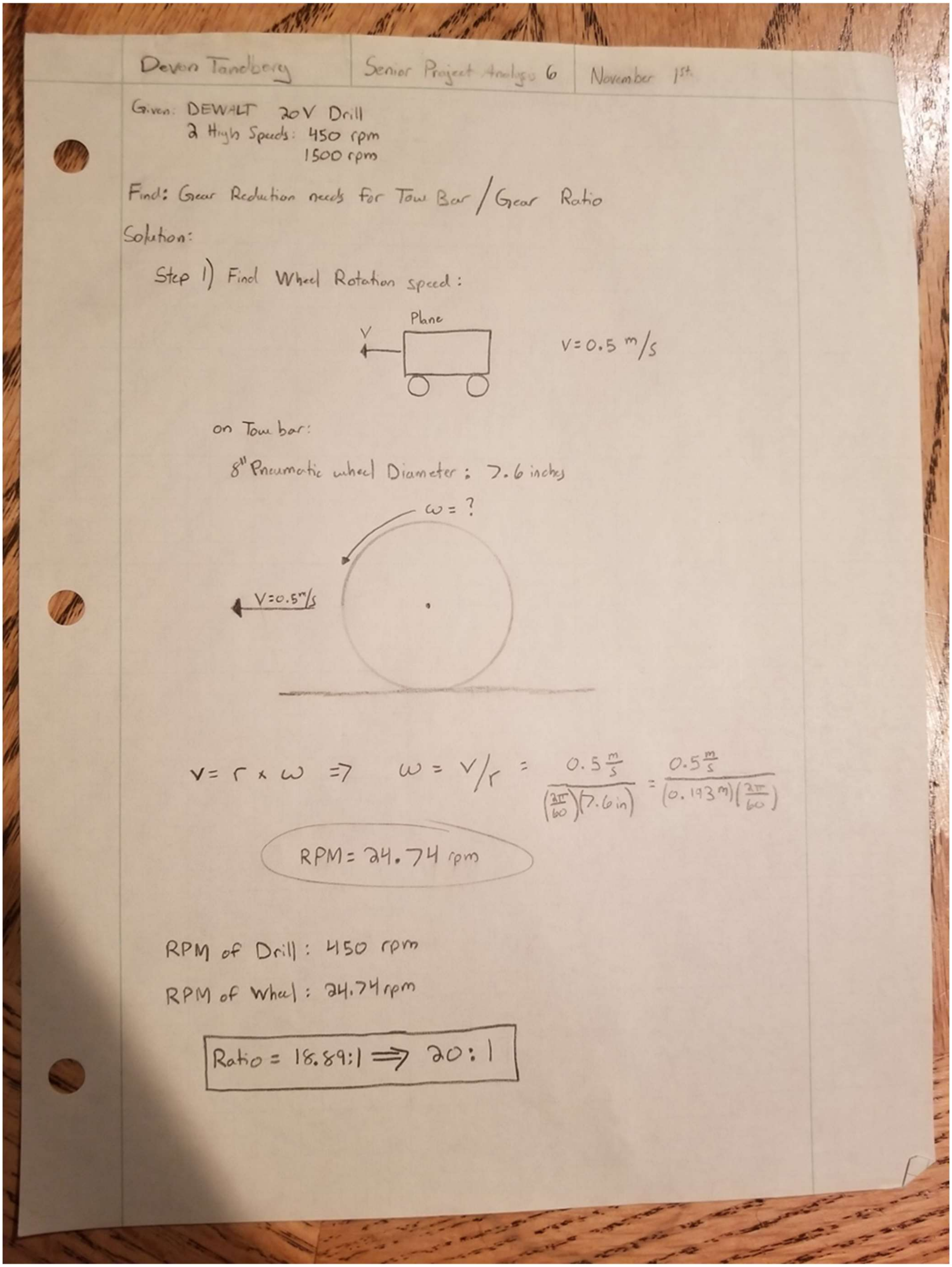
$$N(22.5) - F_H(64.5) = 0$$

$$F_H = \frac{N(22.5)}{64.5}$$

$$= \frac{81.66(22.5)}{64.5}$$

$$\boxed{F_H = 28.486 \text{ lb}}$$

Analysis 7: Worm Gear Ratio Required for Linear Velocity



Devon Tandberg | Senior Project Analysis 6 | November 1st

Given: DEWALT 20V Drill
2 High Speeds: 450 rpm
1500 rpm

Find: Gear Reduction needs for Tow Bar / Gear Ratio

Solution:

Step 1) Find Wheel Rotation speed:

V = 0.5 m/s

on Tow bar:

8" Pneumatic wheel Diameter: 7.6 inches

$$V = r \times \omega \Rightarrow \omega = V/r = \frac{0.5\,\frac{m}{s}}{\left(\frac{2\pi}{60}\right)(7.6\,in)} = \frac{0.5\,\frac{m}{s}}{(0.193\,m)\left(\frac{2\pi}{60}\right)}$$

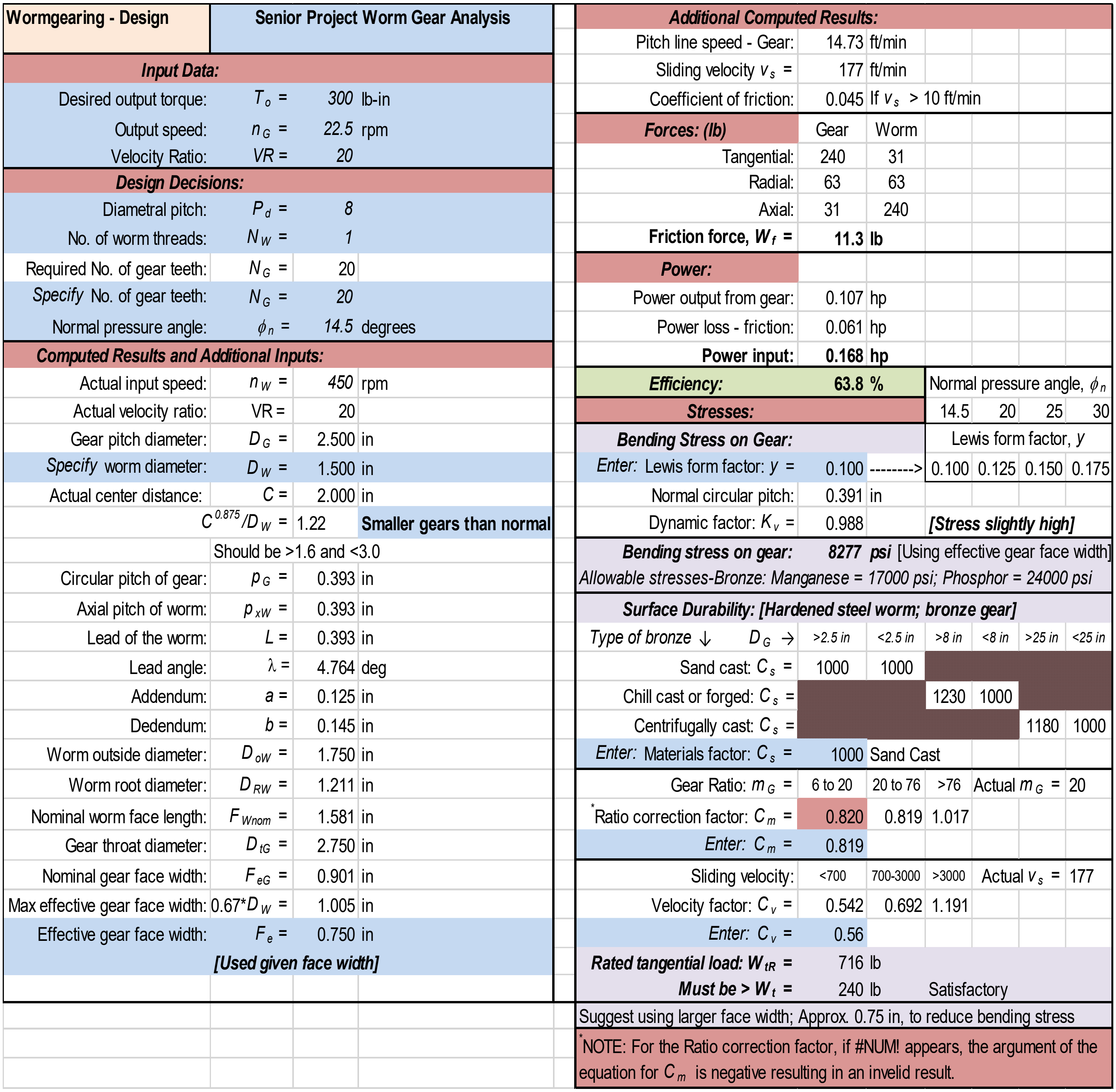
RPM = 24.74 rpm

RPM of Drill: 450 rpm

RPM of Wheel: 24.74 rpm

$$\boxed{\text{Ratio} = 18.89:1 \Rightarrow 20:1}$$

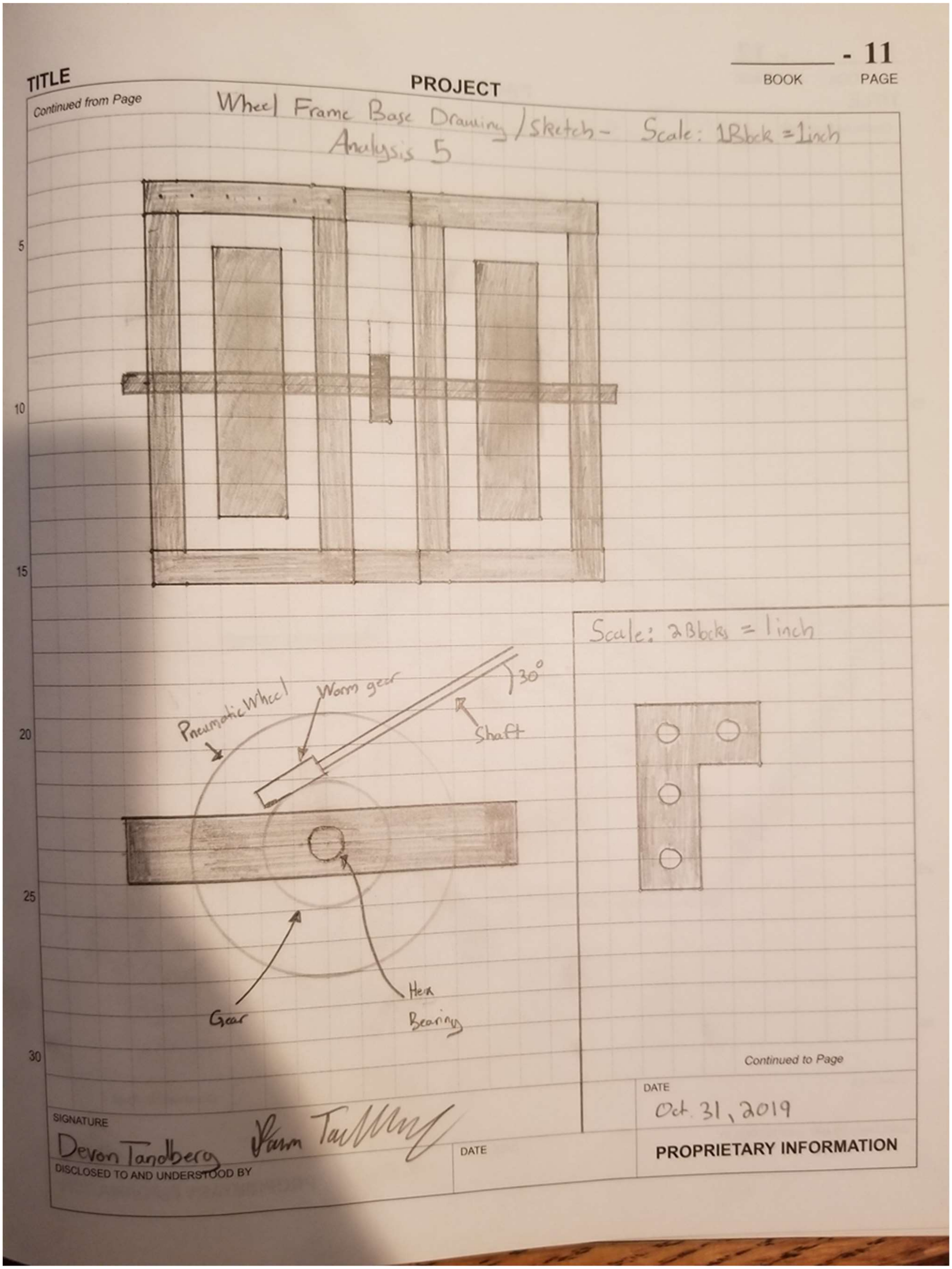
Analysis 8: Worm Gear Analysis



Wormgearing - Design	**Senior Project Worm Gear Analysis**		
Input Data:			
Desired output torque:	T_o =	*300*	lb-in
Output speed:	n_G =	*22.5*	rpm
Velocity Ratio:	*VR* =	*20*	
Design Decisions:			
Diametral pitch:	P_d =	*8*	
No. of worm threads:	N_W =	*1*	
Required No. of gear teeth:	N_G =	20	
Specify No. of gear teeth:	N_G =	*20*	
Normal pressure angle:	ϕ_n =	*14.5*	degrees
Computed Results and Additional Inputs:			
Actual input speed:	n_W =	*450*	rpm
Actual velocity ratio:	VR =	20	
Gear pitch diameter:	D_G =	2.500	in
Specify worm diameter:	D_W =	1.500	in
Actual center distance:	*C* =	2.000	in
	$C^{0.875}/D_W$ =	1.22	**Smaller gears than normal**
	Should be >1.6 and <3.0		
Circular pitch of gear:	p_G =	0.393	in
Axial pitch of worm:	p_{xW} =	0.393	in
Lead of the worm:	*L* =	0.393	in
Lead angle:	λ =	4.764	deg
Addendum:	*a* =	0.125	in
Dedendum:	*b* =	0.145	in
Worm outside diameter:	D_{oW} =	1.750	in
Worm root diameter:	D_{RW} =	1.211	in
Nominal worm face length:	F_{Wnom} =	1.581	in
Gear throat diameter:	D_{tG} =	2.750	in
Nominal gear face width:	F_{eG} =	0.901	in
Max effective gear face width:	$0.67{*}D_W$ =	1.005	in
Effective gear face width:	F_e =	0.750	in
	[Used given face width]		

Additional Computed Results:						
Pitch line speed - Gear:	14.73	ft/min				
Sliding velocity v_s =	177	ft/min				
Coefficient of friction:	0.045	If v_s > 10 ft/min				
Forces: (lb)	Gear	Worm				
Tangential:	240	31				
Radial:	63	63				
Axial:	31	240				
Friction force, W_f =	**11.3**	**lb**				
Power:						
Power output from gear:	0.107	hp				
Power loss - friction:	0.061	hp				
Power input:	**0.168**	**hp**				
Efficiency:	**63.8**	**%**	Normal pressure angle, ϕ_n			
Stresses:			14.5	20	25	30
Bending Stress on Gear:			Lewis form factor, *y*			
Enter: Lewis form factor: *y* =	0.100	-------->	0.100	0.125	0.150	0.175
Normal circular pitch:	0.391	in				
Dynamic factor: K_v =	0.988		***[Stress slightly high]***			
Bending stress on gear:	***8277***	***psi*** [Using effective gear face width]				
Allowable stresses-Bronze: Manganese = 17000 psi; Phosphor = 24000 psi						
Surface Durability: [Hardened steel worm; bronze gear]						
Type of bronze ↓ D_G →	*>2.5 in*	*<2.5 in*	*>8 in*	*<8 in*	*>25 in*	*<25 in*
Sand cast: C_s =	1000	1000				
Chill cast or forged: C_s =			1230	1000		
Centrifugally cast: C_s =					1180	1000
Enter: Materials factor: C_s =	1000	Sand Cast				
Gear Ratio: m_G =	6 to 20	20 to 76	>76	Actual m_G =		20
*Ratio correction factor: C_m =	0.820	0.819	1.017			
Enter: C_m =	0.819					
Sliding velocity:	<700	700-3000	>3000	Actual v_s =		177
Velocity factor: C_v =	0.542	0.692	1.191			
Enter: C_v =	0.56					
Rated tangential load: W_{tR} =	716	lb				
Must be > W_t =	240	lb	Satisfactory			
Suggest using larger face width; Approx. 0.75 in, to reduce bending stress						
*NOTE: For the Ratio correction factor, if #NUM! appears, the argument of the equation for C_m is negative resulting in an invelid result.						

Analysis 9: Sketch of Frame Shape and Basic Dimensions



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TITLE

PROJECT

Continued from Page

Wheel Frame Base Drawing/Sketch - Scale: 1Block = 1inch
Analysis 5

Continued to Page

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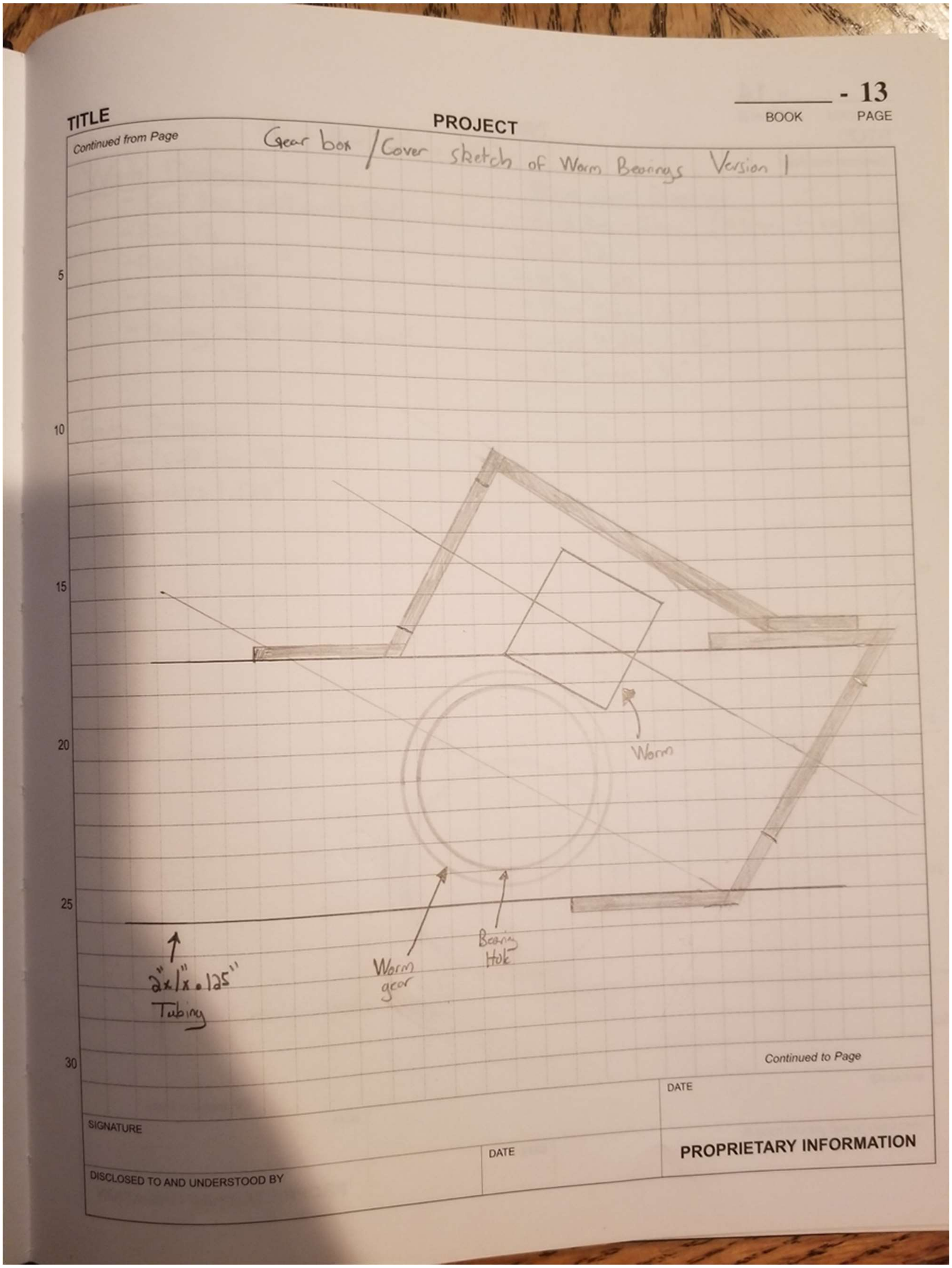
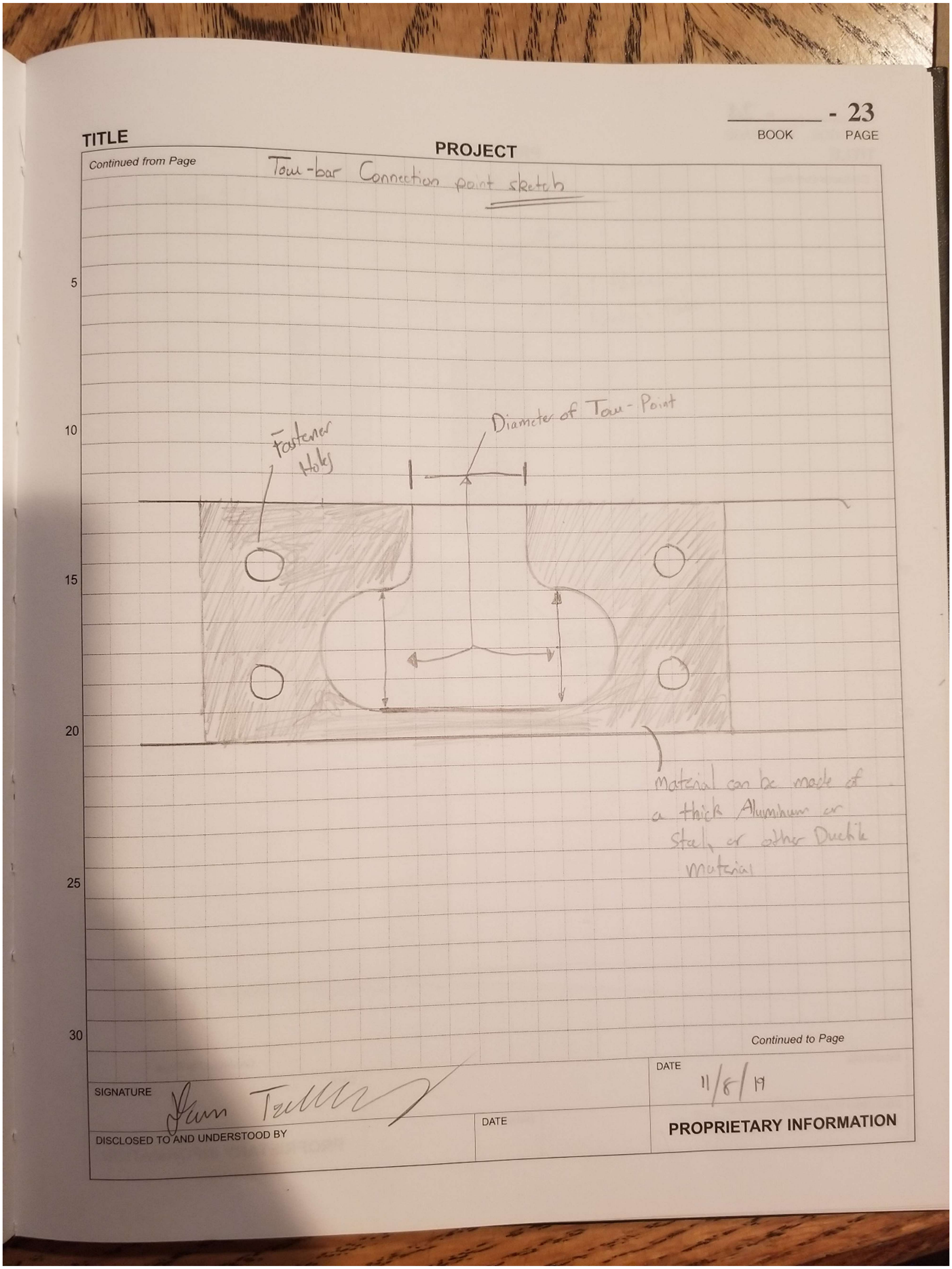
Analysis 10: Sketch of Gear Box



Analysis 11: Sketch of Tow Bar Attachment Part



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Tow-bar Connection point sketch

material can be made of a thick Aluminum or Steel, or other Ductile material

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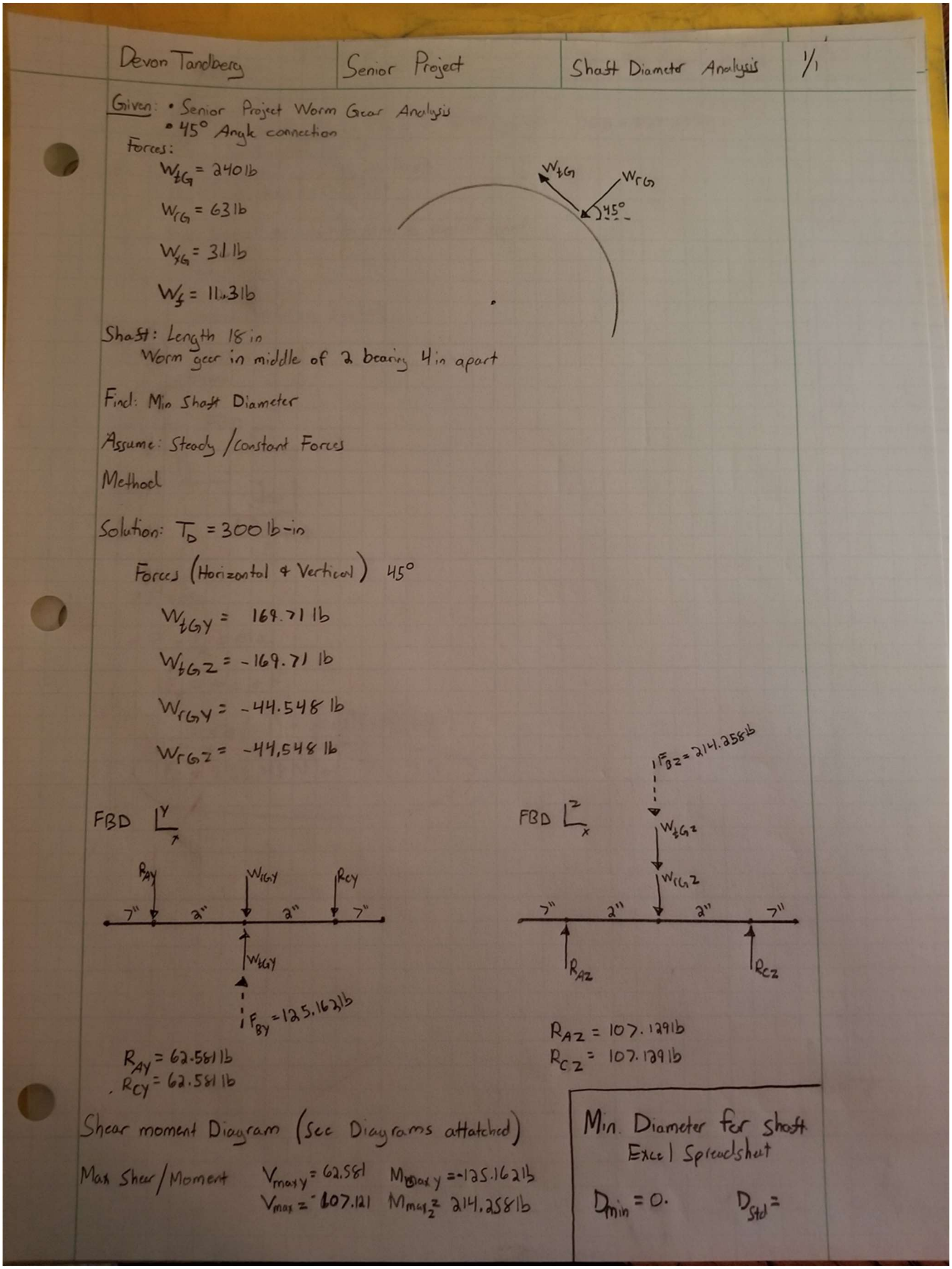
Analysis 12: Drive Train Shaft Analysis



Devon Tandberg | Senior Project | Shaft Diameter Analysis | 1/1

Given: • Senior Project Worm Gear Analysis
• 45° Angle connection

Forces:

$W_{tG} = 240 lb$

$W_{rG} = 63 lb$

$W_{xG} = 31 lb$

$W_f = 11.3 lb$

Shaft: Length 18 in
Worm gear in middle of 2 bearing 4 in apart

Find: Min Shaft Diameter

Assume: Steady / constant Forces

Method

Solution: $T_D = 300 lb\text{-}in$

Forces (Horizontal & Vertical) 45°

$W_{tGY} = 169.71 lb$

$W_{tGZ} = -169.71 lb$

$W_{rGY} = -44.548 lb$

$W_{rGZ} = -44.548 lb$

FBD

$R_{AY} = 62.581 lb$
$R_{CY} = 62.581 lb$

FBD

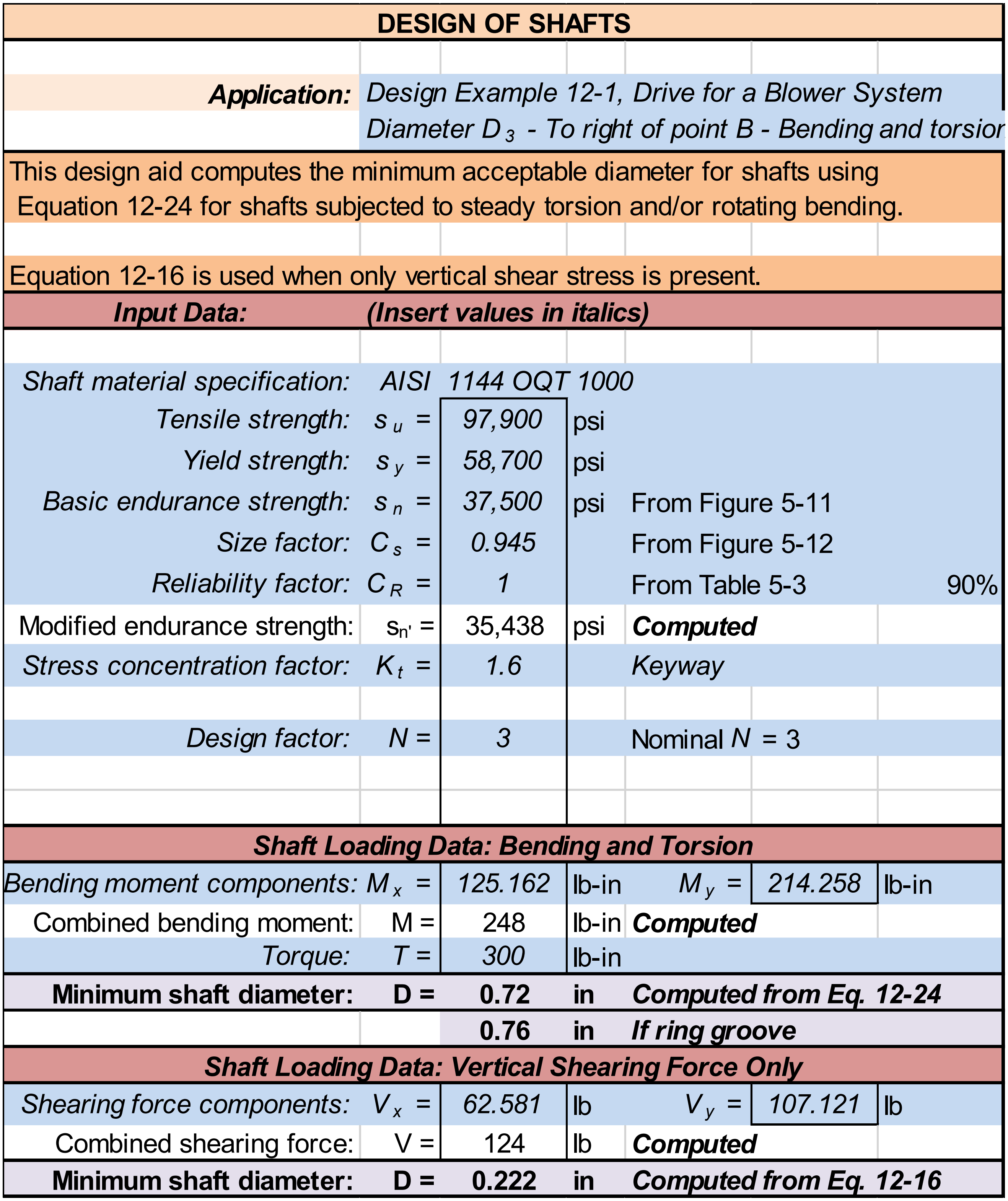
$R_{AZ} = 107.129 lb$
$R_{CZ} = 107.129 lb$

Shear moment Diagram (See Diagrams attatched)

Max Shear/Moment $V_{max\,y} = 62.581$ $M_{max\,y} = -125.162 lb$
$V_{max\,z} = -107.121$ $M_{max\,z} = 214.258 lb$

Min. Diameter for shaft
Excel Spreadsheet

$D_{min} = 0.$ $D_{std} =$



DESIGN OF SHAFTS

Application: *Design Example 12-1, Drive for a Blower System*
Diameter D_3 - To right of point B - Bending and torsior

This design aid computes the minimum acceptable diameter for shafts using Equation 12-24 for shafts subjected to steady torsion and/or rotating bending.

Equation 12-16 is used when only vertical shear stress is present.

Input Data: ***(Insert values in italics)***

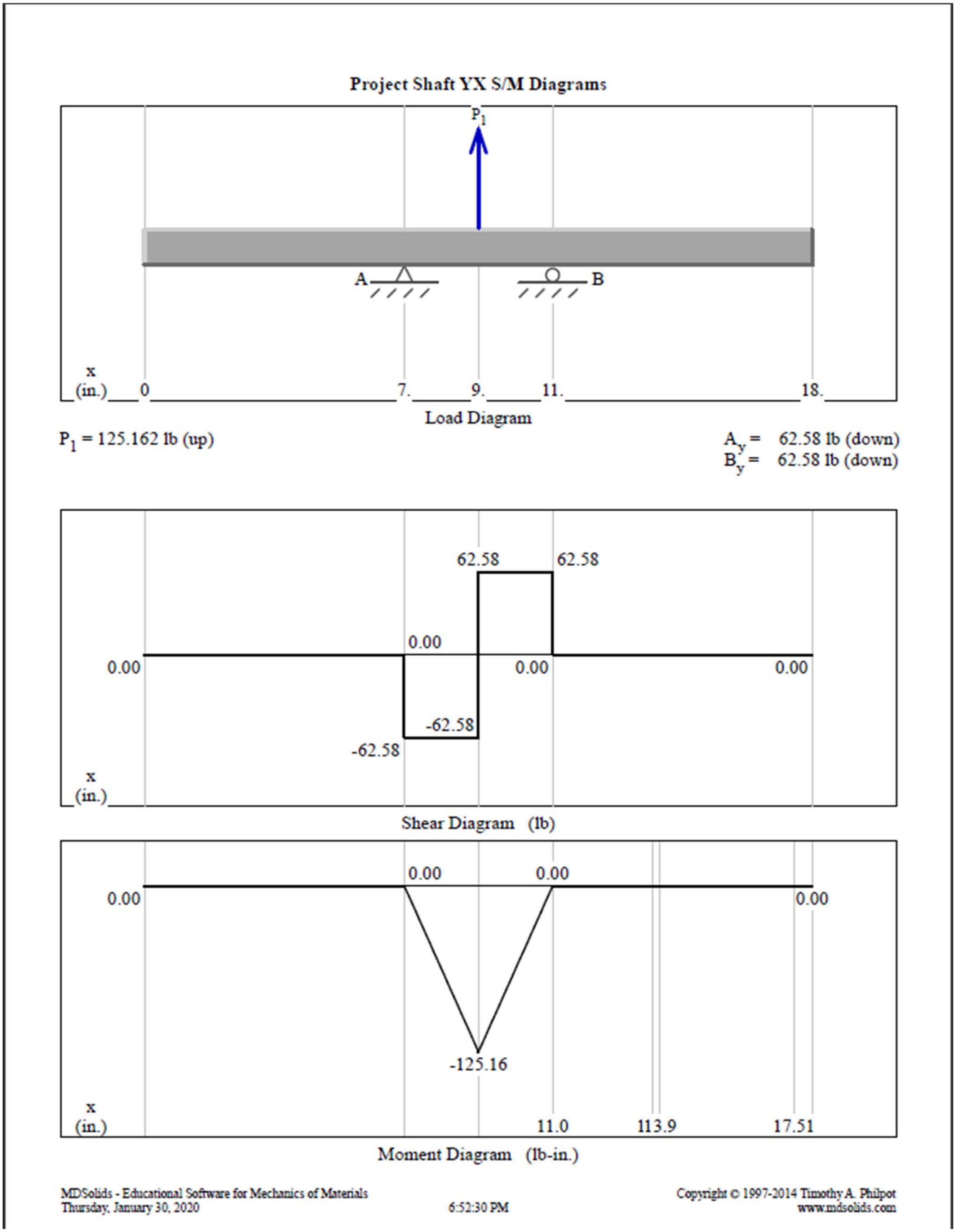
Shaft material specification:	*AISI*	*1144 OQT 1000*			
Tensile strength:	s_u =	*97,900*	psi		
Yield strength:	s_y =	*58,700*	psi		
Basic endurance strength:	s_n =	*37,500*	psi	From Figure 5-11	
Size factor:	C_s =	*0.945*		From Figure 5-12	
Reliability factor:	C_R =	*1*		From Table 5-3	90%
Modified endurance strength:	$s_{n'}$ =	35,438	psi	***Computed***	
Stress concentration factor:	K_t =	*1.6*		*Keyway*	
Design factor:	N =	*3*		Nominal N = 3	

Shaft Loading Data: Bending and Torsion

Bending moment components:	M_x =	*125.162*	lb-in	M_y =	*214.258*	lb-in
Combined bending moment:	M =	248	lb-in	***Computed***		
Torque:	T =	*300*	lb-in			
Minimum shaft diameter:	**D =**	**0.72**	**in**	***Computed from Eq. 12-24***		
		0.76	**in**	***If ring groove***		

Shaft Loading Data: Vertical Shearing Force Only

Shearing force components:	V_x =	*62.581*	lb	V_y =	*107.121*	lb
Combined shearing force:	V =	124	lb	***Computed***		
Minimum shaft diameter:	**D =**	**0.222**	**in**	***Computed from Eq. 12-16***		



Project Shaft YX S/M Diagrams

Load Diagram

P_1 = 125.162 lb (up)

A_y = 62.58 lb (down)
B_y = 62.58 lb (down)

Shear Diagram (lb)

Moment Diagram (lb-in.)

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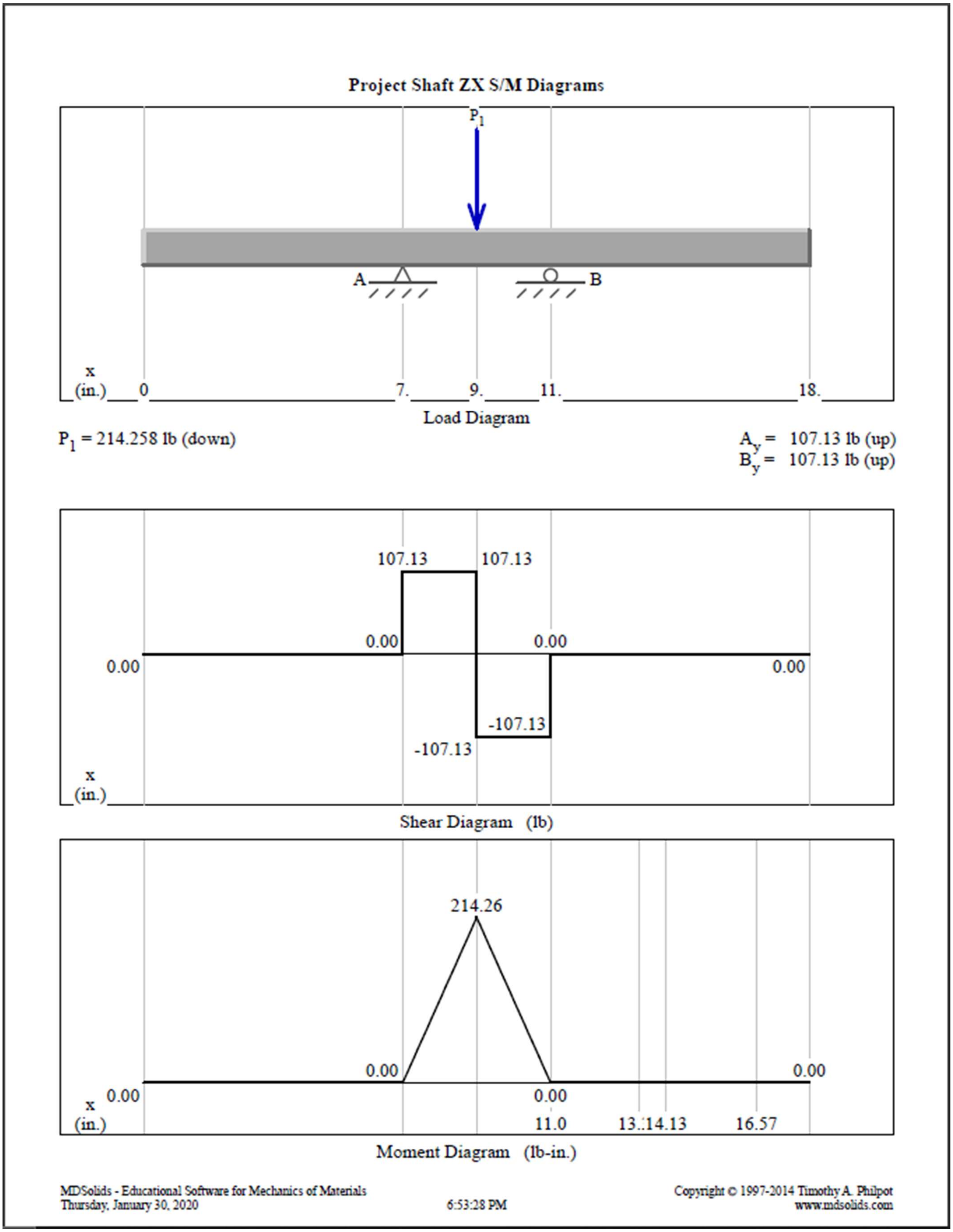

Project Shaft ZX S/M Diagrams

Load Diagram

P_1 = 214.258 lb (down)

A_y = 107.13 lb (up)
B_y = 107.13 lb (up)

Shear Diagram (lb)

Moment Diagram (lb-in.)

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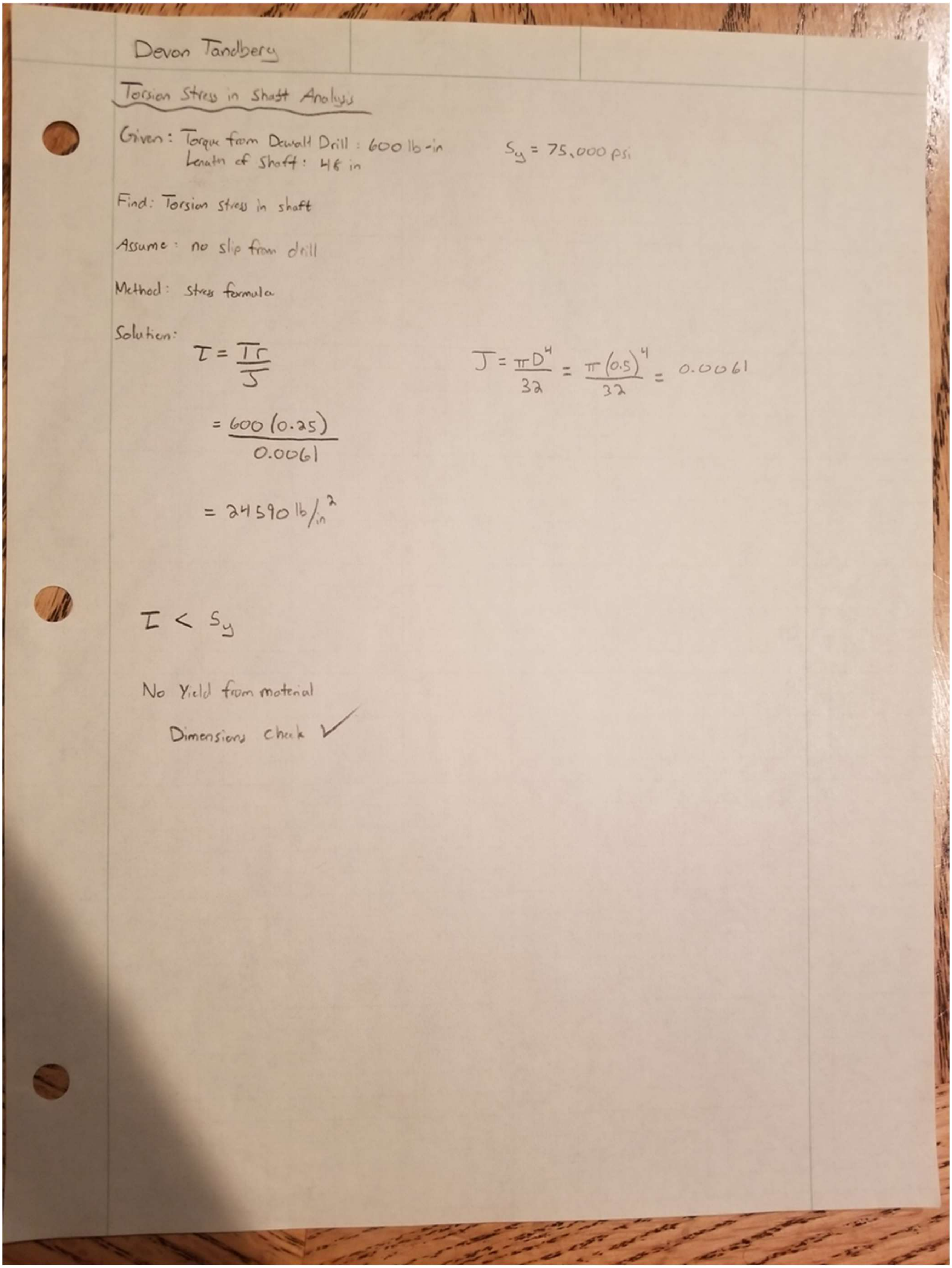
Analysis 13: Handle Arm Torsion Stress Analysis



Devon Tandberg

Torsion Stress in Shaft Analysis

Given: Torque from Dewalt Drill : 600 lb-in
Length of Shaft : 48 in

$S_y = 75{,}000$ psi

Find: Torsion stress in shaft

Assume: no slip from drill

Method: stress formula

Solution:

$$\tau = \frac{Tr}{J}$$

$$J = \frac{\pi D^4}{32} = \frac{\pi (0.5)^4}{32} = 0.0061$$

$$= \frac{600\,(0.25)}{0.0061}$$

$$= 24590\ \mathrm{lb}/\mathrm{in}^2$$

$$\tau < S_y$$

No Yield from material

Dimensions check ✓

Appendix B – Drawings

Figure B1: Part 20-0001 Drawing – Frame Piece 1 Length 15”

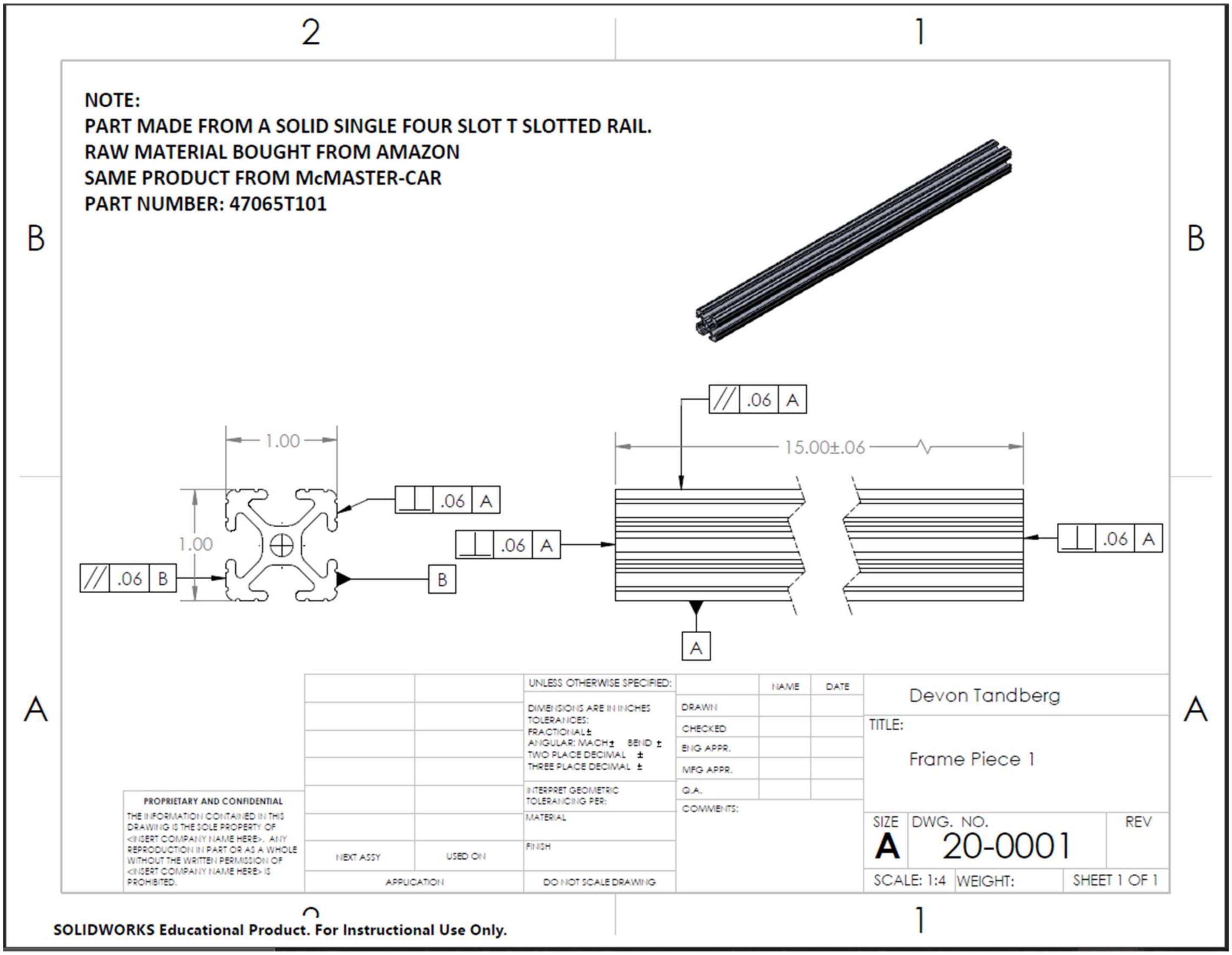


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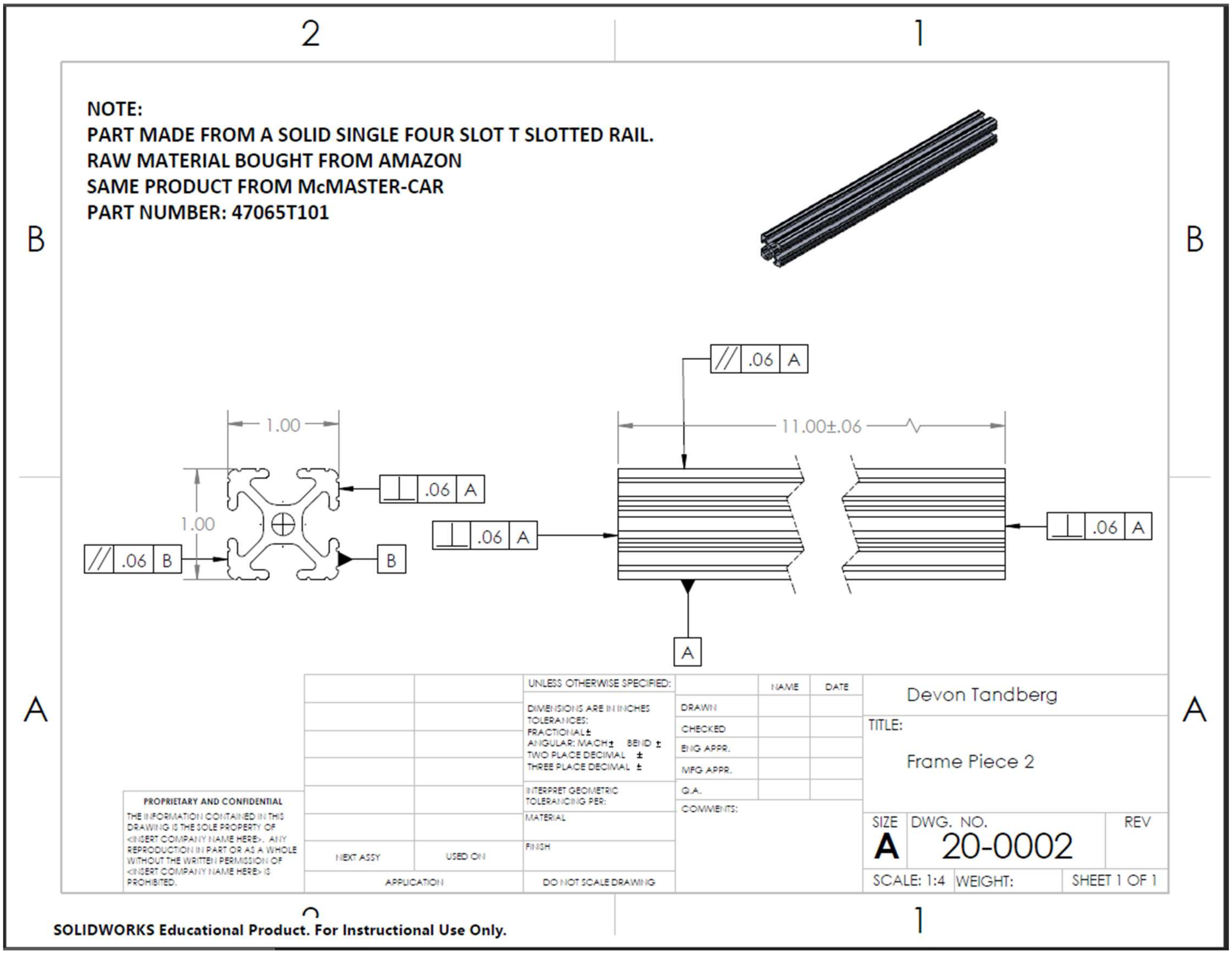
Figure B2: Part 20-0002 Drawing – Frame Piece 2 Length 11”



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FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
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MFG APPR.		
Q.A.		

COMMENTS:

Devon Tandberg
TITLE:
Frame Piece 2
SIZE A
DWG. NO. 20-0002
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1

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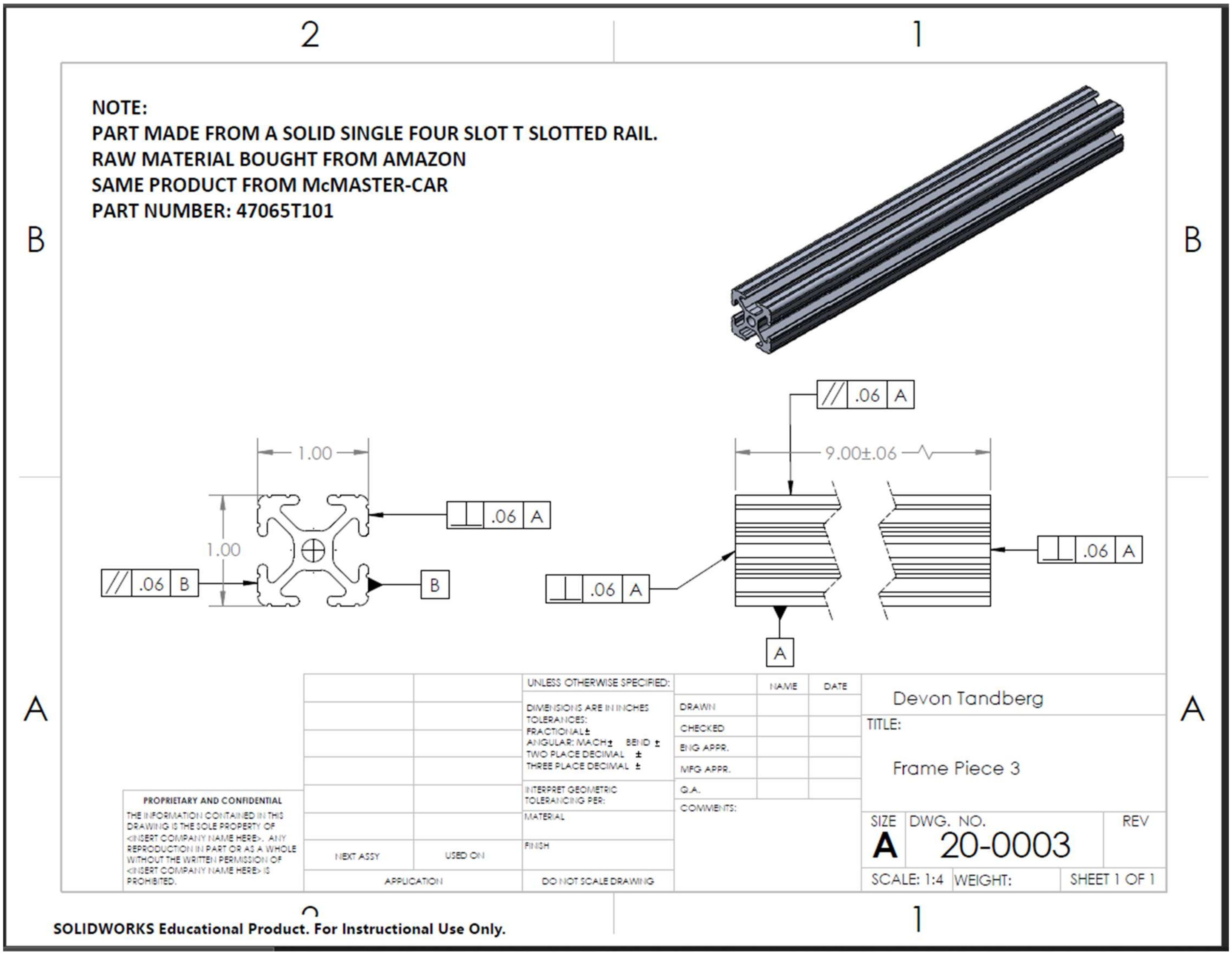
Figure B3: Part 20-0003 – Frame Piece 3 Length 9"



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THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
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Q.A.		

COMMENTS:

Devon Tandberg
TITLE:
Frame Piece 3
SIZE A
DWG. NO. 20-0003
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1

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Figure B4: Part 20-0004 Drawing – Frame Piece 4 Length 7”

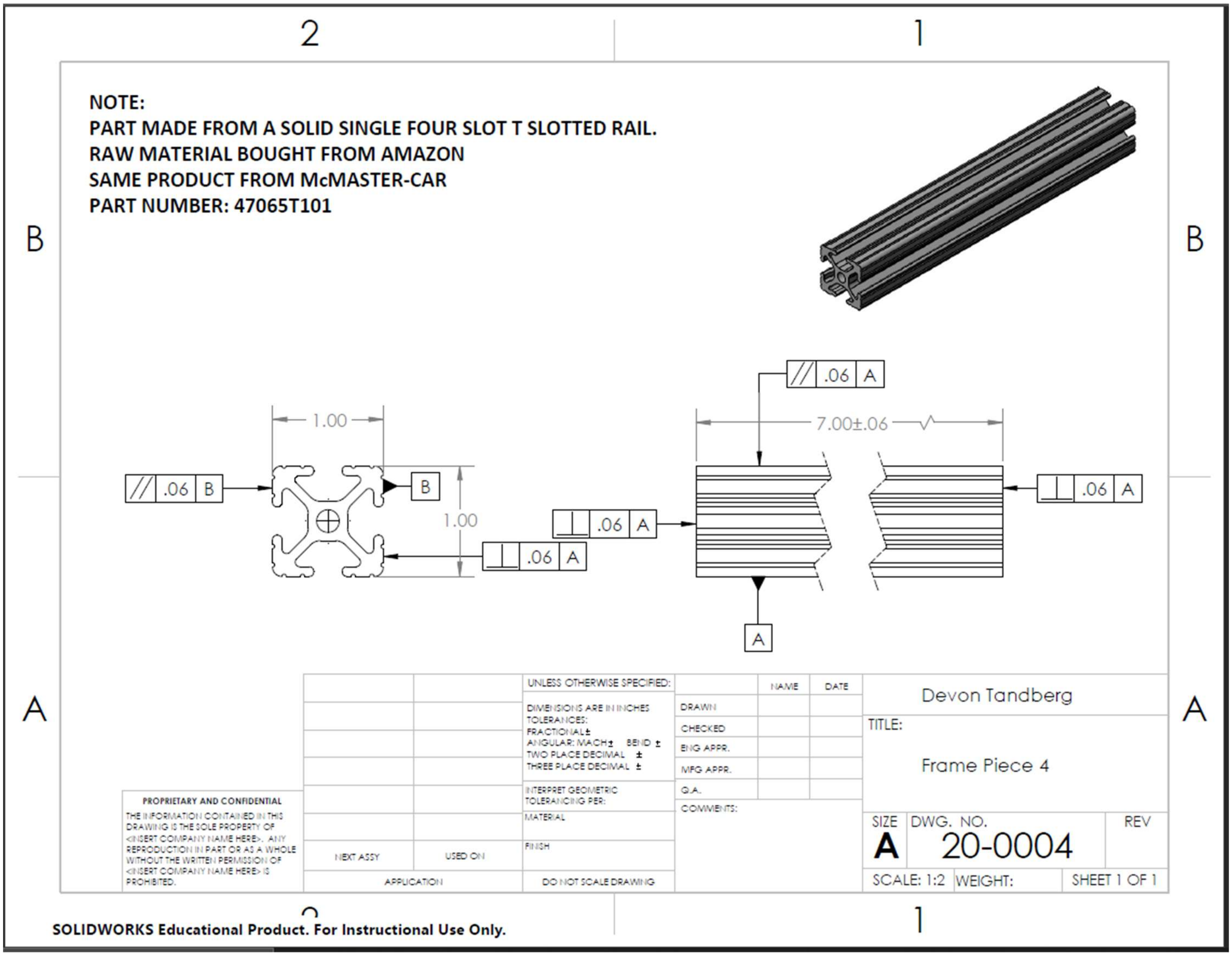

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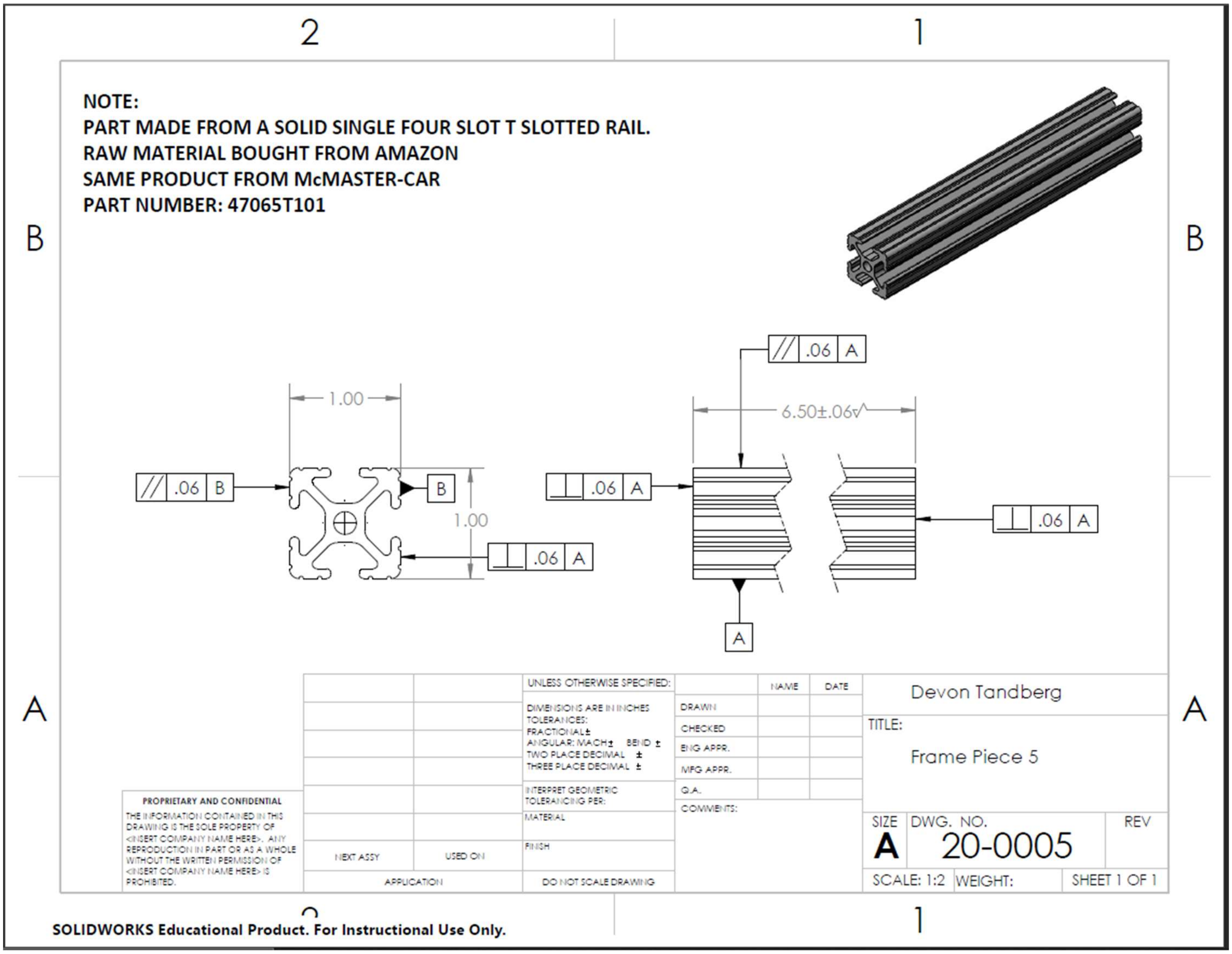
Figure B5: Part 20-0005 Drawing – Frame Piece 5 Length 6.5”



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TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH

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MFG APPR.
Q.A.
COMMENTS:

Devon Tandberg

TITLE: Frame Piece 5

SIZE: A
DWG. NO. 20-0005
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1

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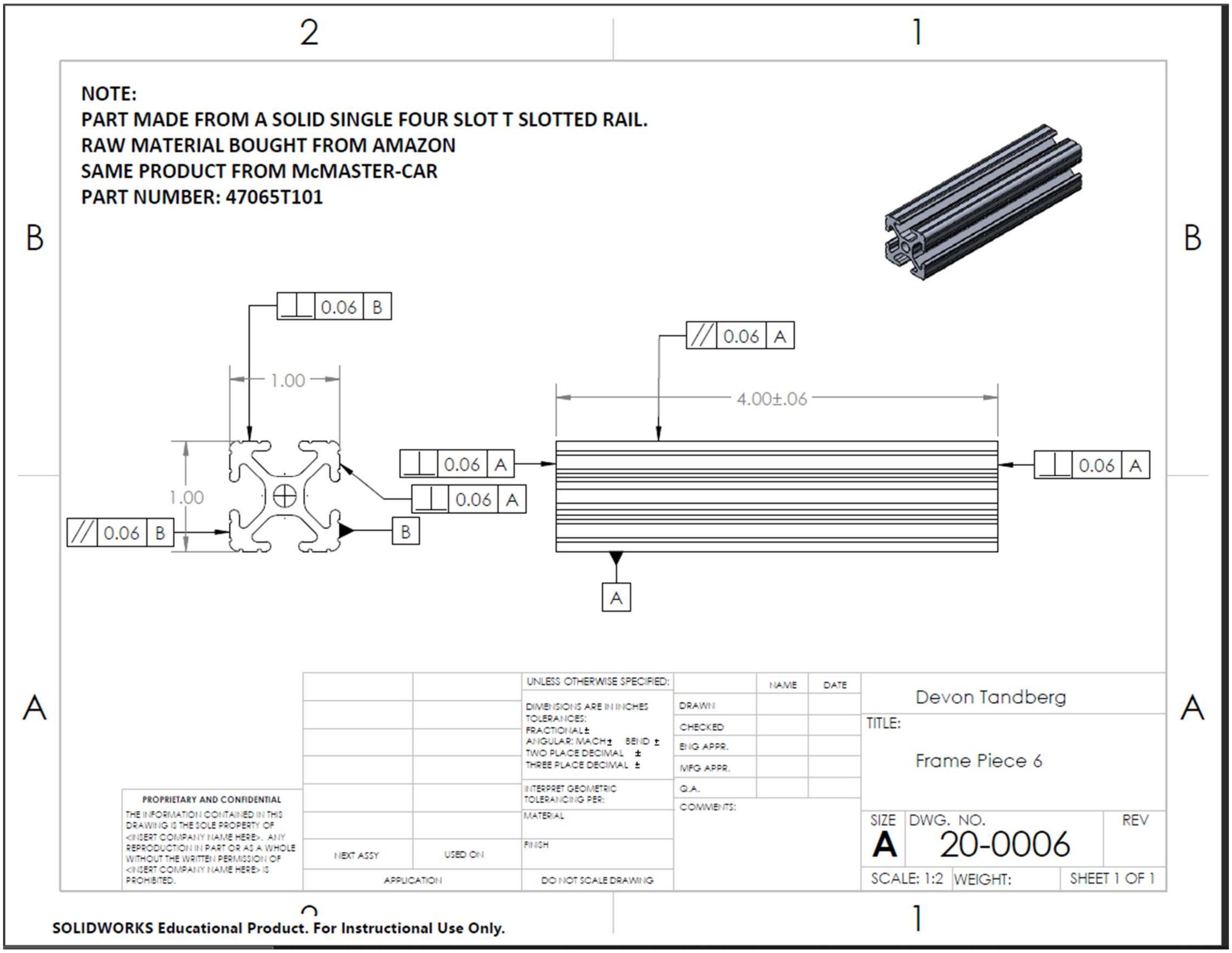
Figure B6: Part 20-0006 Drawing – Frame Piece 6 Length 4”



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RAW MATERIAL BOUGHT FROM AMAZON
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PART NUMBER: 47065T101

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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
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COMMENTS:

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TITLE:
Frame Piece 6

SIZE A DWG. NO. 20-0006 REV
SCALE: 1:2 WEIGHT: SHEET 1 OF 1

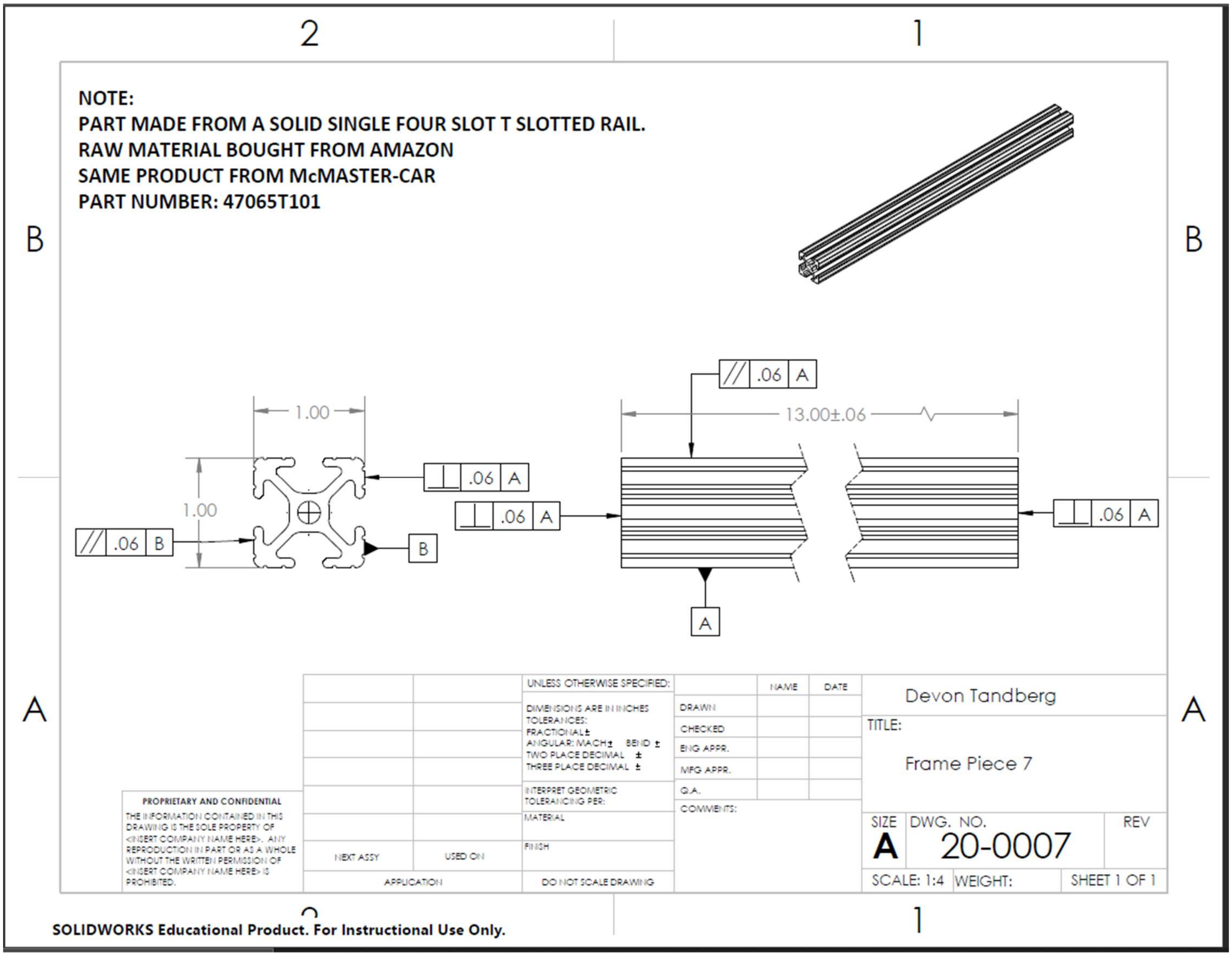

Figure B7: Part 20-0007 Drawing – Frame Piece 7 Length 13”

NOTE:
PART MADE FROM A SOLID SINGLE FOUR SLOT T SLOTTED RAIL.
RAW MATERIAL BOUGHT FROM AMAZON
SAME PRODUCT FROM McMASTER-CAR
PART NUMBER: 47065T101

Devon Tandberg
TITLE: Frame Piece 7
SIZE A
DWG. NO. 20-0007
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
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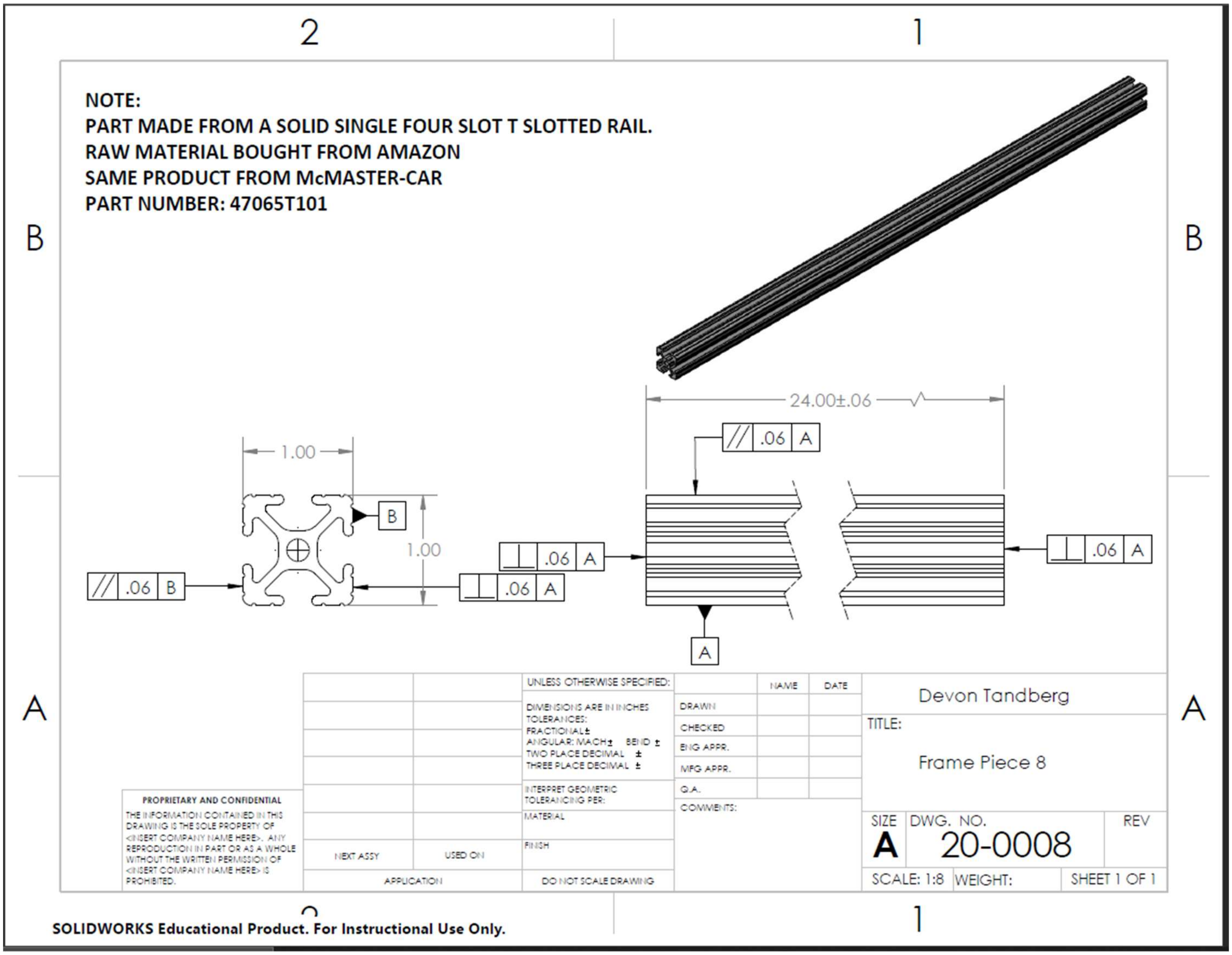
Figure B8: Part 20-0008 Drawing – Frame Piece 8 Length 24”



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PART NUMBER: 47065T101

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TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
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COMMENTS:

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TITLE: Frame Piece 8

SIZE A
DWG. NO. 20-0008
REV
SCALE: 1:8
WEIGHT:
SHEET 1 OF 1

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Figure B9: Part 20-0009 Drawing – Frame Piece 9 Length 50”

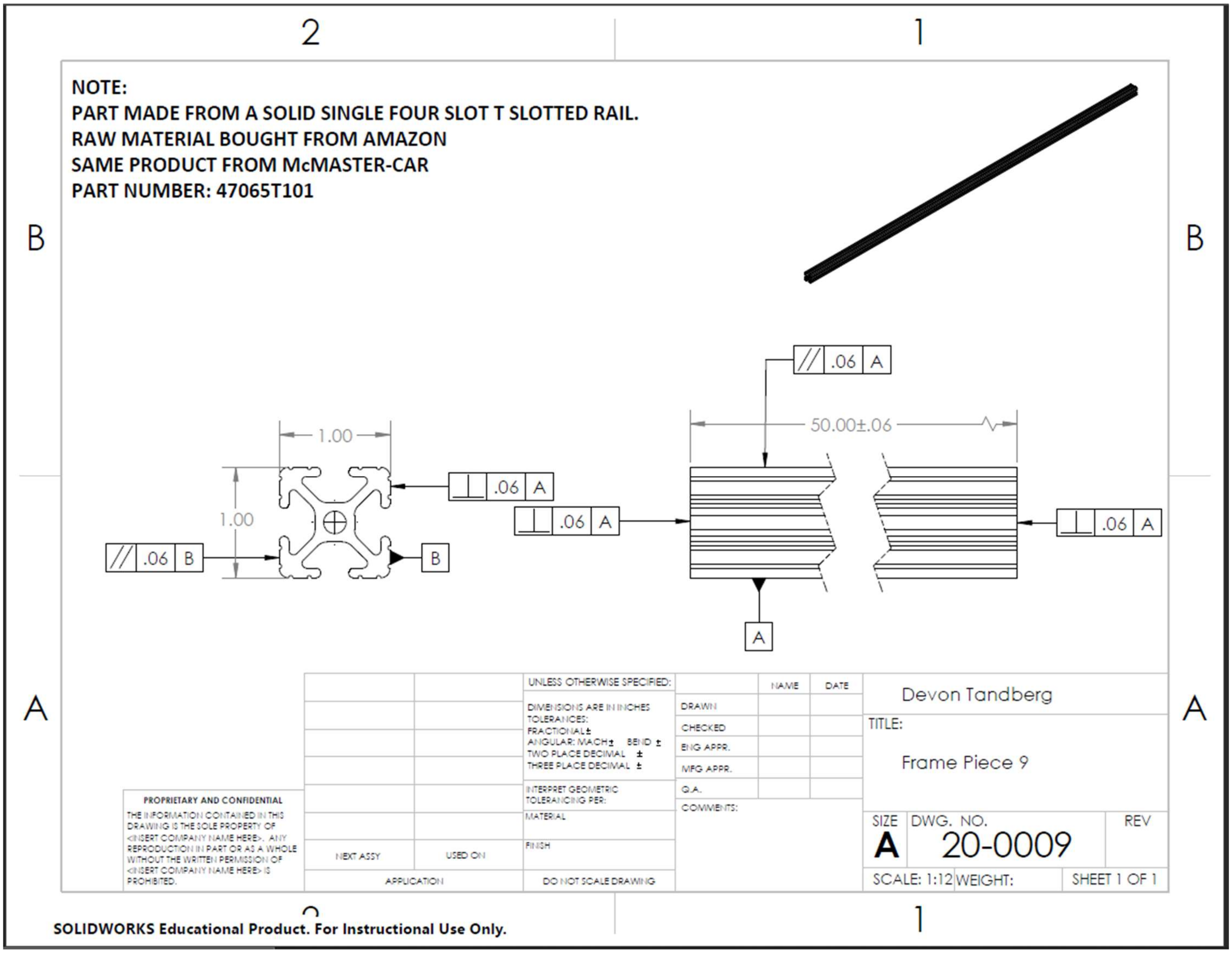


Figure B10: Part 20-0010 Drawing – Tow Bar Attachment Part

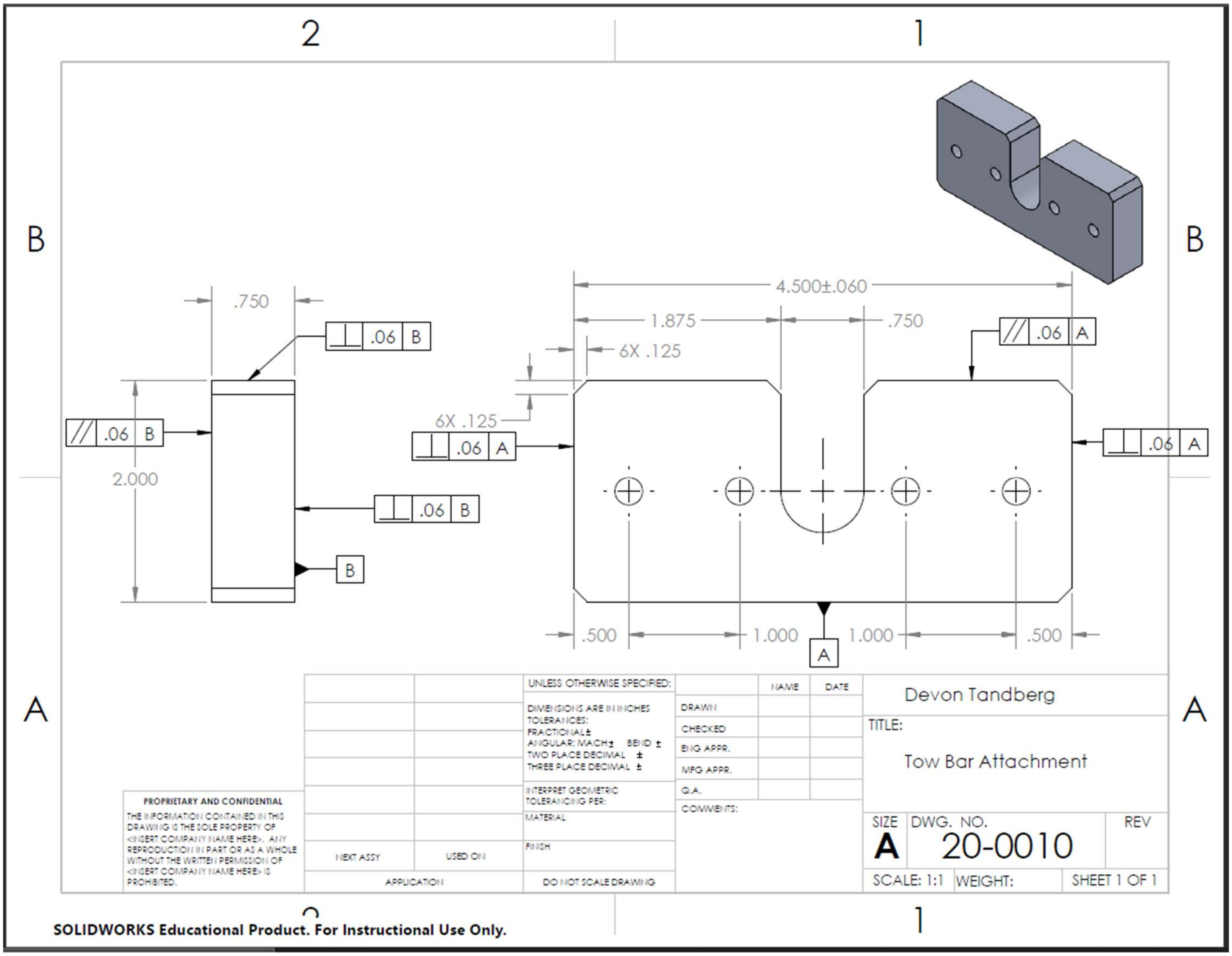


Figure B11: Part 20-0011 Drawing – 0.75in Keyed Wheel Hub

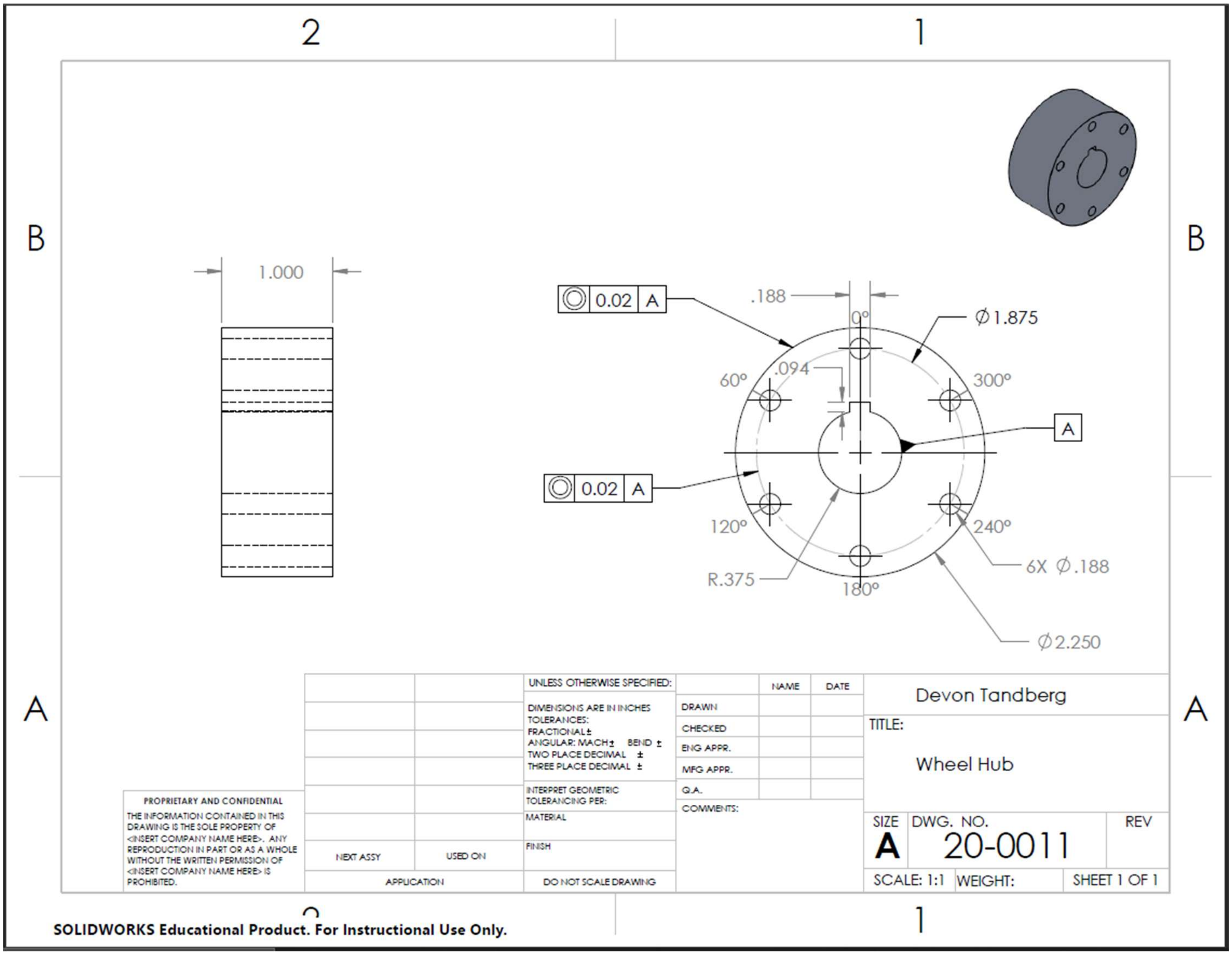
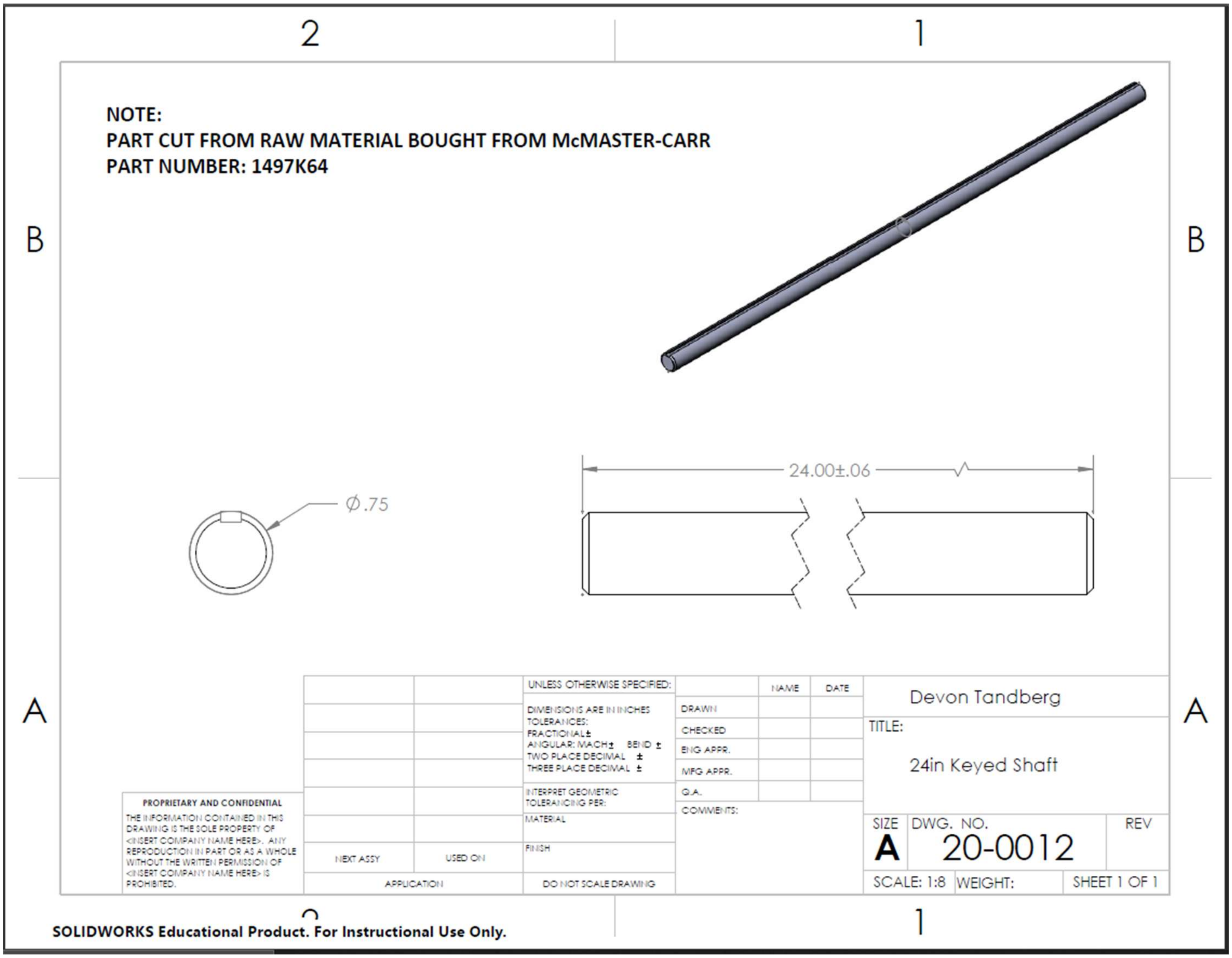
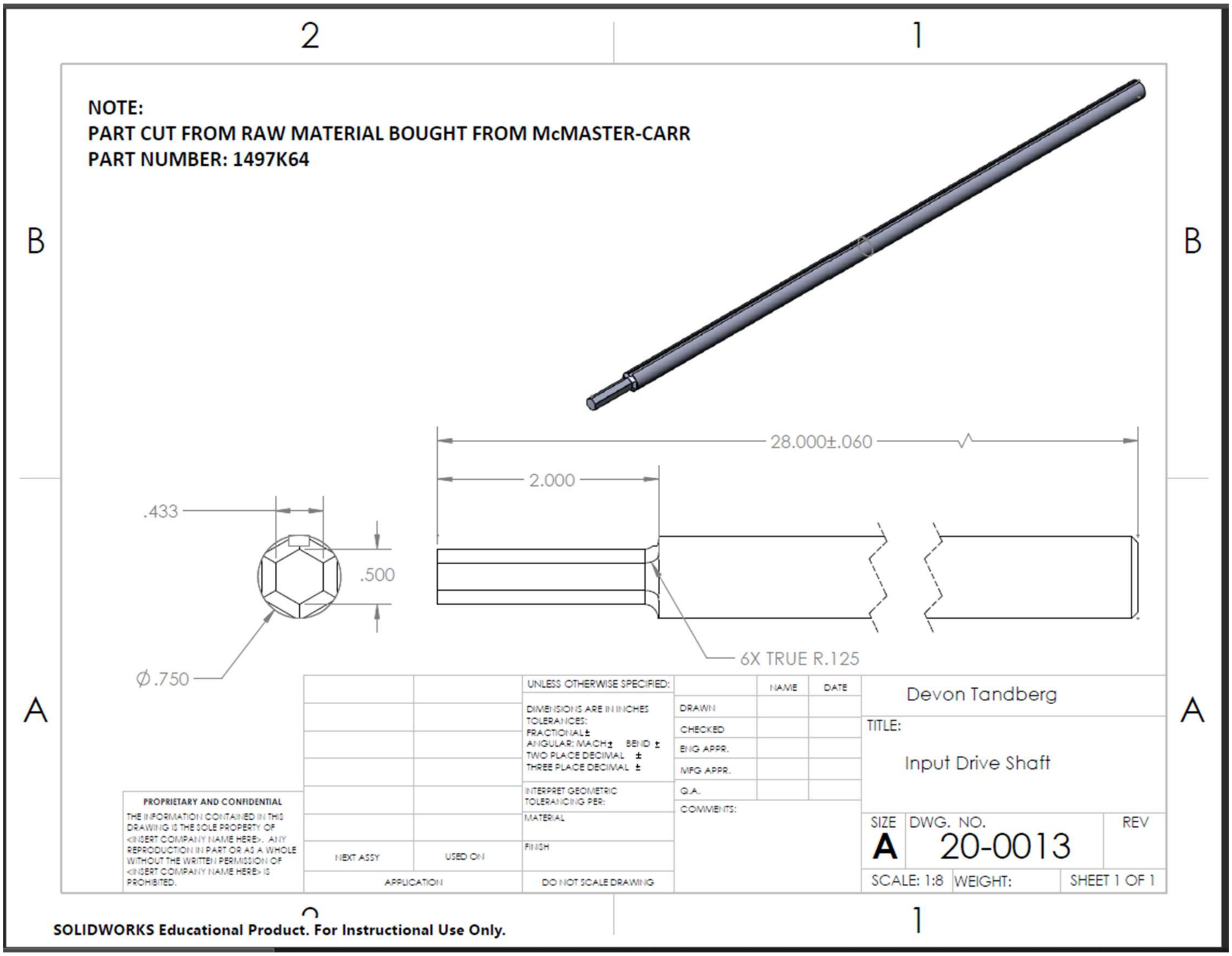


Figure B12: Part 20-0012 Drawing – 0.75in Dia. Keyed Shaft Length 24”



NOTE:
PART CUT FROM RAW MATERIAL BOUGHT FROM McMASTER-CARR
PART NUMBER: 1497K64

Figure B13: Part 20-0013 Drawing – Drive Shaft



NOTE:
PART CUT FROM RAW MATERIAL BOUGHT FROM McMASTER-CARR
PART NUMBER: 1497K64

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TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Devon Tandberg
TITLE:
Input Drive Shaft

SIZE A | DWG. NO. 20-0013 | REV
SCALE: 1:8 | WEIGHT: | SHEET 1 OF 1

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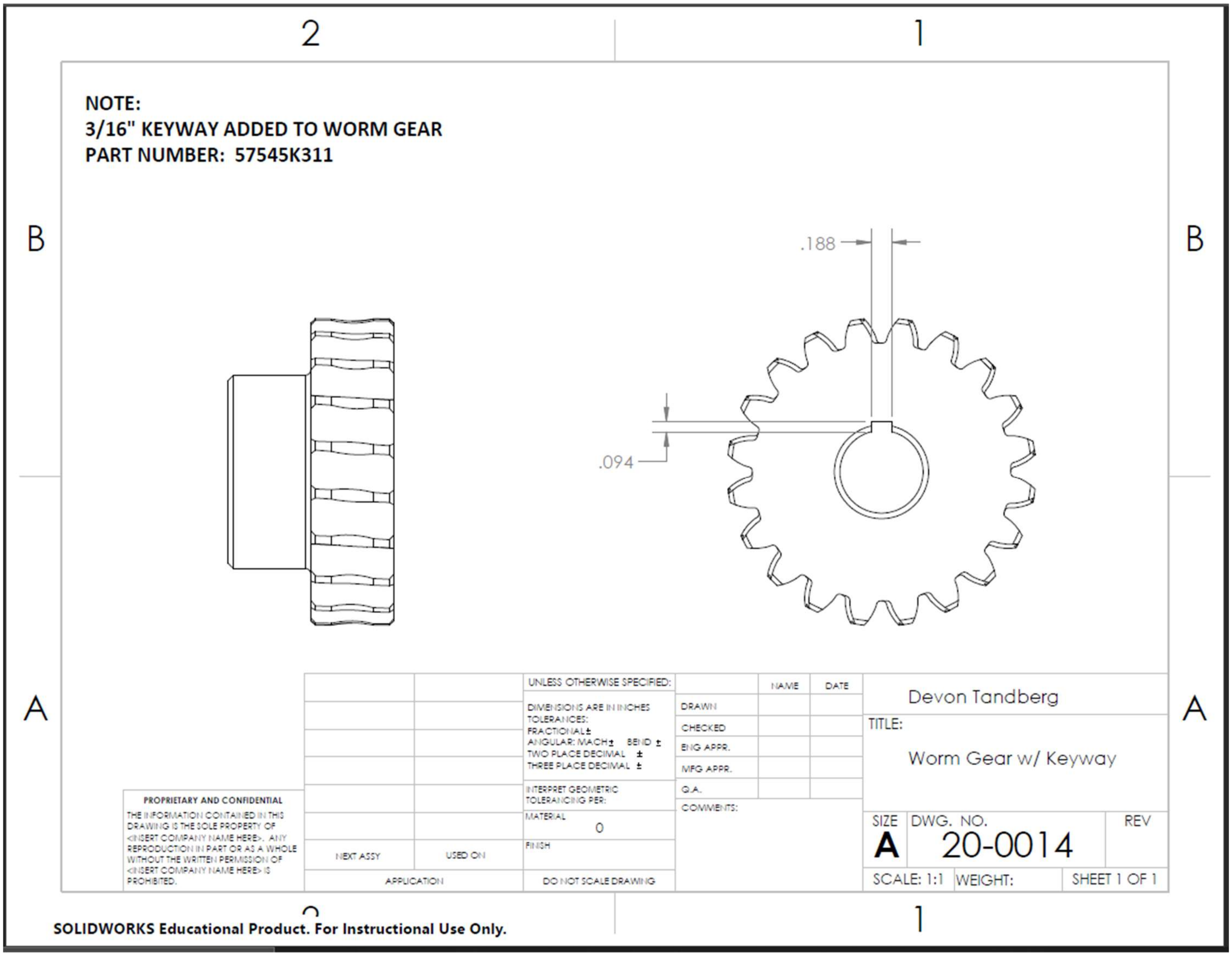
Figure B14: Part 20-0014 Drawing – Worm Gear w/ Keyway



NOTE:
3/16" KEYWAY ADDED TO WORM GEAR
PART NUMBER: 57545K311

DRAWN: Devon Tandberg

TITLE: Worm Gear w/ Keyway

SIZE: A

DWG. NO. 20-0014

MATERIAL: 0

SCALE: 1:1

WEIGHT:

SHEET 1 OF 1

Figure B15: Part 50-0001 Drawing – Worm Drawing (McMaster-Carr)

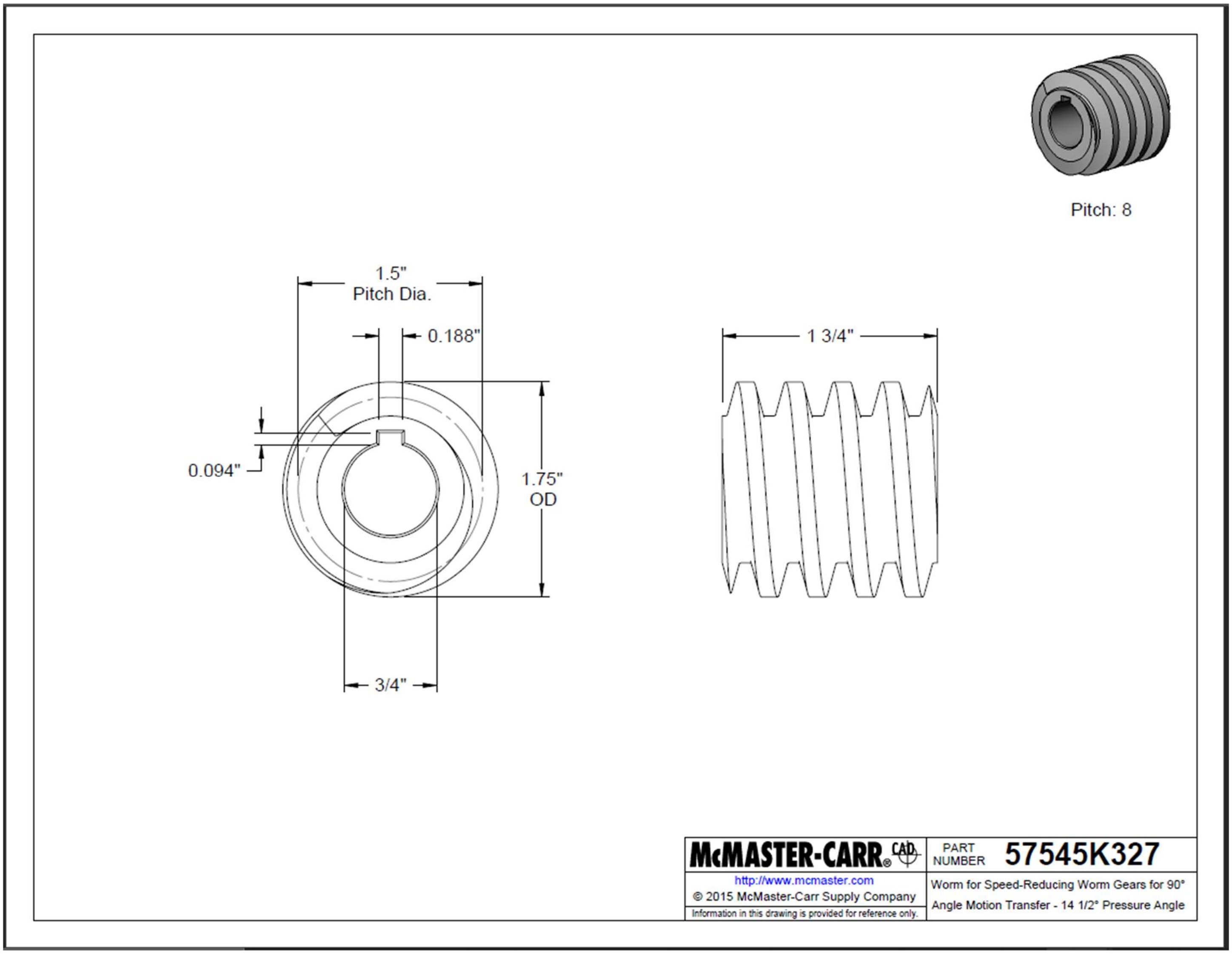


Figure B16: Part 50-0002 Drawing – Drive Train 0.75in Keyed Shaft

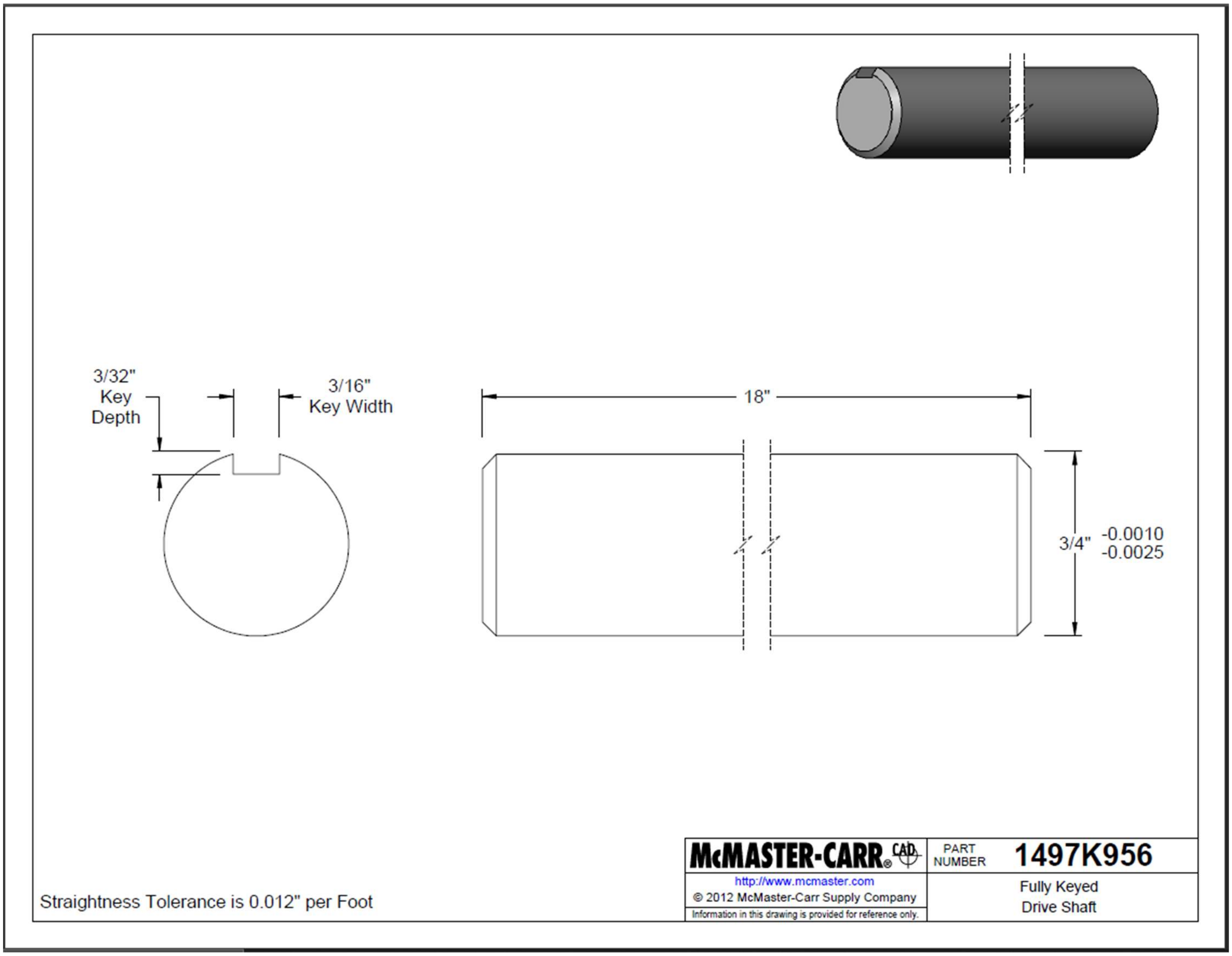


Figure B17: Part 50-0003 Drawing – Tee T Slot Bracket

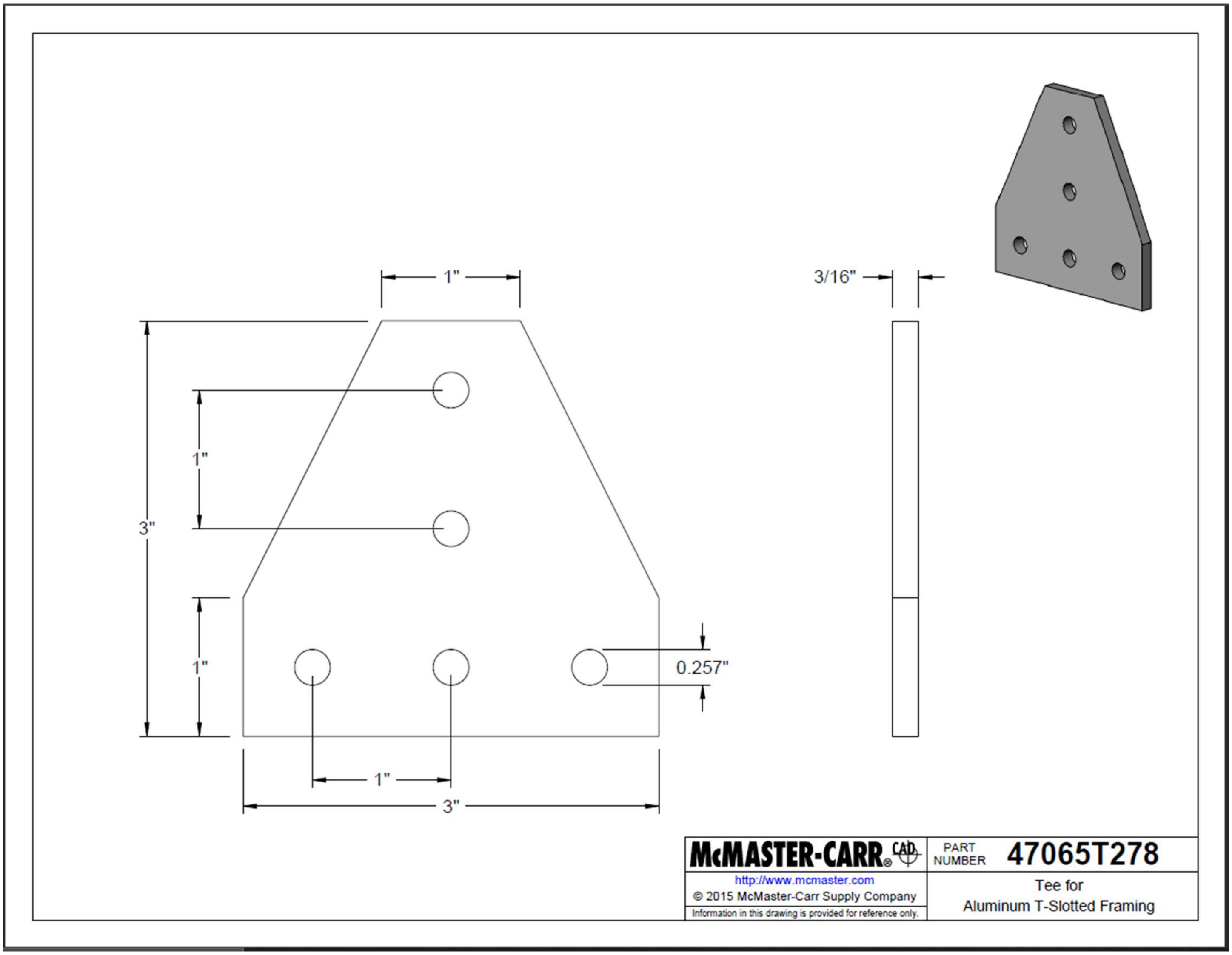


Figure B18: Part 50-0004 Drawing – 45 T Slot Bracket

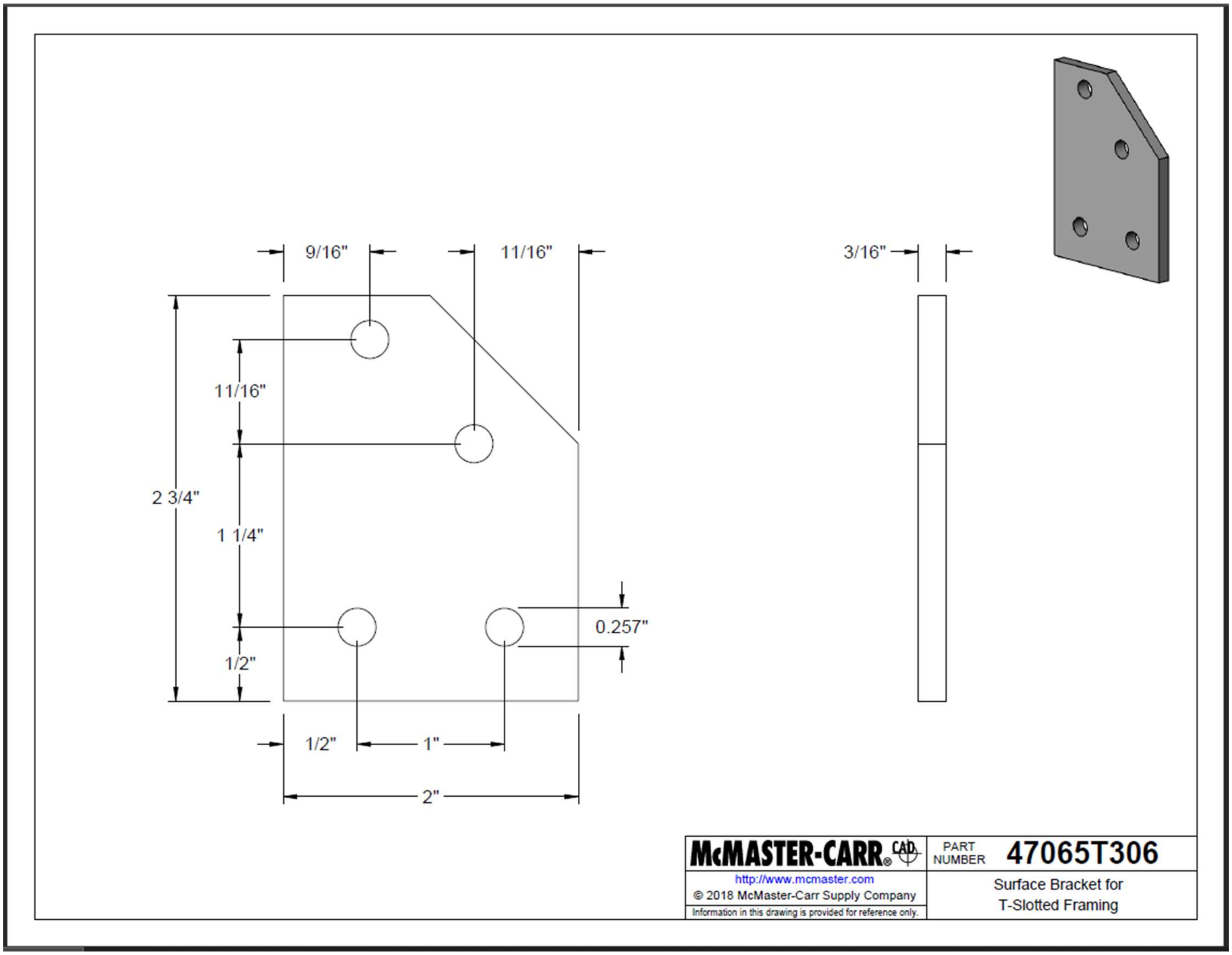


Figure B19: Part 50-0005 Drawing – Single T Slot Gusset

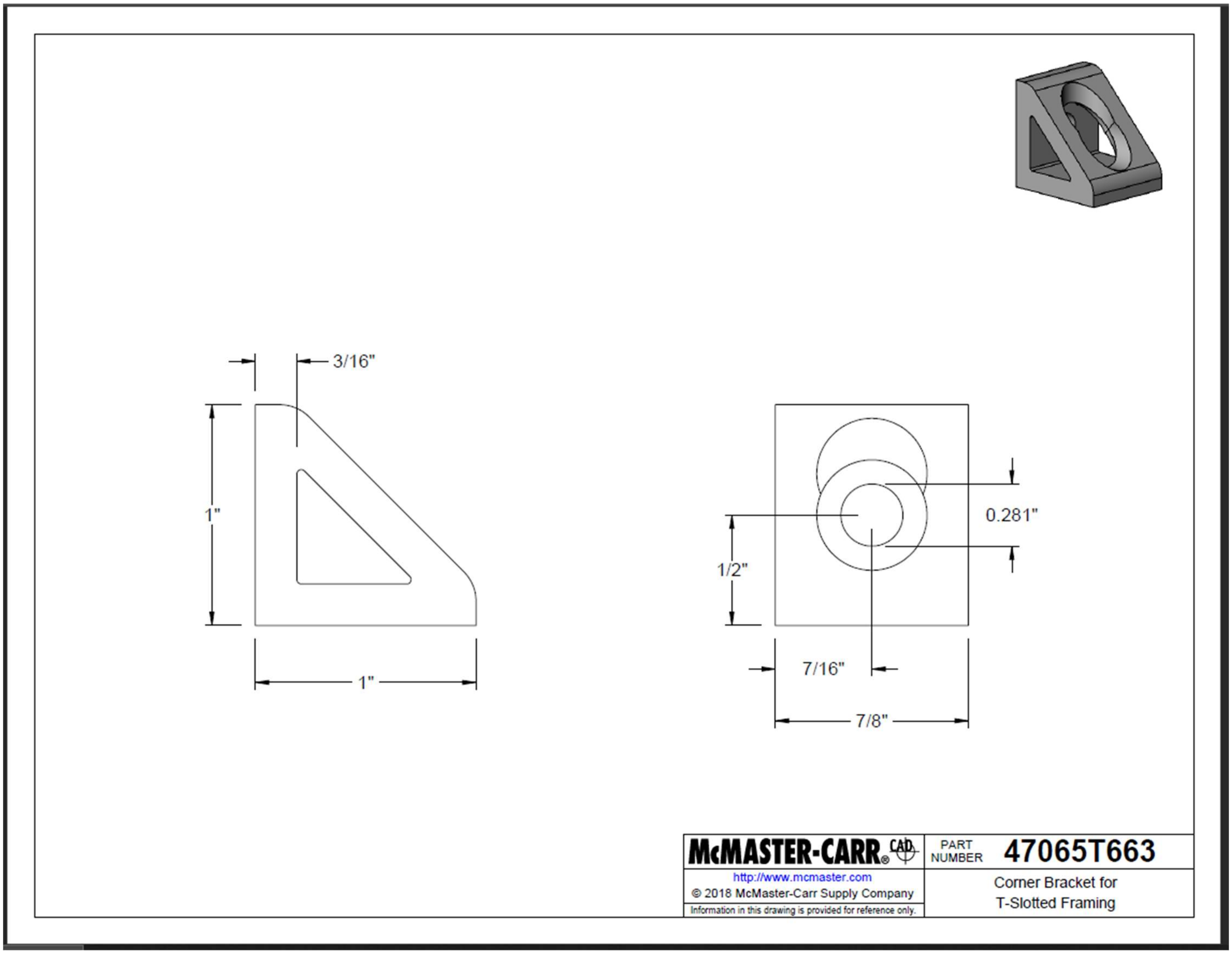


Figure B20: Part 50-0006 Drawing – Double Single T Slot Gusset

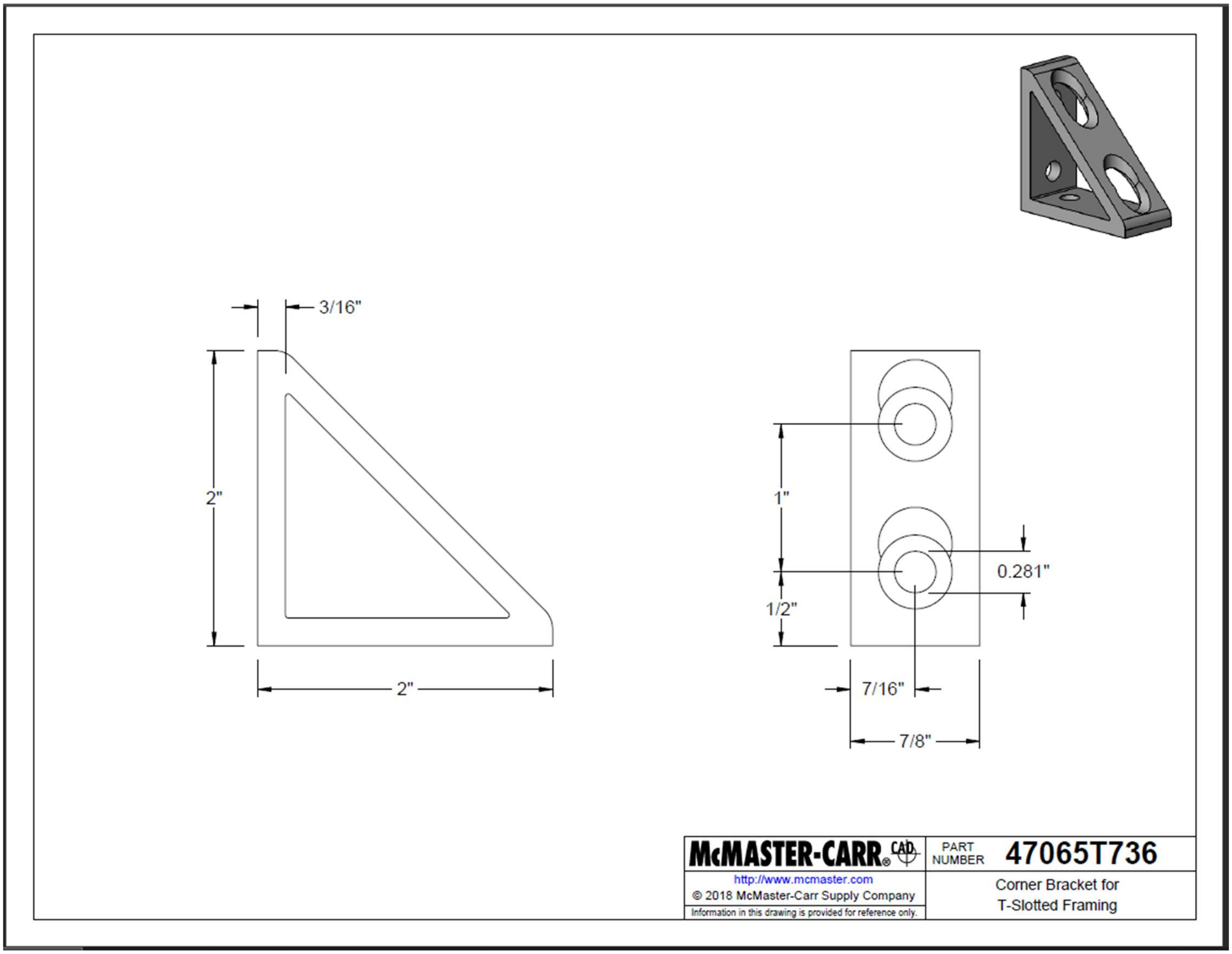


Figure B21: Part 50-0008 Drawing - Locking T Slot Connector

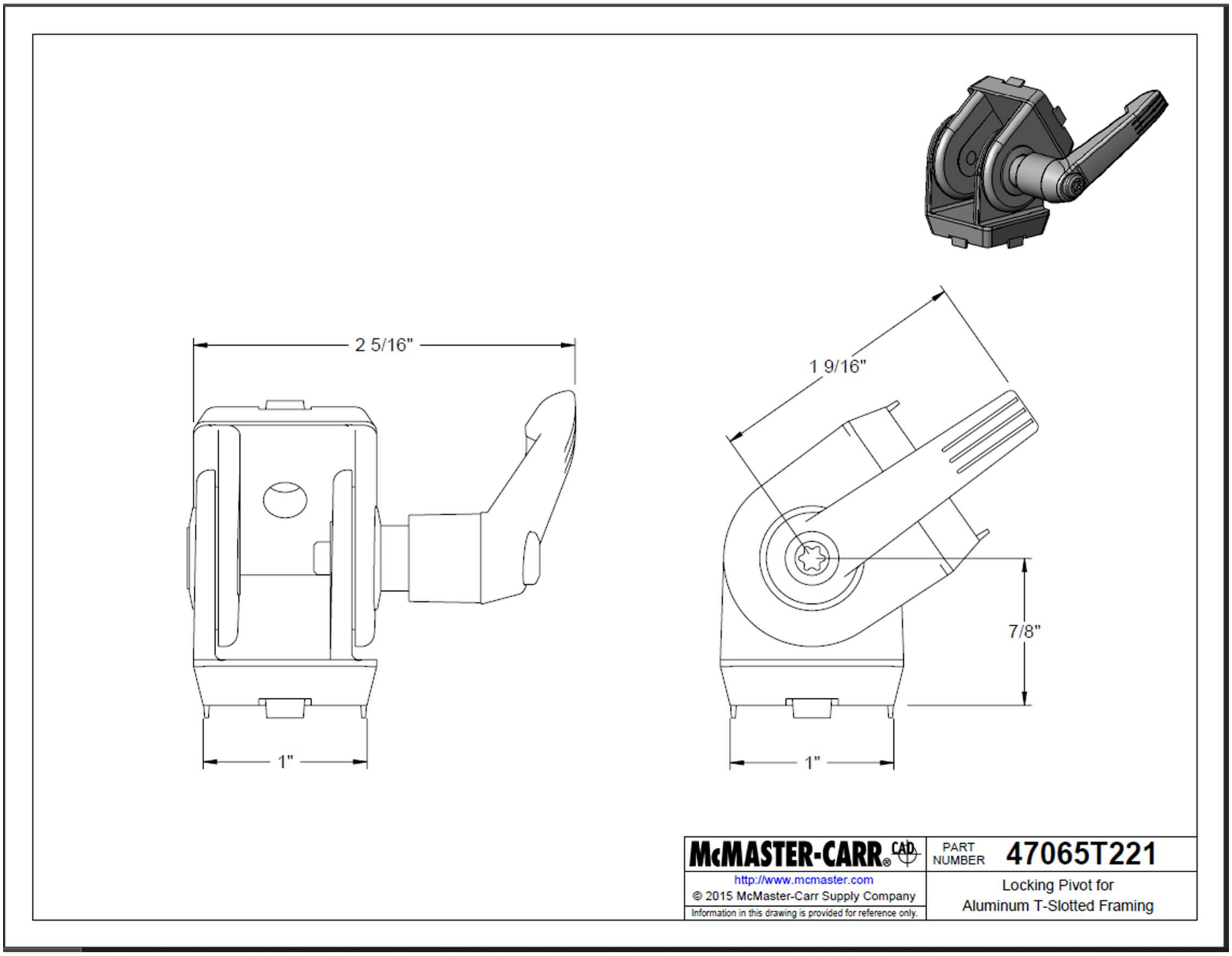


Figure B22: Part 50-0009 Drawing – 0.75” Dia. Collar

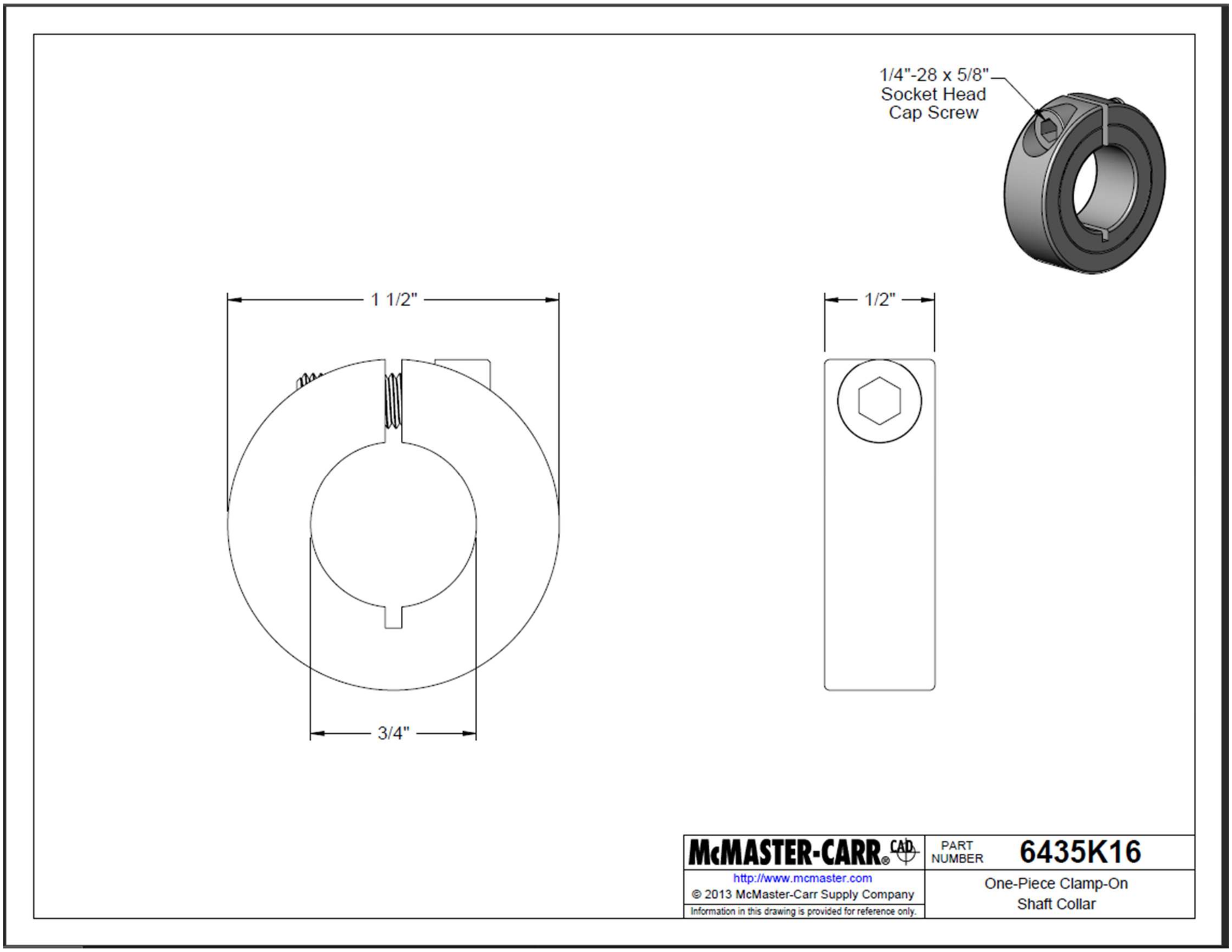


Figure B23: Part 50-0010 Drawing – 0.75in Dia. Mounted Ball Bearing

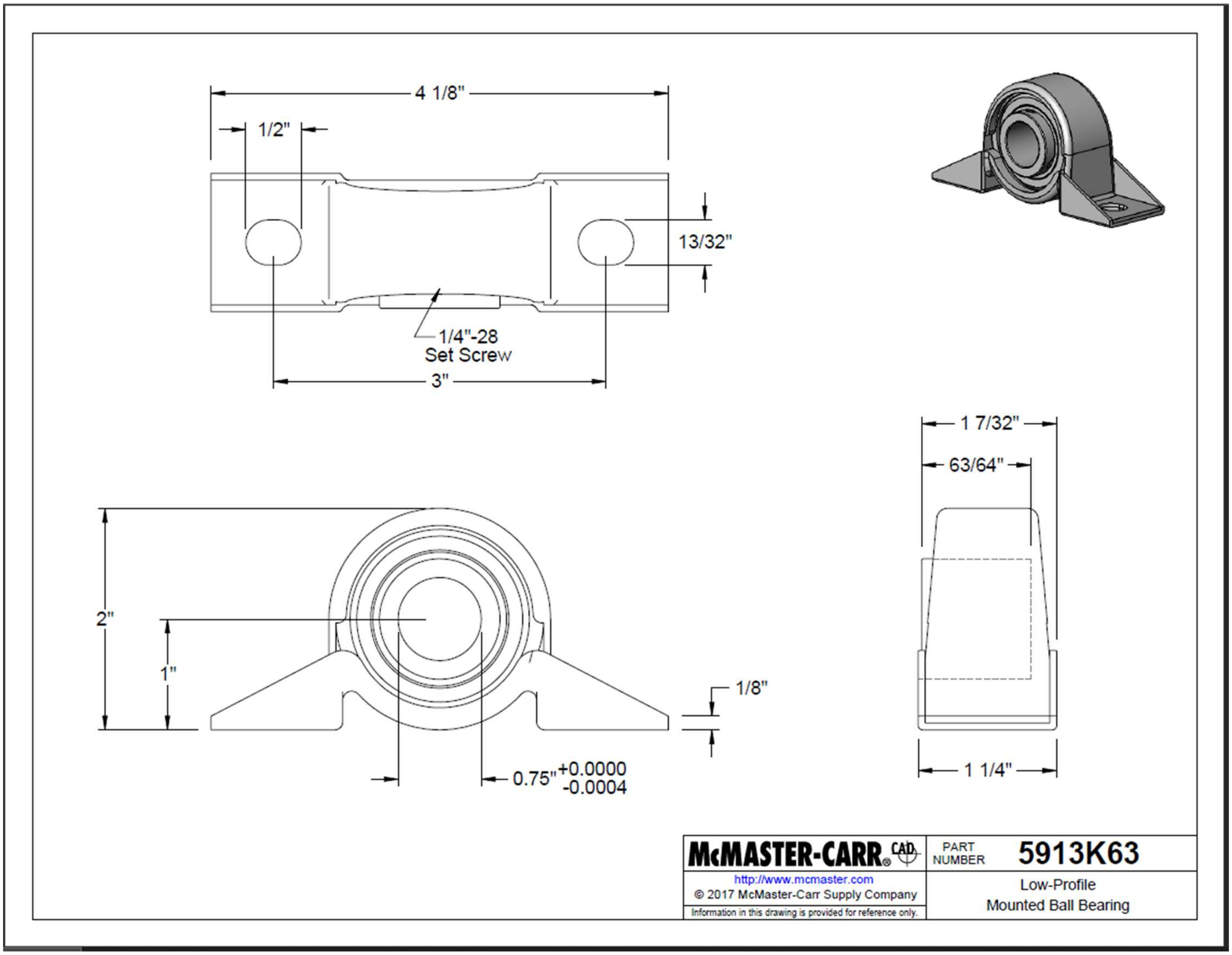


Figure B24: Part 50-0011 Drawing – 0.75” Dia. Coupling

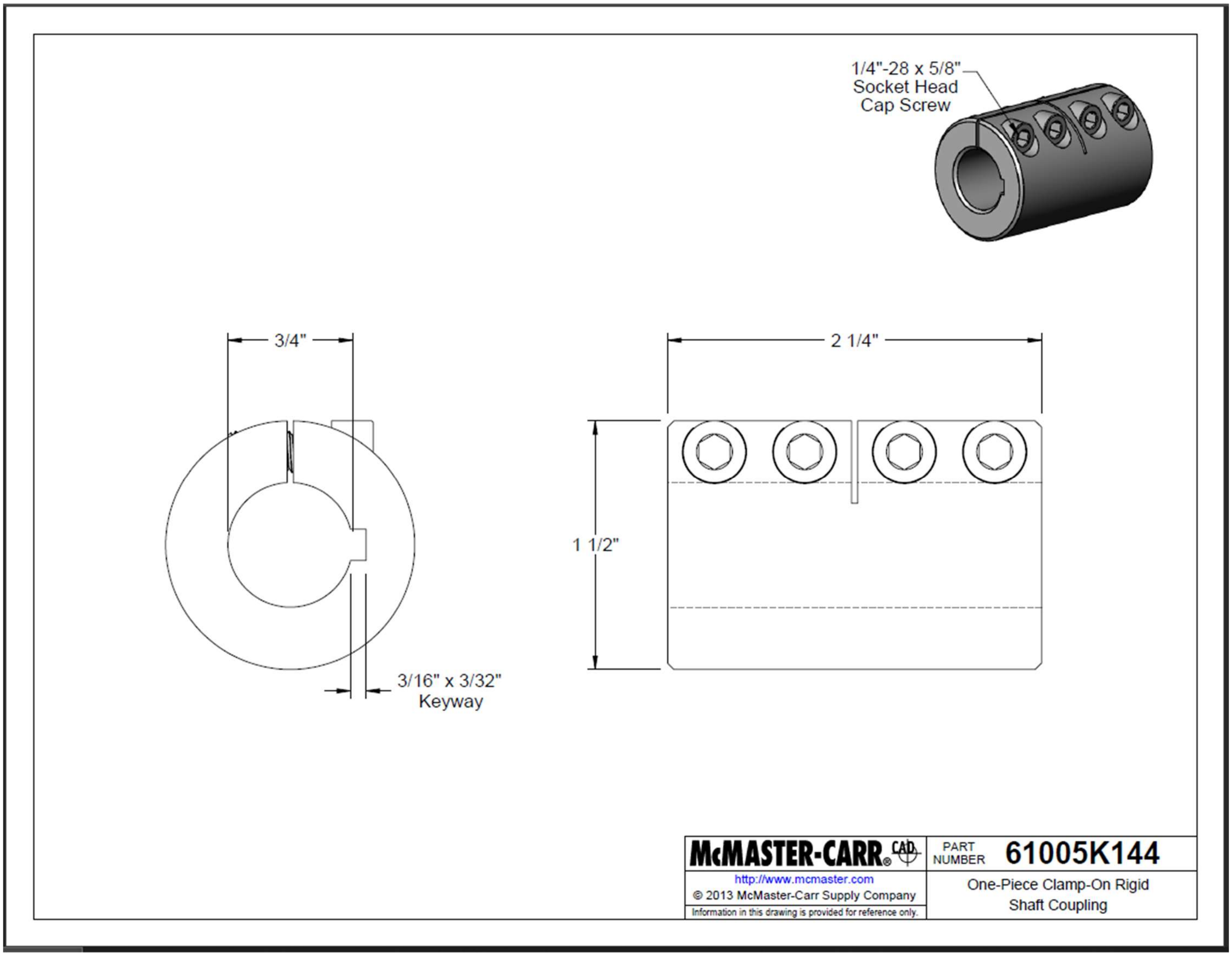


Figure B25: Part 50-0012 Drawing – 8in Pneumatic Wheel

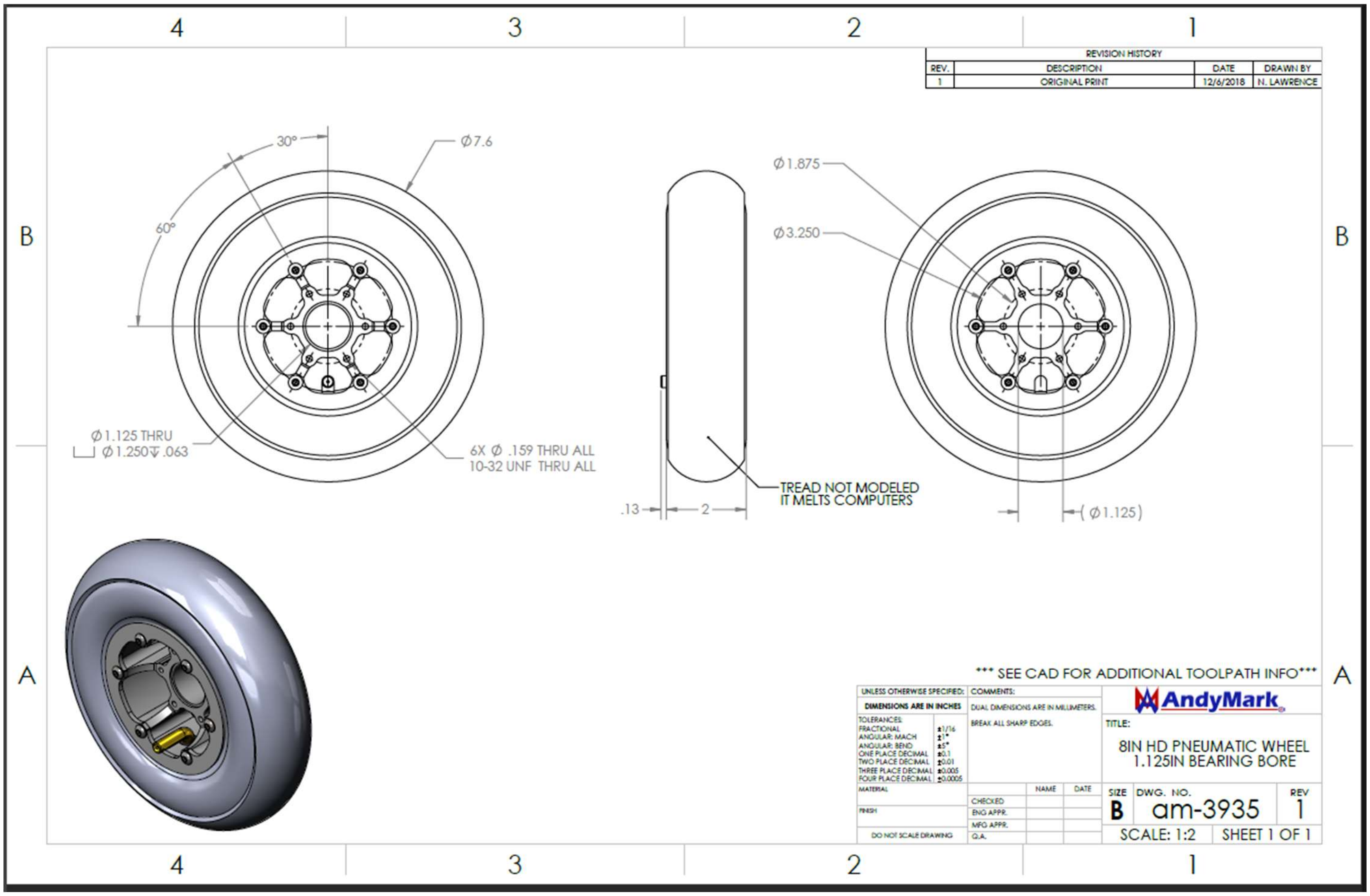


Figure B26: Part 50-0013 Drawing – T Slot Fastener

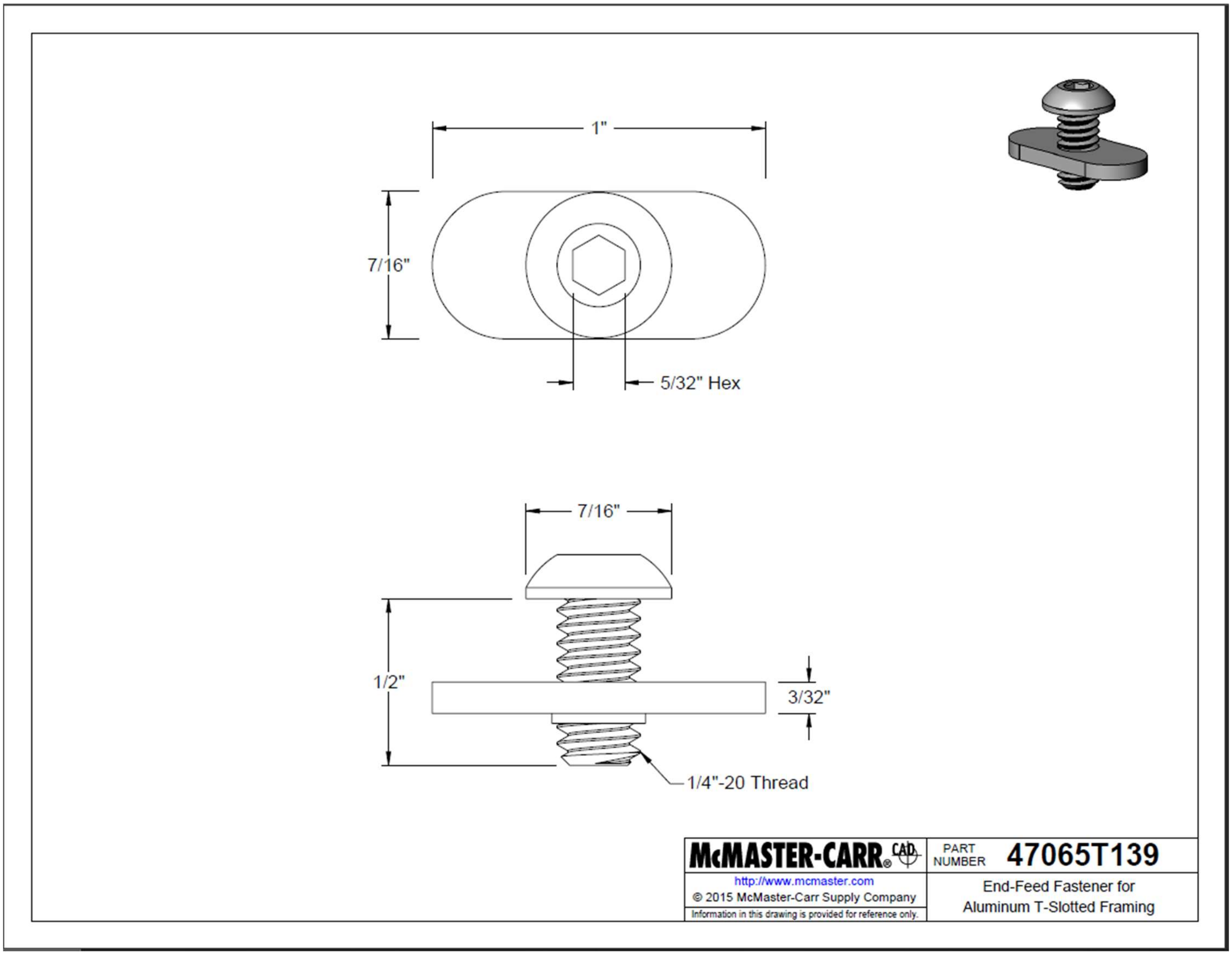


Figure B27: Part 50-0014 Drawing – 0.25in Dia. Washer

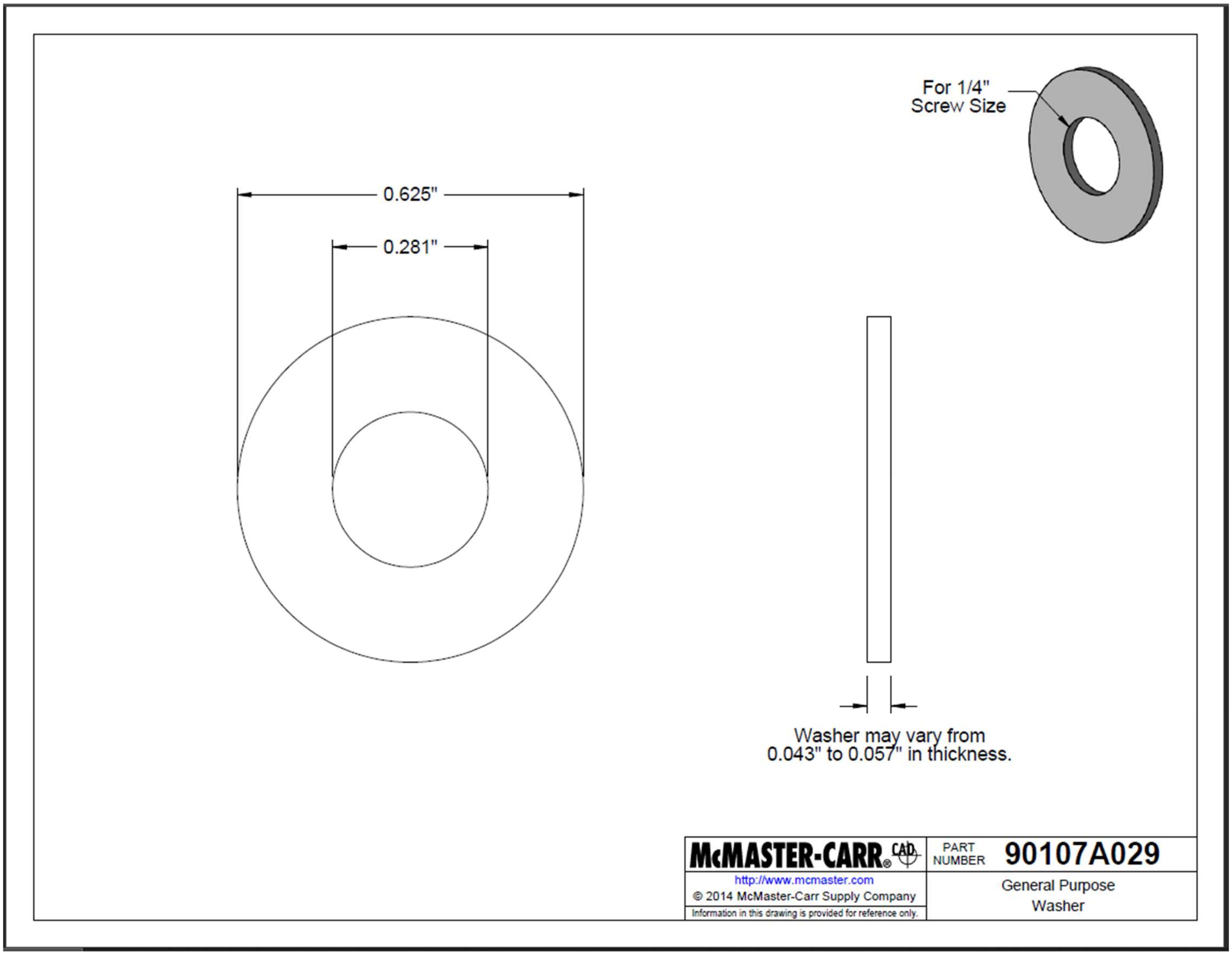
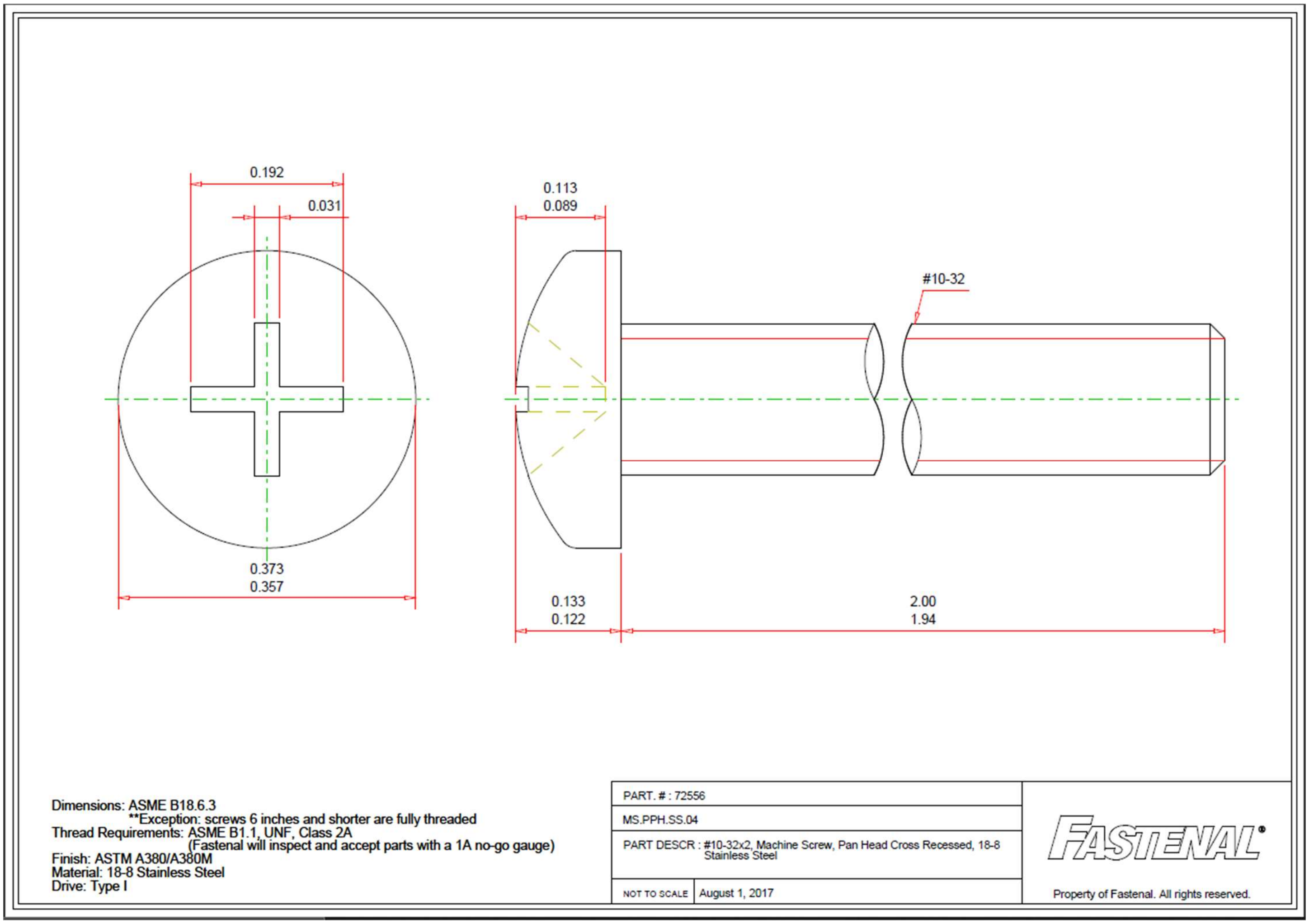


Figure B28: Part 50-0015 Drawing – 10-32 Screw Length 2”



Dimensions: ASME B18.6.3
**Exception: screws 6 inches and shorter are fully threaded
Thread Requirements: ASME B1.1, UNF, Class 2A
(Fastenal will inspect and accept parts with a 1A no-go gauge)
Finish: ASTM A380/A380M
Material: 18-8 Stainless Steel
Drive: Type I

PART. # : 72556

MS.PPH.SS.04

PART DESCR : #10-32x2, Machine Screw, Pan Head Cross Recessed, 18-8 Stainless Steel

NOT TO SCALE August 1, 2017

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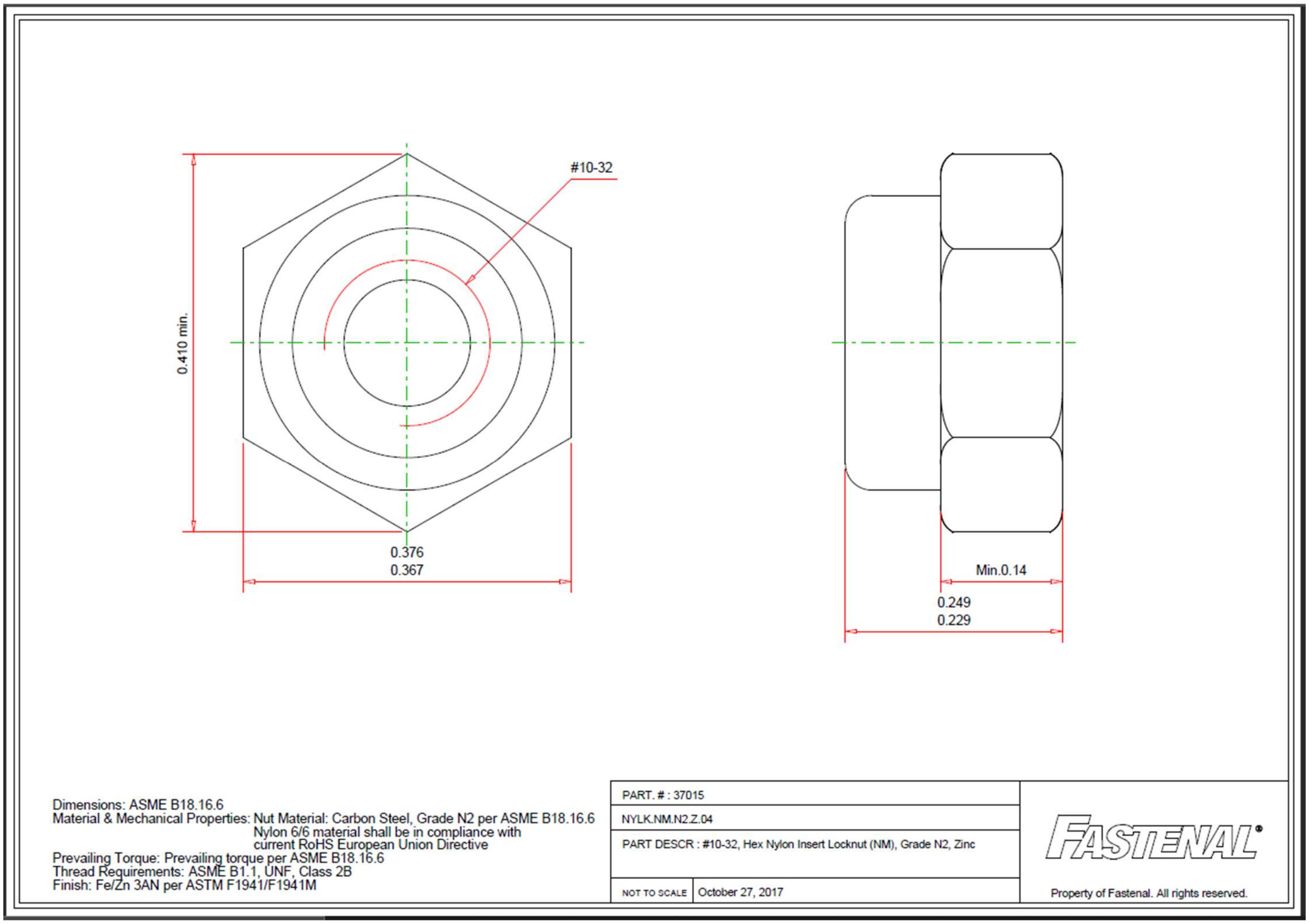
Figure B29: Part 50-0016 Drawing – 10-32 Nut



Dimensions: ASME B18.16.6
Material & Mechanical Properties: Nut Material: Carbon Steel, Grade N2 per ASME B18.16.6
Nylon 6/6 material shall be in compliance with current RoHS European Union Directive
Prevailing Torque: Prevailing torque per ASME B18.16.6
Thread Requirements: ASME B1.1, UNF, Class 2B
Finish: Fe/Zn 3AN per ASTM F1941/F1941M

PART. # : 37015
NYLK.NM.N2.Z.04
PART DESCR : #10-32, Hex Nylon Insert Locknut (NM), Grade N2, Zinc
NOT TO SCALE October 27, 2017

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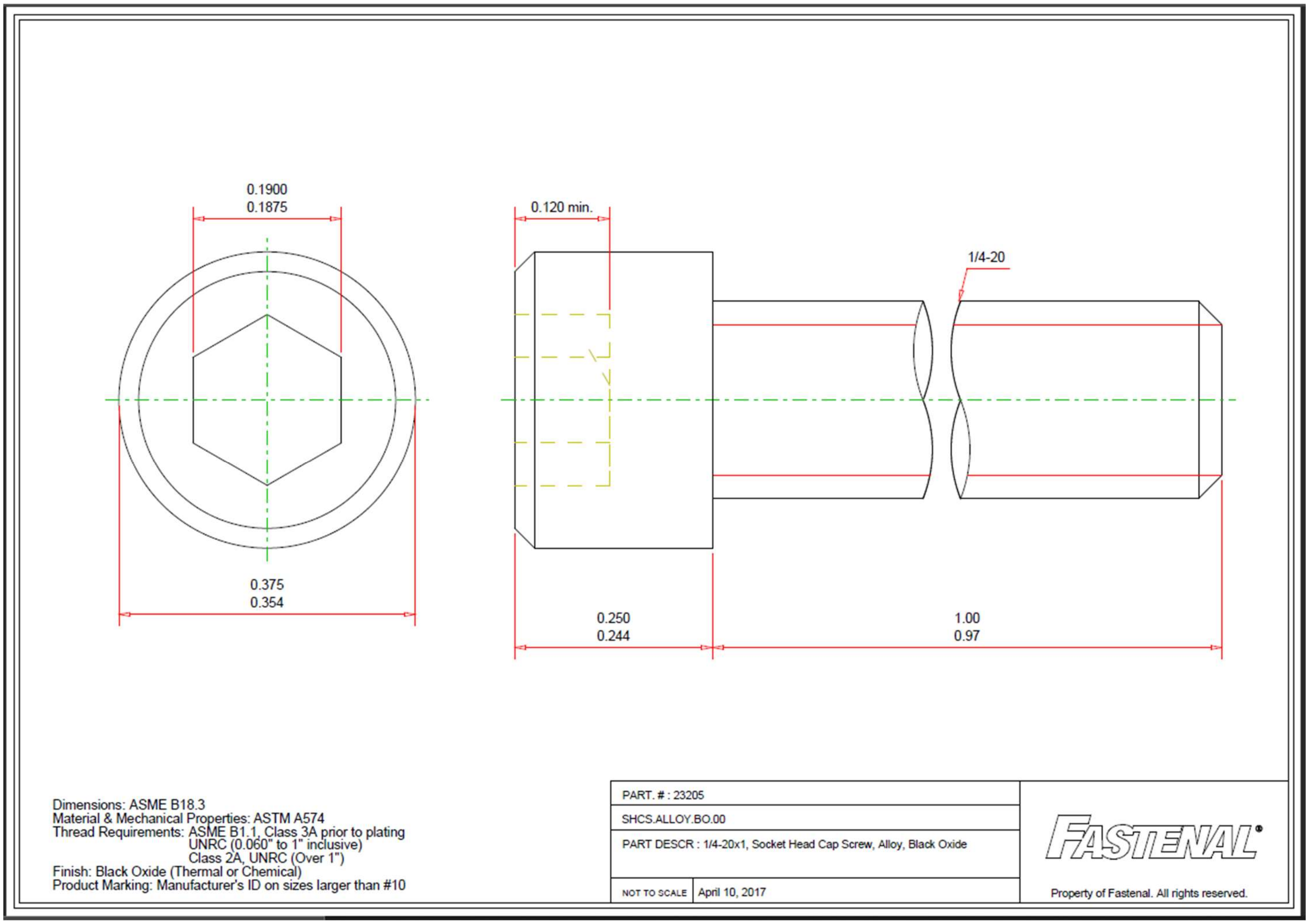
Figure B30: Part 50-0017 Drawing – 23205 Fastenal Drawing



Dimensions: ASME B18.3
Material & Mechanical Properties: ASTM A574
Thread Requirements: ASME B1.1, Class 3A prior to plating
UNRC (0.060" to 1" inclusive)
Class 2A, UNRC (Over 1")
Finish: Black Oxide (Thermal or Chemical)
Product Marking: Manufacturer's ID on sizes larger than #10

PART. # : 23205
SHCS.ALLOY.BO.00
PART DESCR : 1/4-20x1, Socket Head Cap Screw, Alloy, Black Oxide
NOT TO SCALE
April 10, 2017

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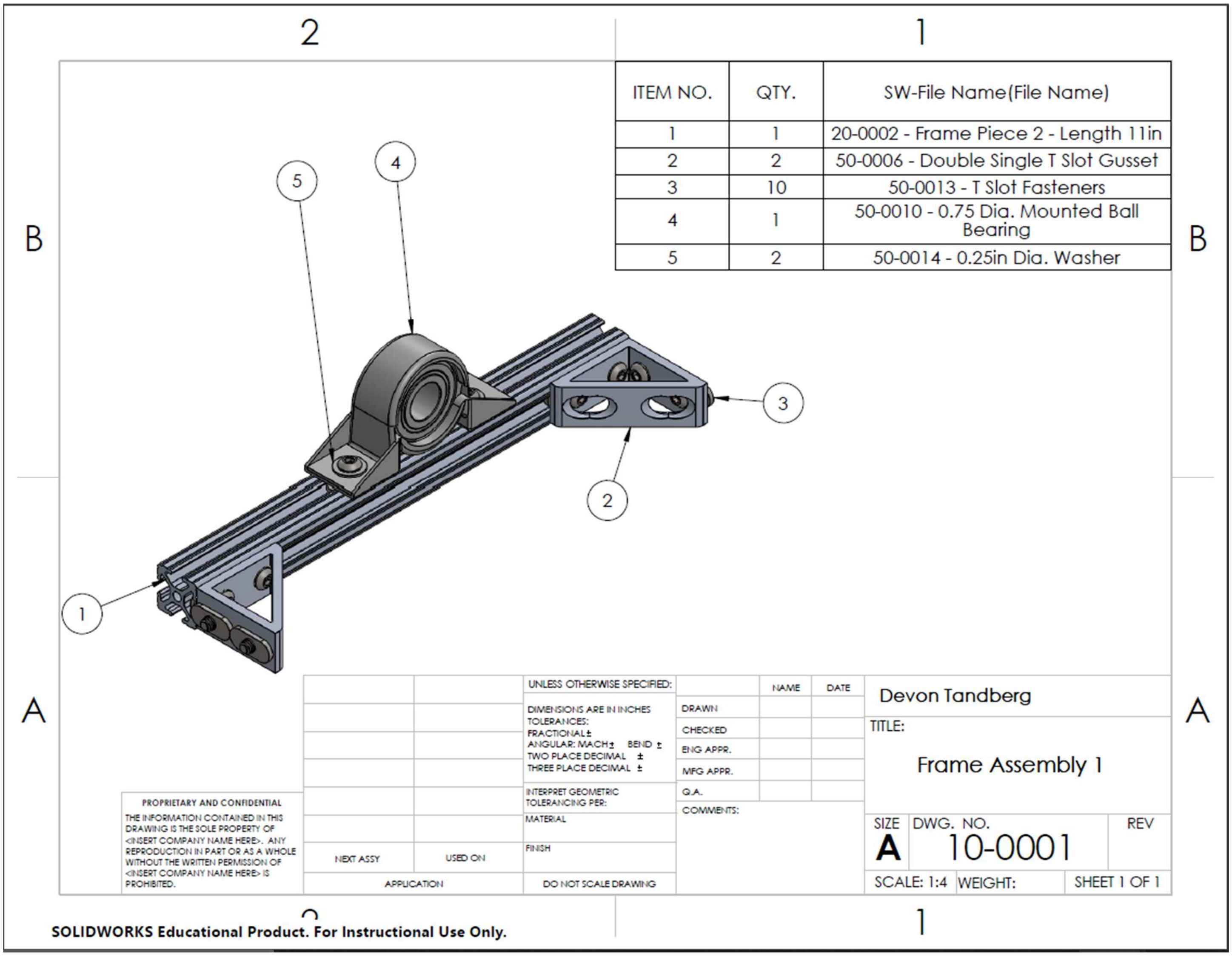
Figure B31: Assembly 10-0001 Drawing – Frame Assembly 1



ITEM NO.	QTY.	SW-File Name(File Name)
1	1	20-0002 - Frame Piece 2 - Length 11in
2	2	50-0006 - Double Single T Slot Gusset
3	10	50-0013 - T Slot Fasteners
4	1	50-0010 - 0.75 Dia. Mounted Ball Bearing
5	2	50-0014 - 0.25in Dia. Washer

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TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

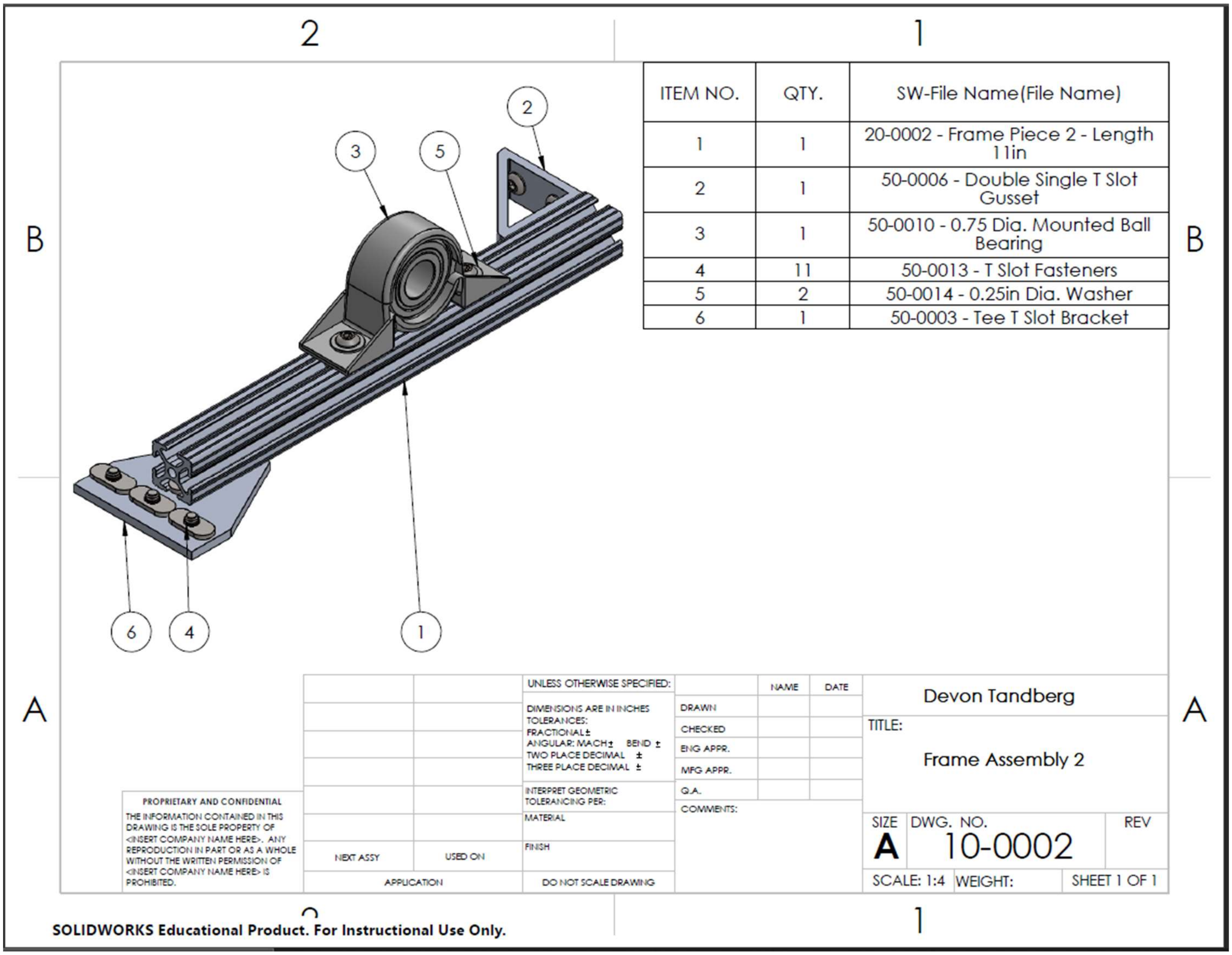
COMMENTS:

Devon Tandberg

TITLE:
Frame Assembly 1

SIZE **A**
DWG. NO. 10-0001
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1

Figure B32: Assembly 10-0002 Drawing – Frame Assembly 2



ITEM NO.	QTY.	SW-File Name(File Name)
1	1	20-0002 - Frame Piece 2 - Length 11in
2	1	50-0006 - Double Single T Slot Gusset
3	1	50-0010 - 0.75 Dia. Mounted Ball Bearing
4	11	50-0013 - T Slot Fasteners
5	2	50-0014 - 0.25in Dia. Washer
6	1	50-0003 - Tee T Slot Bracket

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ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Devon Tandberg

TITLE:
Frame Assembly 2

SIZE A
DWG. NO. 10-0002
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1

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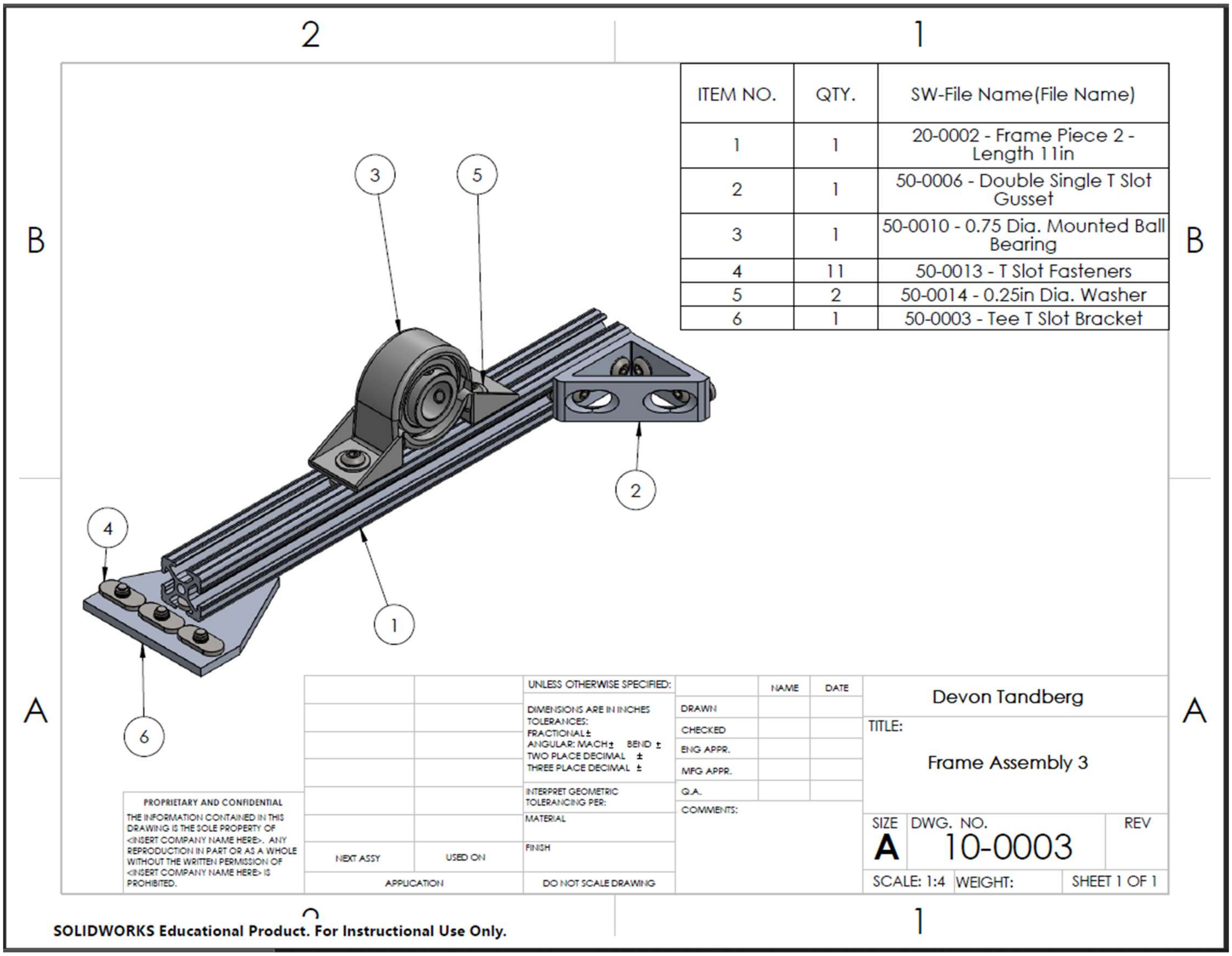
Figure B33: Assembly 10-0003 Drawing – Frame Assembly 3



ITEM NO.	QTY.	SW-File Name(File Name)
1	1	20-0002 - Frame Piece 2 - Length 11in
2	1	50-0006 - Double Single T Slot Gusset
3	1	50-0010 - 0.75 Dia. Mounted Ball Bearing
4	11	50-0013 - T Slot Fasteners
5	2	50-0014 - 0.25in Dia. Washer
6	1	50-0003 - Tee T Slot Bracket

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ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Devon Tandberg
TITLE:
Frame Assembly 3
SIZE A
DWG. NO. 10-0003
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1

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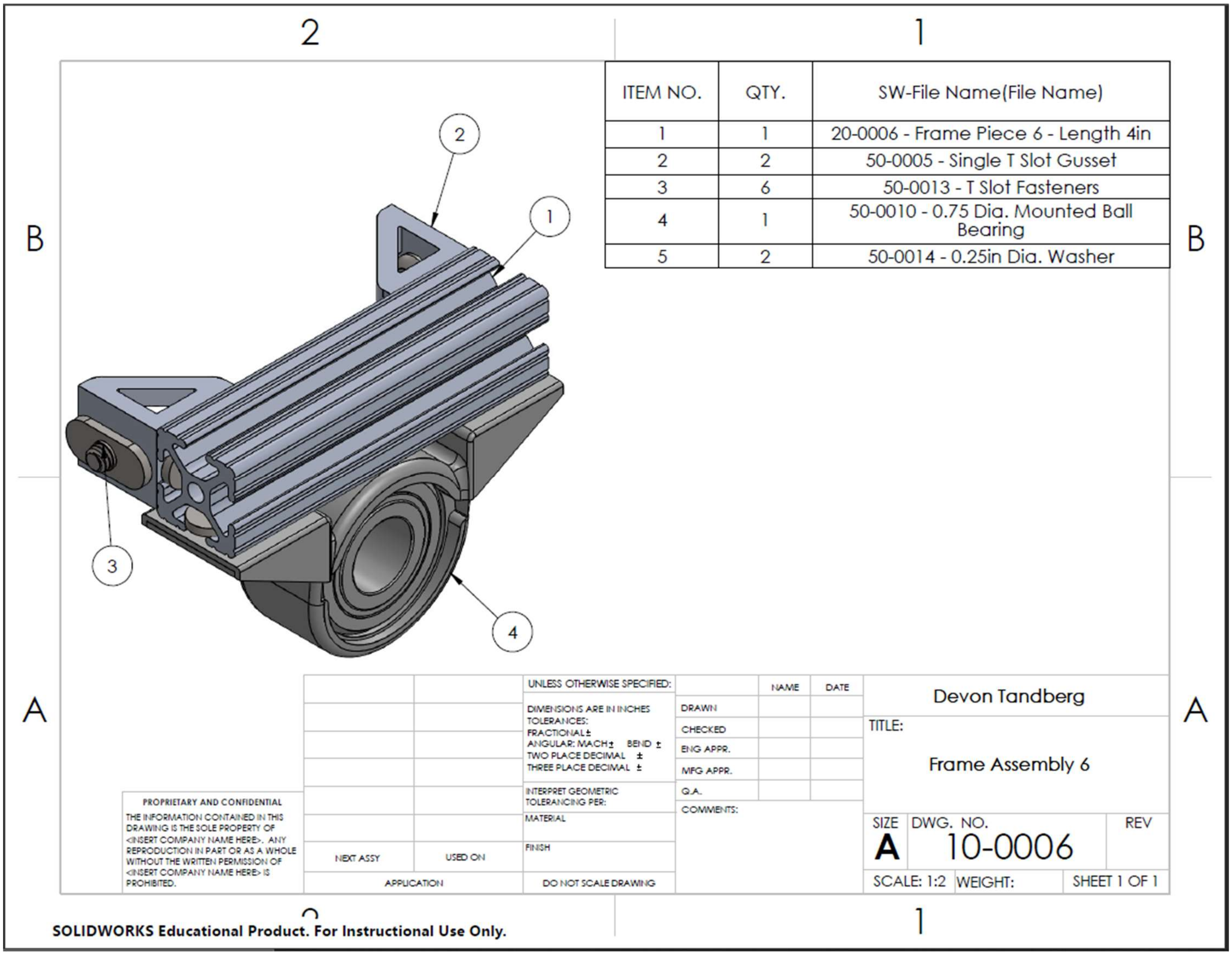
Figure B34: Assembly 10-0006 Drawing – Frame Assembly 6



ITEM NO.	QTY.	SW-File Name(File Name)
1	1	20-0006 - Frame Piece 6 - Length 4in
2	2	50-0005 - Single T Slot Gusset
3	6	50-0013 - T Slot Fasteners
4	1	50-0010 - 0.75 Dia. Mounted Ball Bearing
5	2	50-0014 - 0.25in Dia. Washer

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC
TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

NEXT ASSY

USED ON

APPLICATION

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Devon Tandberg

TITLE:

Frame Assembly 6

SIZE A

DWG. NO. 10-0006

REV

SCALE: 1:2

WEIGHT:

SHEET 1 OF 1

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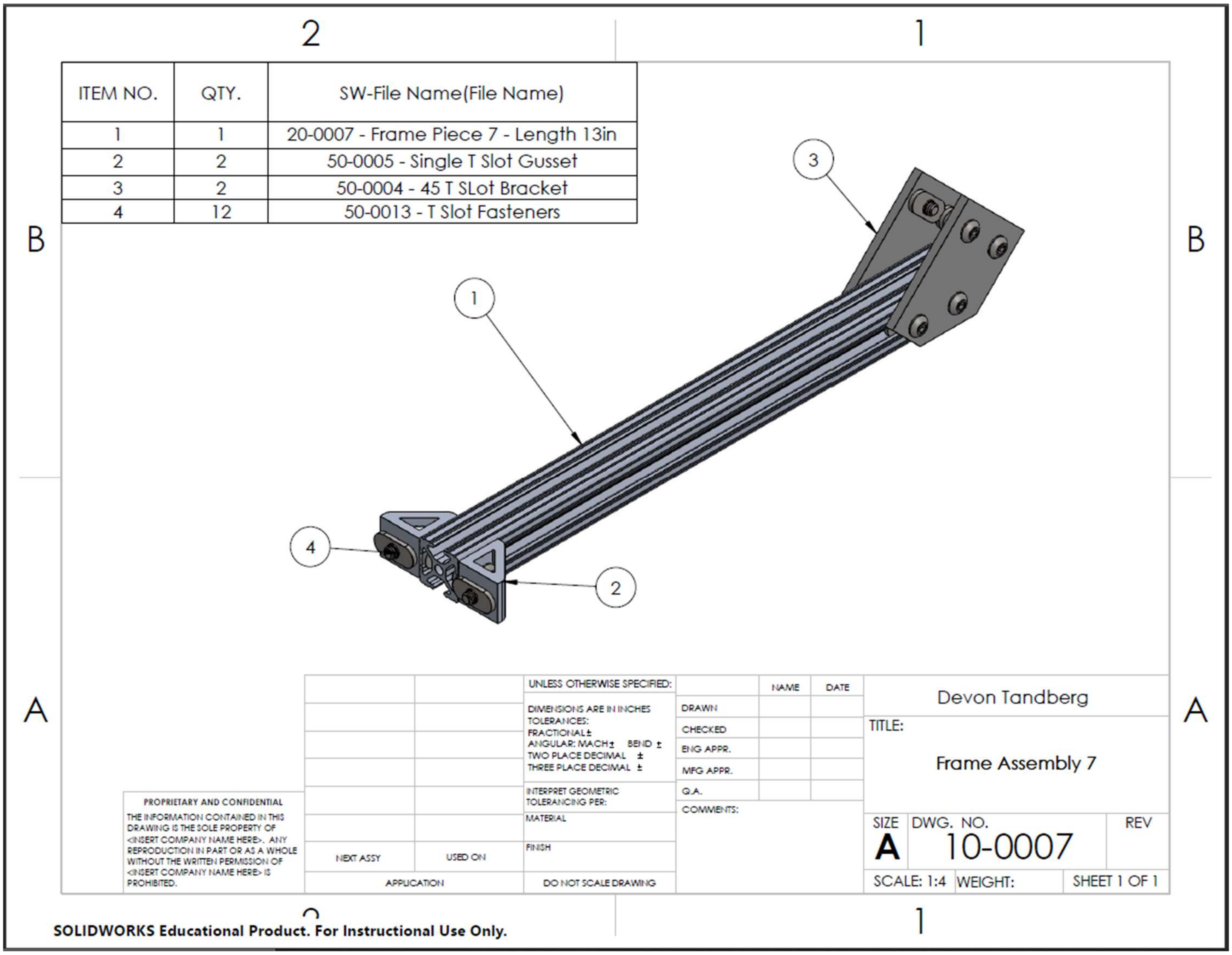
Figure B35: Assembly 10-0007 Drawing – Frame Assembly 7



ITEM NO.	QTY.	SW-File Name(File Name)
1	1	20-0007 - Frame Piece 7 - Length 13in
2	2	50-0005 - Single T Slot Gusset
3	2	50-0004 - 45 T SLot Bracket
4	12	50-0013 - T Slot Fasteners

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

NEXT ASSY	USED ON
APPLICATION	

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Devon Tandberg

TITLE:
Frame Assembly 7

SIZE	DWG. NO.	REV
A	10-0007	

SCALE: 1:4 WEIGHT: SHEET 1 OF 1

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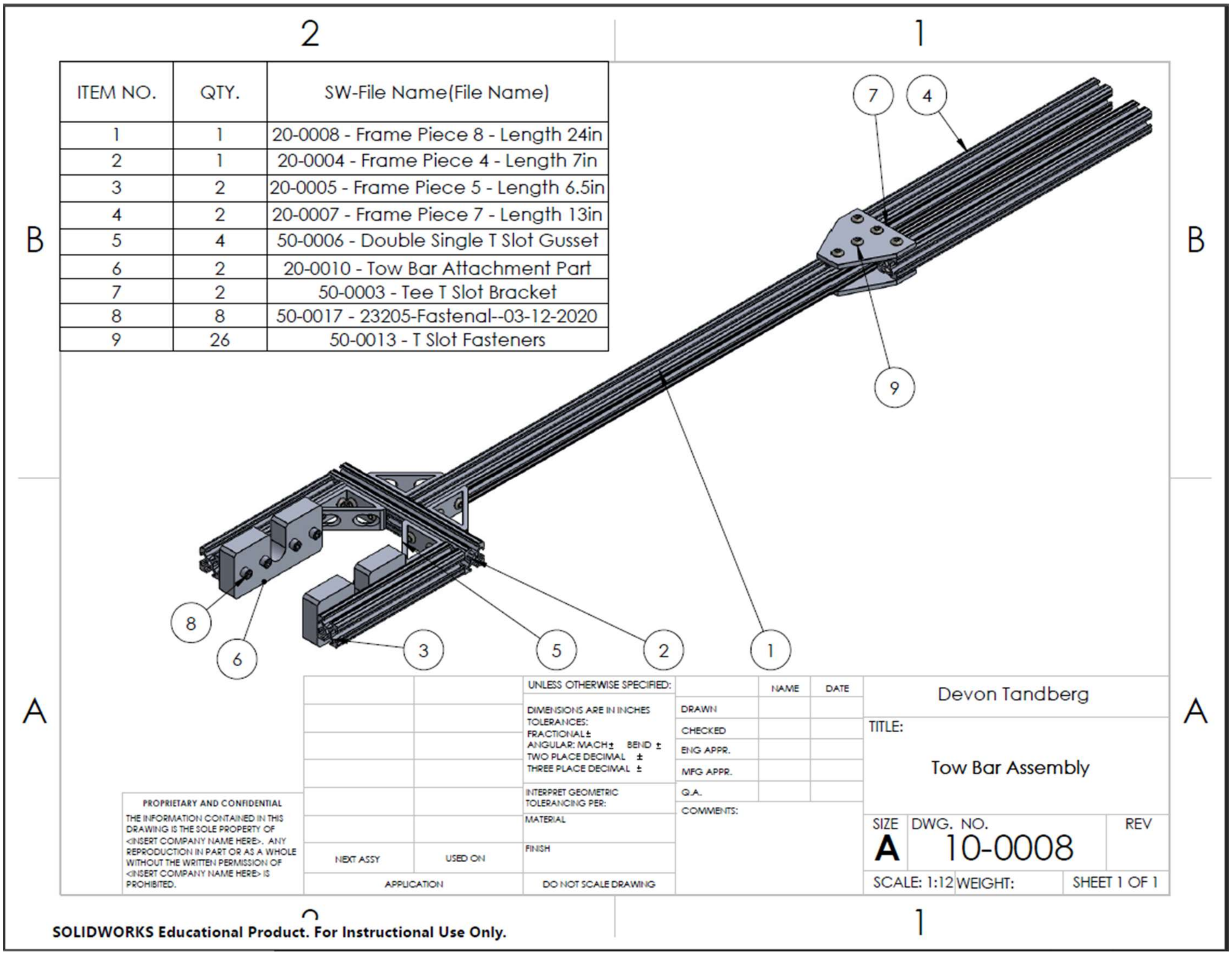
Figure B36: Assembly 10-0008 Drawing – Tow Bar Assembly



ITEM NO.	QTY.	SW-File Name(File Name)
1	1	20-0008 - Frame Piece 8 - Length 24in
2	1	20-0004 - Frame Piece 4 - Length 7in
3	2	20-0005 - Frame Piece 5 - Length 6.5in
4	2	20-0007 - Frame Piece 7 - Length 13in
5	4	50-0006 - Double Single T Slot Gusset
6	2	20-0010 - Tow Bar Attachment Part
7	2	50-0003 - Tee T Slot Bracket
8	8	50-0017 - 23205-Fastenal--03-12-2020
9	26	50-0013 - T Slot Fasteners

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

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USED ON
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Devon Tandberg

TITLE:
Tow Bar Assembly

SIZE A
DWG. NO. 10-0008
REV

SCALE: 1:12
WEIGHT:
SHEET 1 OF 1

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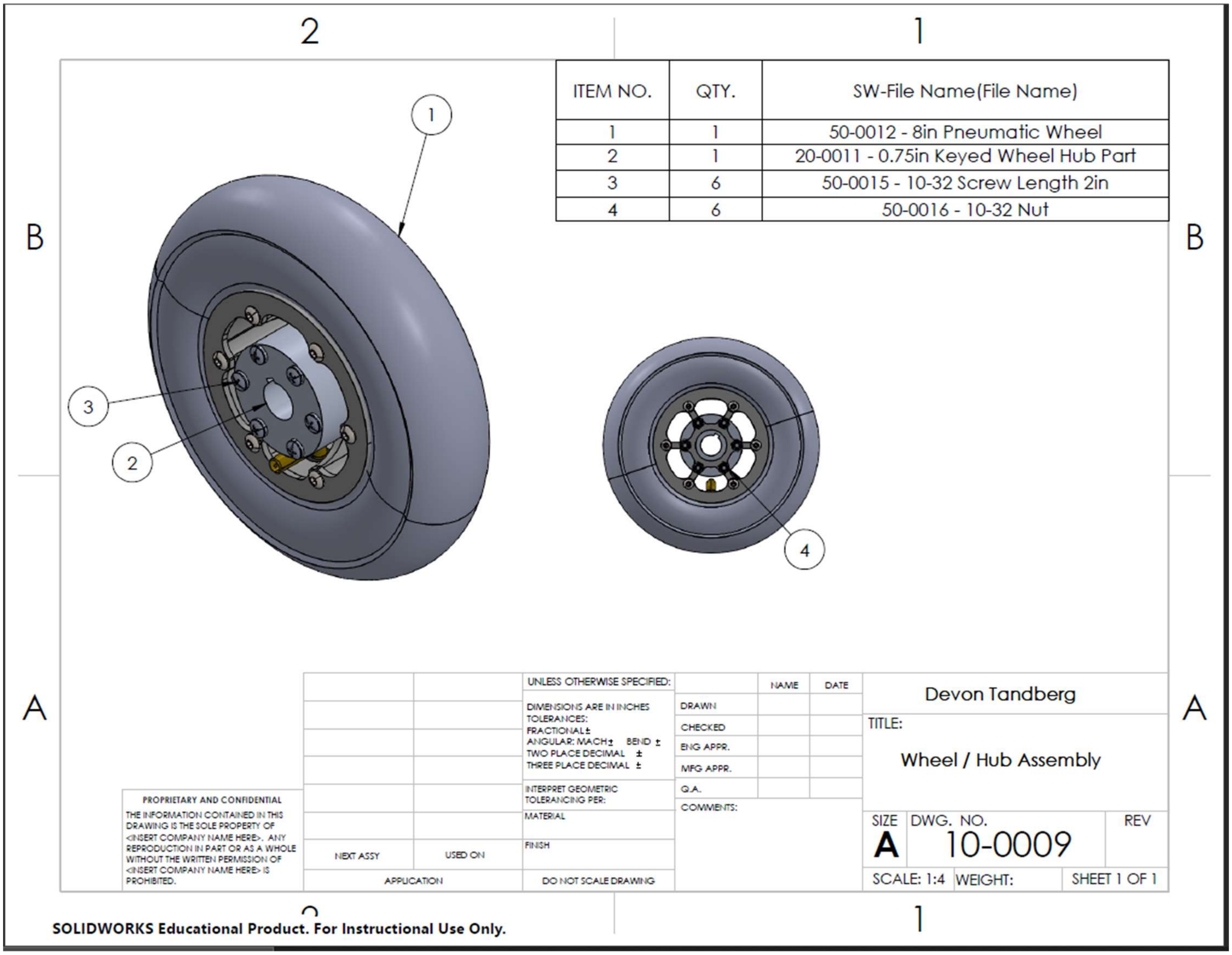
Figure B37: Assembly 10-0009 Drawing – Wheel / Hub Assembly



ITEM NO.	QTY.	SW-File Name(File Name)
1	1	50-0012 - 8in Pneumatic Wheel
2	1	20-0011 - 0.75in Keyed Wheel Hub Part
3	6	50-0015 - 10-32 Screw Length 2in
4	6	50-0016 - 10-32 Nut

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TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Devon Tandberg

TITLE:
Wheel / Hub Assembly

SIZE A
DWG. NO. 10-0009
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1

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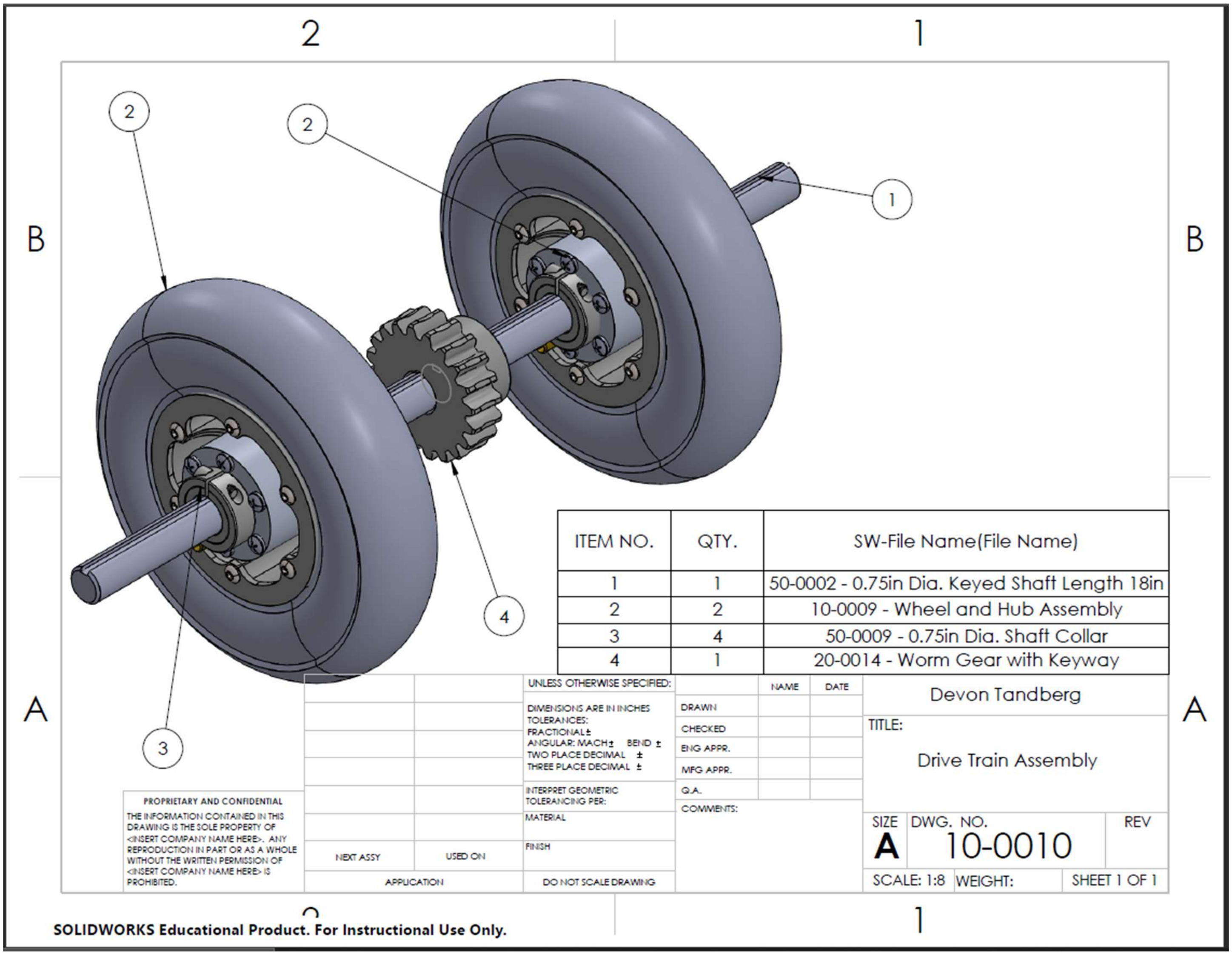
Figure B38: Assembly 10-0010 Drawing – Drive Train Assembly



ITEM NO.	QTY.	SW-File Name(File Name)
1	1	50-0002 - 0.75in Dia. Keyed Shaft Length 18in
2	2	10-0009 - Wheel and Hub Assembly
3	4	50-0009 - 0.75in Dia. Shaft Collar
4	1	20-0014 - Worm Gear with Keyway

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TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Devon Tandberg

TITLE:
Drive Train Assembly

SIZE A
DWG. NO. 10-0010
REV

SCALE: 1:8
WEIGHT:
SHEET 1 OF 1

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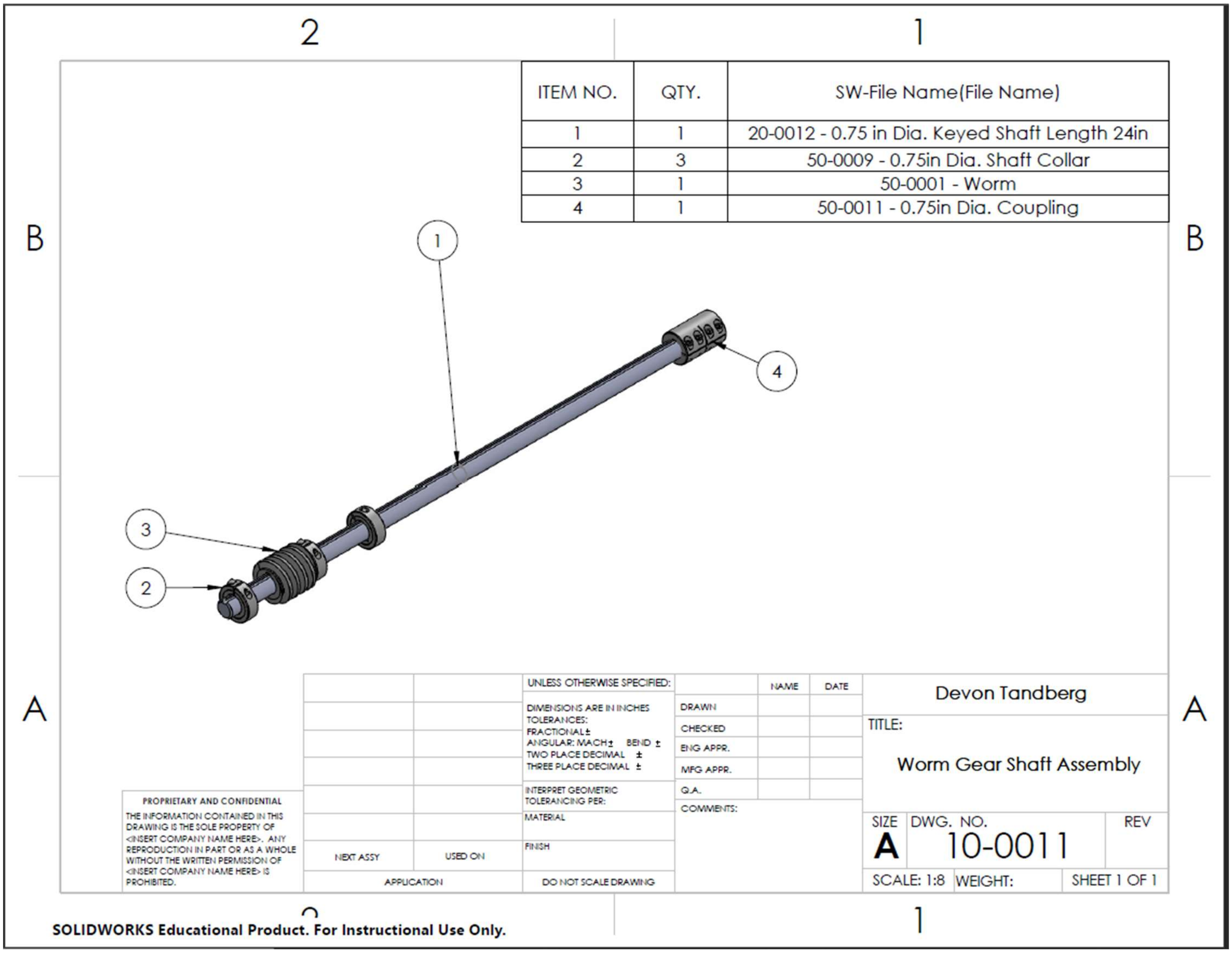
Figure B39: Assembly 10-0011 Drawing – Worm Gear Shaft Assembly



ITEM NO.	QTY.	SW-File Name(File Name)
1	1	20-0012 - 0.75 in Dia. Keyed Shaft Length 24in
2	3	50-0009 - 0.75in Dia. Shaft Collar
3	1	50-0001 - Worm
4	1	50-0011 - 0.75in Dia. Coupling

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC
TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

NEXT ASSY USED ON

APPLICATION

PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

Devon Tandberg

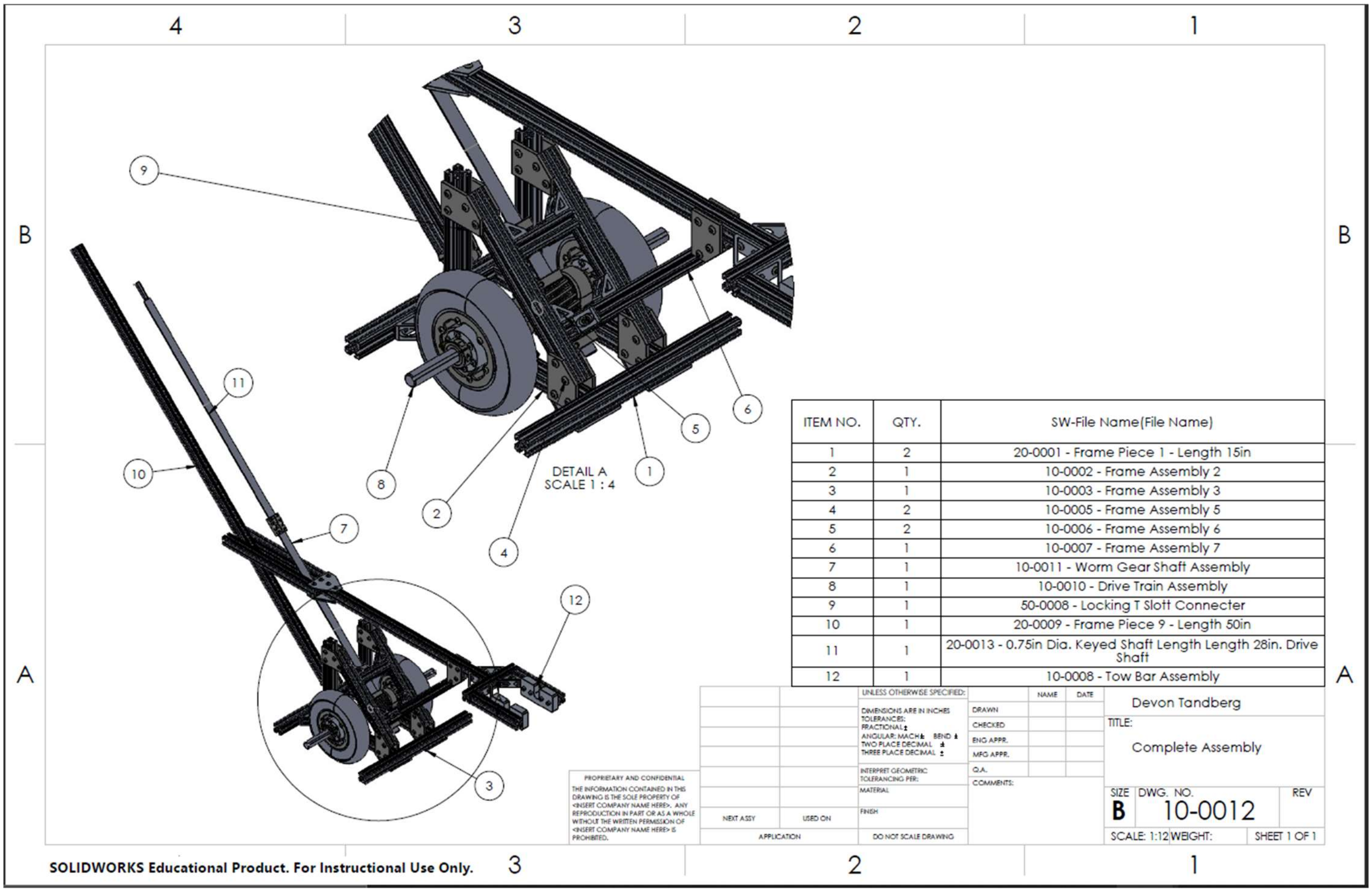
TITLE:

Worm Gear Shaft Assembly

SIZE A DWG. NO. 10-0011 REV

SCALE: 1:8 WEIGHT: SHEET 1 OF 1

Figure B40: Assembly 10-0012 Drawing – Complete Assembly



ITEM NO.	QTY.	SW-File Name(File Name)
1	2	20-0001 - Frame Piece 1 - Length 15in
2	1	10-0002 - Frame Assembly 2
3	1	10-0003 - Frame Assembly 3
4	2	10-0005 - Frame Assembly 5
5	2	10-0006 - Frame Assembly 6
6	1	10-0007 - Frame Assembly 7
7	1	10-0011 - Worm Gear Shaft Assembly
8	1	10-0010 - Drive Train Assembly
9	1	50-0008 - Locking T Slott Connecter
10	1	20-0009 - Frame Piece 9 - Length 50in
11	1	20-0013 - 0.75in Dia. Keyed Shaft Length Length 28in. Drive Shaft
12	1	10-0008 - Tow Bar Assembly

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

NEXT ASSY
USED ON
APPLICATION

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Devon Tandberg

TITLE:
Complete Assembly

SIZE B
DWG. NO. 10-0012
REV
SCALE: 1:12
WEIGHT:
SHEET 1 OF 1

Appendix C – Budget

Devon Tandberg Senior Project
Complete Budget
General Aviation Tow Bar

Item ID	Item Description	Item Source	Model/SM	Price/Cost	Quantity	Cost: Subtotals	Notes
	Framing Material						
1	1"x1" T Slotted Framing x97" Long	Amazon	1010-97	$36.49	3	$109.47	
	Framing Brackets						
2	Tee T Slot Bracket	McMaster Carr	47065T278	$7.95	4	$31.80	Fasteners Included
3	45 T Slot Bracket	McMaster Carr	47065T306	$9.78	10	$97.80	Fasteners Included
4	Single T Slot Gusset	McMaster Carr	47065T663	$6.54	12	$78.48	Fasteners Included
5	Double Single T Slott Gusset	McMaster Carr	47065T736	$9.99	10	$99.90	Fasteners Included
6	Locking T Slott Connection	McMaster Carr	47065T221	$20.50	1	$20.50	Fasteners Included
7	Adjustable Angle Surface Brackets	McMaster Carr	3136N168	$15.56	8	$124.48	Fasteners Included
	Raw Materials						
8	Aluminum Bar - 2" x 0.75" x 1'	McMaster Carr	8975K78	$13.96	1	$13.96	
9	Aluminum Round Stock Dia: 2.5" x 6"	McMaster Carr	8974K77	$23.59	1	$23.59	
	Gears						
10	Worm	McMaster Carr	57545K327	$70.82	1	$70.82	
11	Worm Gear	McMaster Carr	57545K311	$90.82	1	$90.82	
	Shafts / Collars / Bearings/ Couplings						
12	3/4" Diameter Shaft, Length 18"	McMaster Carr	1497K956	$28.87	1	$28.87	
13	3/4" Diameter Shaft, Length 60"	McMaster Carr	1497K64	$69.41	1	$69.41	
14	3/4" Diameter Collars	McMaster Carr	6435L16	$3.03	10	$30.30	
15	3/4" Diameter Shaft Coupling	McMaster Carr	61005K144	$54.86	1	$54.86	
16	3/4" Diameter Mounted Ball Bearings	McMaster Carr	5913K63	$11.78	6	$70.68	
	Wheels						
17	8" Diameter Pneumatic Wheels	Andymark	am-3935	$45.00	2	$90.00	
	Fasteners / Nuts / Washers / Keys						
18	T Slot Single Nut with Button Head	McMaster Carr	47065T139	$1.85	5	$9.25	Packs of 5
19	#10-32 x 2" Socket Head Cap Screw	Fastenal	23172	$0.36	12	$4.32	
20	#10-32 Lock Nut	Fastenal	37015	$0.07	12	$0.84	
21	1/4"-20 x 1" Socket Head Screw	Fastenal	23205	$0.23	8	$1.84	
22	1/4" Washer	Fastenal	11250165	$0.05	12	$0.60	Provided by CWU
23	3/16" Keyway Stock L: 12"	Fastenal	989957	$26.66	1	$26.66	
	Motor						
24	20V Dewalt Cordless Drill	Home Depot		$159.00	1	$0.00	Drill Already Owned

Total Estimate Subtotal:	$1,149.25
Tax:	$114.93
Total Budget:	**$1,264.18**

Orders Tracking for Total Spent

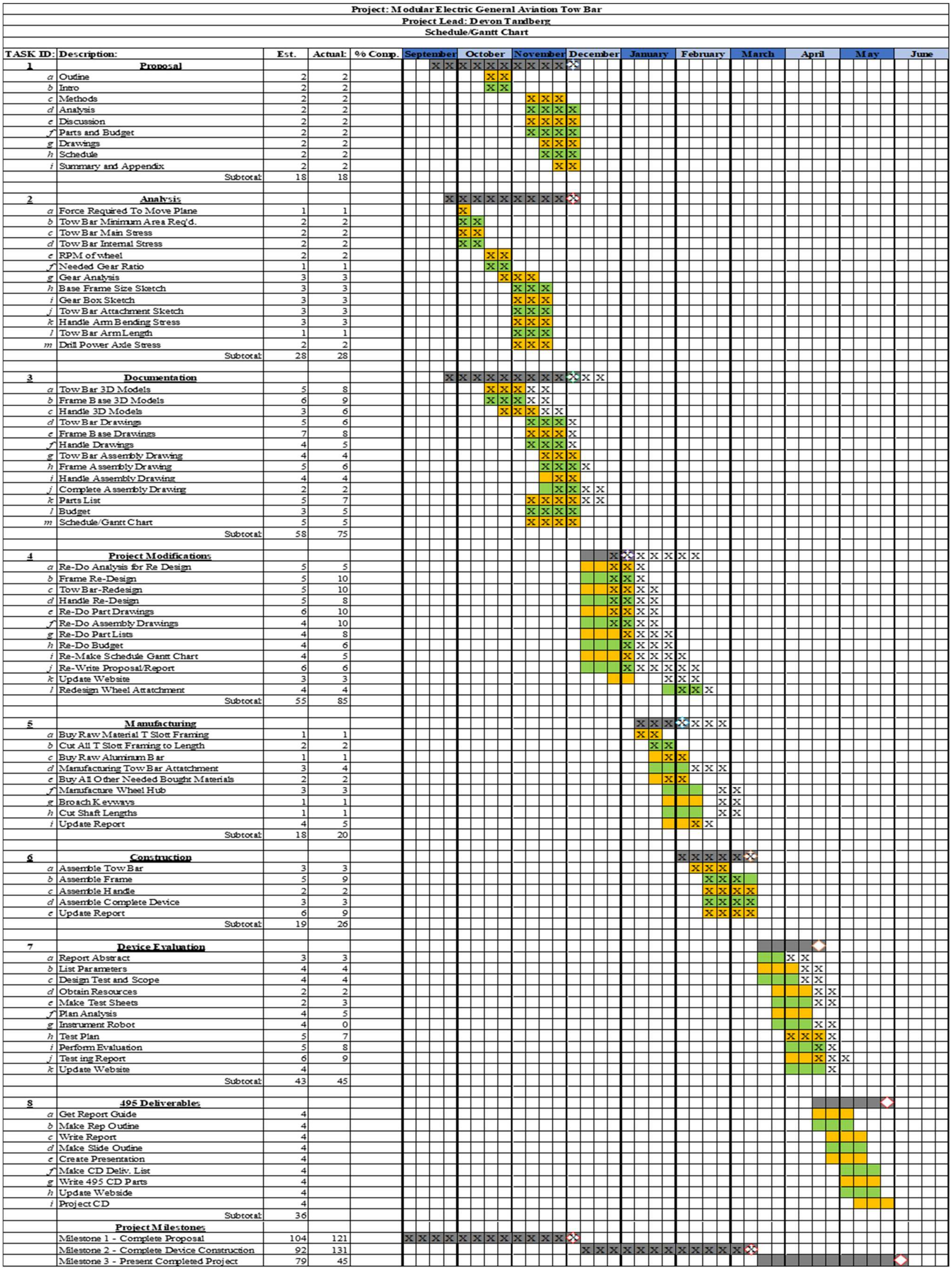
Order Number:	Total:
Order 1: Amazon	$118.89
Order 2: McMaster-Carr	$905.32
Order 3: McMaster-Carr	$139.32
Order 4: Andymark	$115.66
Total:	**$1,279.19**

Appendix D – Part Lists

Devon Tandberg Senior Project
Complete Part List
General Aviation Tow Bar

Part Number	Part Name	Description	Source	Made From	Quantity
		Manufactured Parts			
20-0001	Frame Piece 1	T Slotted Framing Length: 15"	Amazon	1010-97	2
20-0002	Frame Piece 2	T Slotted Framing Length: 11"	Amazon	1010-97	4
20-0003	Frame Piece 3	T Slotted Framing Length: 9"	Amazon	1010-97	2
20-0004	Frame Piece 4	T Slotted Framing Length: 7"	Amazon	1010-97	1
20-0005	Frame Piece 5	T Slotted Framing Length: 6.5"	Amazon	1010-97	2
20-0006	Frame Piece 6	T Slotted Framing Length: 4"	Amazon	1010-97	2
20-0007	Frame Piece 7	T Slotted Framing Length: 13"	Amazon	1010-97	3
20-0008	Frame Piece 8	T Slotted Framing Length: 24"	Amazon	1010-97	1
20-0009	Frame Piece 9	T Slotted Framing Length: 50"	Amazon	1010-97	1
20-0010	Attachment Point	Plane Attachment Point	McMaster-Carr	8975K78	2
20-0011	Wheel Hub	3/4" Diameter Keyed Wheel Hub	McMaster-Carr	8974K77	2
20-0012	3/4" Dia. Shaft Length: 24"	3/4" Diameter Keyed Shaft L: 24"	McMaster-Carr	1497K64	1
20-0013	3/4" Dia. Shaft Length: 28"	3/4" Diameter keyed Shaft L: 28"	McMaster-Carr	1497K64	1
20-0014	Worm Gear	Worm Gear with a keyway added	McMaster-Carr	57545K311	1
50-0001	Worm	Keyed Worm Gear	McMaster-Carr	57545K327	1
50-0002	3/4" Dia. Shaft L: 18"	Keyed Shaft for Drive Train	McMaster-Carr	1497K956	1
50-0003	Tee T Slot Bracket	Tee T Slot Bracket	McMaster-Carr	47065T278	4
50-0004	45 T Slot Bracket	46 T Slot Bracket	McMaster-Carr	47065T306	10
50-0005	Single T Slot Gusset	Single T Slot Gusset	McMaster-Carr	47065T663	12
50-0006	Double Single T Slott Gusset	Double Single T Slott Gusset	McMaster-Carr	47065T736	10
50-0007	Adjustable Angle Surface Bracket	Adjustable Angle Surface Bracket	McMaster-Carr	3136N168	8
50-0008	Locking T Slott Connection	Locking T Slott Connection	McMaster-Carr	47065T221	1
50-0009	Shaft Collar	3/4" Shaft Collar	McMaster-Carr	6435L16	10
50-0010	Mounted Ball Bearing	3/4" Diameter Mounted Ball Bearing	McMaster-Carr	5913K63	4
50-0011	Shaft Coupling	3/4" Shaft Coupling	McMaster-Carr	61005K144	1
50-0012	Pneumatic Wheel	8" Pneumatic Wheel	AndyMark	am-3935	2
50-0013	Single Nut w/ Button Head fastener	T Slot Fasteners	McMaster-Carr	47065T139	132
50-0014	1/4" Washer	1/4" Washer	Fastenal	11250165	8
50-0015	#10-32 x 2" Socket Head Cap Screw	#10-32 x 2" Socket Head Cap Screw	Fastenal	23172	12
50-0016	#10-32 Lock Nut	#10-32 Lock Nut	Fastenal	37015	12
50-0017	1/4"-20 x 1" Socket Head Screw	1/4"-20 x 1" Socket Head Screw	Fastenal	23205	8

Appendix E – Schedule



Project: Modular Electric General Aviation Tow Bar

Project Lead: Devon Tandberg

Schedule/Gantt Chart

September October November December January February March April May June

TASK ID:	Description:	Est.	Actual:	% Comp.
1	**Proposal**			
a	Outline	2	2	
b	Intro	2	2	
c	Methods	2	2	
d	Analysis	2	2	
e	Discussion	2	2	
f	Parts and Budget	2	2	
g	Drawings	2	2	
h	Schedule	2	2	
i	Summary and Appendix	2	2	
	Subtotal:	18	18	
2	**Analysis**			
a	Force Required To Move Plane	1	1	
b	Tow Bar Minimum Area Req'd.	2	2	
c	Tow Bar Main Stress	2	2	
d	Tow Bar Internal Stress	2	2	
e	RPM of wheel	2	2	
f	Needed Gear Ratio	1	1	
g	Gear Analysis	3	3	
h	Base Frame Size Sketch	3	3	
i	Gear Box Sketch	3	3	
j	Tow Bar Attachment Sketch	3	3	
k	Handle Arm Bending Stress	3	3	
l	Tow Bar Arm Length	1	1	
m	Drill Power Axle Stress	2	2	
	Subtotal:	28	28	
3	**Documentation**			
a	Tow Bar 3D Models	5	8	
b	Frame Base 3D Models	6	9	
c	Handle 3D Models	3	6	
d	Tow Bar Drawings	5	6	
e	Frame Base Drawings	7	8	
f	Handle Drawings	4	5	
g	Tow Bar Assembly Drawing	4	4	
h	Frame Assembly Drawing	5	6	
i	Handle Assembly Drawing	4	4	
j	Complete Assembly Drawing	2	2	
k	Parts List	5	7	
l	Budget	3	5	
m	Schedule/Gantt Chart	5	5	
	Subtotal:	58	75	
4	**Project Modifications**			
a	Re-Do Analysis for Re Design	5	5	
b	Frame Re-Design	5	10	
c	Tow Bar-Redesign	5	10	
d	Handle Re-Design	5	8	
e	Re-Do Part Drawings	6	10	
f	Re-Do Assembly Drawings	4	10	
g	Re-Do Part Lists	4	8	
h	Re-Do Budget	4	6	
i	Re-Make Schedule Gantt Chart	4	5	
j	Re-Write Proposal/Report	6	6	
k	Update Website	3	3	
l	Redesign Wheel Attatchment	4	4	
	Subtotal:	55	85	
5	**Manufacturing**			
a	Buy Raw Material T Slott Framing	1	1	
b	Cut All T Slott Framing to Length	2	2	
c	Buy Raw Aluminum Bar	1	1	
d	Manufacturing Tow Bar Attatchment	3	4	
e	Buy All Other Needed Bought Materials	2	2	
f	Manufacture Wheel Hub	3	3	
g	Broach Keyways	1	1	
h	Cut Shaft Lengths	1	1	
i	Update Report	4	5	
	Subtotal:	18	20	
6	**Construction**			
a	Assemble Tow Bar	3	3	
b	Assemble Frame	5	9	
c	Assemble Handle	2	2	
d	Assemble Complete Device	3	3	
e	Update Report	6	9	
	Subtotal:	19	26	
7	**Device Evaluation**			
a	Report Abstract	3	3	
b	List Parameters	4	4	
c	Design Test and Scope	4	4	
d	Obtain Resources	2	2	
e	Make Test Sheets	2	3	
f	Plan Analysis	4	5	
g	Instrument Robot	4	0	
h	Test Plan	5	7	
i	Perform Evaluation	5	8	
j	Test ing Report	6	9	
k	Update Website	4		
	Subtotal:	43	45	
8	**495 Deliverables**			
a	Get Report Guide	4		
b	Make Rep Outline	4		
c	Write Report	4		
d	Make Slide Outline	4		
e	Create Presentation	4		
f	Make CD Deliv. List	4		
g	Write 495 CD Parts	4		
h	Update Webside	4		
i	Project CD	4		
	Subtotal:	36		
	Project Milestones			
	Milestone 1 - Complete Proposal	104	121	
	Milestone 2 - Complete Device Construction	92	131	
	Milestone 3 - Present Completed Project	79	45	

Appendix F – Expertise and Resources

Human Resources

- CWU Dr. Craig Johnson: Provided guidance throughout the design phase of this project
- CWU Charles Pringle- Provided guidance throughout the design phase of this project.
- CWU Jeunghwan Choi – Provided guidance throughout the design phase of this project.
- CWU Tedman Bramble – Provided access to the Hogue Machine Shop.
- Dustin Braun – Knowledge in CNC Programming.

Physical Resources

- CWU Hogue Machine Shop
- Tandberg Family Work Shop
- Tandberg Family Cessna 175 N7154M
- CWU Hogue Materials Lab
- CWU Hogue CAD Lab

Soft Resources

- Dassault Systems Solidworks
- Microsoft Excel
- Microsoft Word

Financial Resources

The tow bar project is being funded by the Tandberg family.

Appendix G – Testing Report

Introduction:

The goal of this project was to create a device that combines the best aspects of general aviation tow bars and tugs. A tow bar is a light weight, small device that is human powered, that allows a pilot to maneuver their aircraft when the power is off. Because of its small nature, it can be stored in a small aircraft to allow the pilot to take it with them. A tug on this other hand is a larger and heavier device that is electrically powered. This makes it much easier for a pilot to move their aircraft as they aren't the one pushing and pulling it themselves. However, since its large and heavy, it is not able to be stored in an aircraft, and thus can't be take with the pilot. Thus, the idea for this project was to combine the best aspects of these devices, creating something that is small and light weight, but also electrically powered taking the physical burden off the pilots and maneuvering their aircraft.

In the beginning of this project, five basic requirements/goals were set. They are the following:

- A device must be able to attach and detach from a tricycle gear aircraft.
- A device must be powered by a drill.
- A device must weigh less than 15 lbs.
- A device must be able to be taken apart and put together in less than two minutes for storage.
- A device must fit in the storage compartment of a Cessna 175.

It is these 5 requirements that will be tested to determine the success of the project. The schedule for this entire testing portion of the project can be found in the appendix of this document, and in the appendix of the Project Report.

Method / Approach:

During the design portion of this project, the worm gear system was designed to have a gear ration of 20:1. Along with this, it was decided to have 8in pneumatic wheels. With an input RPM of 450, the calculated linear speed for the device is 0.5 m/s (approx. 1 mph and normal walking speed). Along with these designs, particular care was taken in choosing material that was both light and easy to work with. Because the goal was to have the device weigh less than 15 lbs., it is expected that the values of the weight be close to this value. Along with weight, size was important, because the device needs to be able to fit inside a plane. The expected result is the device will fit inside a plane when taken apart. The final requirement was for the device to be taken apart and put together both in less than two minutes. Because the final design consists of 5 small assemblies, this timing should be achieved.

The device has been designed to work with pilots in their own ways, and as such, the device will be tested in a similar area, in and around a plane, and its storage area (in this case, a hangar that is owned by the family). This will keep the testing as accurate as possible when it comes to working with the device. Overall the testing will need to be done during the day to allow for the best vision around the plane to ensure no damage comes to the property of the owner.

Test Procedure:

Test One: Weight of Device

Summary:
In aviation, weight is everything. It allows a pilot to determine how much their aircraft weights with everything in it, and weather the airplane is safe to fly. A pilot needs to know how much their equipment weights, and that is why this test is being conducted. The goal of this device is to be taken with a pilot on their everyday trips.

Time/Duration/Location:
This test can be done at any part of the day, and will take approximately 15 minutes. This test will be done at the Tandberg family house hold. This test could be done anywhere that has a hard flat surface.

Resources Needed:
The resources that are needed for this test are:

- Tow Bar Device
- Scale
- Means of recording weight value

Steps:

1. Place Scale on flat surface and ensure it is powered on and working
2. Ensure device is completely assembled and place wheels onto scale
    a. Ensure that handle is supported so that all the weight is placed onto the wheels
3. Record value shown on the scale
4. Repeat multiple times until value shown on scale reads within 1lb three times in a row.

Risk and Safety:
Ensure that the device is not dropped, as it could cause injury to a leg or foot. Also, do not drop the device onto the scale as damage to the scale could create inaccurate results.

Test Two: Device Speed

Summary:
When it comes to pushing and pulling an airplane around by hand, speed is important. When a plane moves too fast, it becomes very difficult to control. When a plane is moving too slow, the device being used becomes useless as the goal is to move the plane at a comfortable rate. So, the goal of this test is to compare the actual speed at which the device maneuvers the plane to the design value of 1 mph.

Time/Duration/Location:
This test will need to be done during the day and will take approximately one hour. It will be done at the Tandberg family home in front of their hangar where their plane is stored.

Resources Needed:
The resources that are needed for this test are:

- Tow Bar Device
- Cessna 175 N7154M (Tandberg Family Plane)
- Open Area
- Tape
- Measuring Tape
- Stopwatch/Timer

- Means of recording data

Steps:

1. Ensure device is completely assembled and ready for use
2. Measure out a 10-yard distance and tape it. Make an additional mark at the 5 yard mark.
3. Place the plane at the beginning of the 10 yards and attach device to the nose wheel of the Cessna 175.
4. Use device to push and pull plane in both directions
5. Use a timer to record times at each measure point (5 yard and 10 yards)
6. Use values to determine the speed the plane is pushed and pulled at.

Risk and Safety:

In this test, it is important to keep an eye on the surroundings. Be especially aware if the plane gets close to anything, as hitting something, even at a slow speed, could significantly damage the plane, or whatever it hits. Also be aware that the plane is moving and ensure no one is around that could get hit by the plane as well.

Test Three: Device Storage

Summary:

Small general aviation planes such as a Cessna 175 have limited storage space for tools and luggage. Similar to weight, everything a pilot takes with them must fit in the plane and have everything closed. For this test, the device will be taken apart to its smallest components and attempted to be placed in the plane for storage.

Time/Duration/Location:

This test can be done at any point in the day, and will take approximately 30 minutes. It will be done at the Tandberg family home.

Resources Needed:

The resources that are needed for this test are:

- Tow Bar Device that is taken apart
- Cessna 175 N7154M (Tandberg family plane)

Steps:

1. Ensure that the tow bar device is taken apart into its smallest assemblies.
2. Attempt to place the unassembled device into the storage compartment of the Cessna 175.
3. Record whether the device can fit into the plane.

Risk and Safety:

Make sure that extra care is taken when handling the device as pinching of fingers in the gears could happen. Also make sure the device does not get dropped as it could both hurt the user as well as damage the device and the plane.

Test Four: Ease of Assembly

Summary:

The goal of this device is to be able to be stored in the plane. Since it is too big to be stored in the plane completely assembled, the device must be stored in multiple pieces. In order to make this practical for the user, the device must be able to be taken apart and put together quickly. In this test, the speed at which the device can be put together and taken apart will be examined.

Time/Duration/Location:

This test will happen during the daytime and will last approximately 1-2 hours. It will be done at the Tandberg family house.

Resources Needed:

The resources that are needed for this test are:

- Completely assembled device
- Hex Key Drill Bit Set (or Allen wrench set)
- Stopwatch

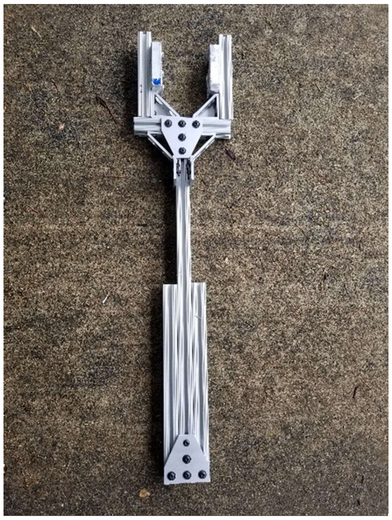
Steps for testing:

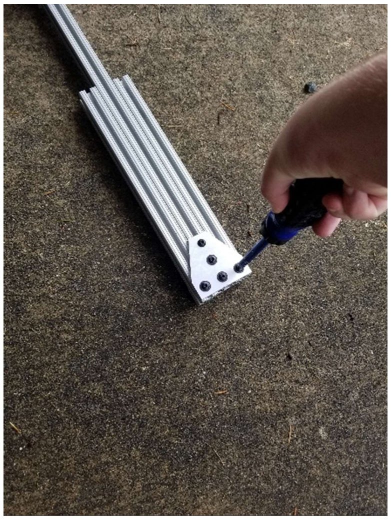
1. Start with the device completely assembled
2. Record time required to take the device apart.
3. Record time required to assemble the device from storage sections.

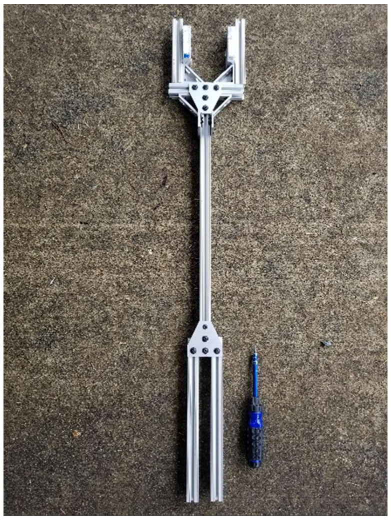
Steps for Assembly:

1. Ensure all five pieces of the device are acquired.

2. Extend arms of tow bar by loosening fasteners and sliding the arms down, then retightening the fasteners.

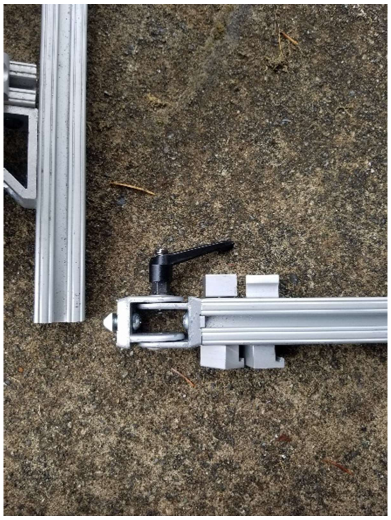


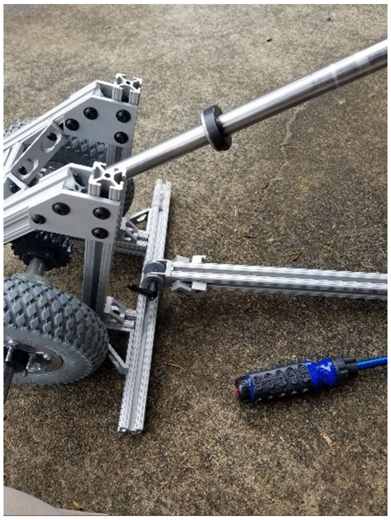




3. Take the front support and slide the 4 fasteners on the front of the drive train into the openings of the support and tighten into place.

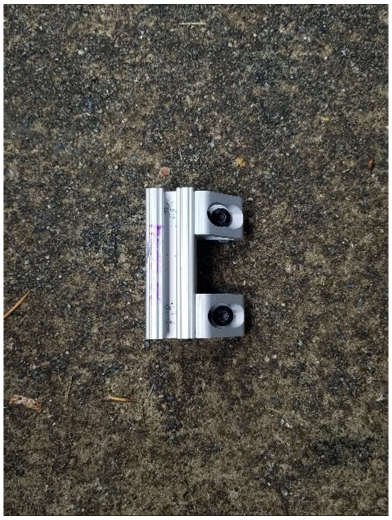
4. Take the Tow bar rear connection piece and loosen the nut on the bottom of the connection point and insert it into the top rear slide and tighten it in the middle of the horizontal bar.



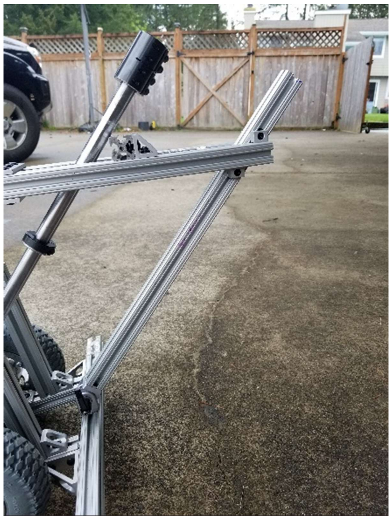


5. Take the Tow bar piece again and slide the connection point onto the front support piece and tighten the fasteners.

6. Take the Shaft Support, and place it on the tow bar arms behind the shaft, and tighten the fasteners.



7. Once the tow bar is one, connect the rear support to the rear of the tow bar, and tighten fasteners.



8. For the final step, take the connection shaft and insert into the coupling, and tighten the fasteners, and the device is completed

Steps for Disassembly:

1. Follow the reverse steps for Assembly.

Risk and Safety:

For this test, there are tools being used, and it is important that they are used safely. Ensure that the device is not dropped when storing to keep the device from being damaged, and keep the plane from being damaged.

Empty Raw Data Form:

Raw Data Records	
Device Works (yes/no)	
5 Yard Pulling time	
10 Yard Pulling Time	
5 Yard Pushing Time	
10 Yard Pushing Time	
Time to take apart	
Time to Assemble	
Device fits into plane	

Throughout the testing, this data recorded.

Empty Final Results Form:

<table>
<tr><th colspan="4">General Aviation Modular Electric Tow bar Testing Results</th></tr>
<tr><th>Device Works (yes/no)</th><th>Avg. Pulling Speed (m/s)</th><th>Avg. Pushing Speed (m/s)</th><th>Device Weight (lb)</th></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><th colspan="2">Device Usability (Apart) (min, sec)</th><th>Device Usability (Together) (min, sec)</th><th>Fits into Plane (yes/no)</th></tr>
<tr><td colspan="2"></td><td></td><td></td></tr>
</table>

The Calculated (for areas that need calculations) final results will be put into this table.

Deliverables:

Raw Data:

Raw Data Records	
Device Works (yes/no)	*Yes*
5 Yard Pulling time	*12 sec*
10 Yard Pulling Time	*22 sec*
5 Yard Pushing Time	*15 sec*
10 Yard Pushing Time	*32 sec*
Time to take apart	*4min, 41sec*
Time to Assemble	*9min, 18sec*
Device fits into plane	*Yes*

Calculated Data:

<table>
<tr><th colspan="4">General Aviation Modular Electric Tow bar Testing Results</th></tr>
<tr><th>Device Works (yes/no)</th><th>Avg. Pulling Speed (m/s)</th><th>Avg. Pushing Speed (m/s)</th><th>Device Weight (lb)</th></tr>
<tr><td>Yes</td><td>0.415 m/s</td><td>0.283 m/s</td><td>31.5 lb</td></tr>
<tr><th colspan="2">Device Usability (Apart) (min, sec)</th><th>Device Usability (Together) (min, sec)</th><th>Fits into Plane (yes/no)</th></tr>
<tr><td colspan="2">4min, 41sec</td><td>9min, 18sec</td><td>Yes</td></tr>
</table>

Discussion:

As can be seen by the results above, the device works. It is highly capable of pushing and pulling a fully loaded Cessna 175. While the speed was not specifically the designed speed, in the video of the testing, it can be seen that the speed is within a comfortable walking distance, and it allows for the person handling the device to have full control of the airplane. Also, the device can be taken part, and it capable of fitting inside the storage area of the Cessna 175. Unfortunately, the amount of time that it takes to take the device apart and put it together, like a person that would buy this device, is far to high. The device is also much heavier than the goal of 15 lbs. Inf future designs, these two areas will need to be addressed and worked on.

Appendix G1: Procedure Checklists

Test One: Weight of Device

Steps:

2. Place Scale on flat surface and ensure it is powered on and working
3. Ensure device is completely assembled and place wheels onto scale
    a. Ensure that handle is supported so that all the weight is placed onto the wheels
4. Record value shown on the scale
5. Repeat multiple times until value shown on scale reads within 1lb three times in a row.

Test Two: Device Speed

Steps:

1. Ensure device is completely assembled and ready for use
2. Measure out a 10-yard distance and tape it. Make an additional mark at the 5 yard mark.
3. Place the plane at the beginning of the 10 yards and attach device to the nose wheel of the Cessna 175.
4. Use device to push and pull plane in both directions
5. Use a timer to record times at each measure point (5 yard and 10 yards)
6. Use values to determine the speed the plane is pushed and pulled at.

Test Three: Device Storage

Steps:

1. Ensure that the tow bar device is taken apart into its smallest assemblies.
2. Attempt to place the unassembled device into the storage compartment of the Cessna 175.
3. Record whether the device can fit into the plane.

Test Four: Ease of Assembly

Steps for testing:

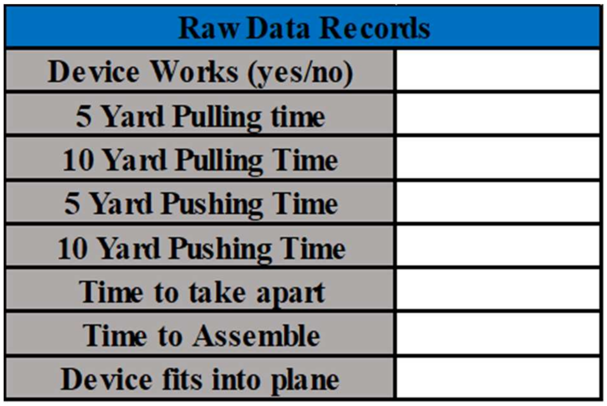
1. Start with the device completely assembled
2. Time taking apart the device.
3. Time getting the device assembled completely.
4. Have another person do both tests given instructions and time them.

Steps for Assembly:

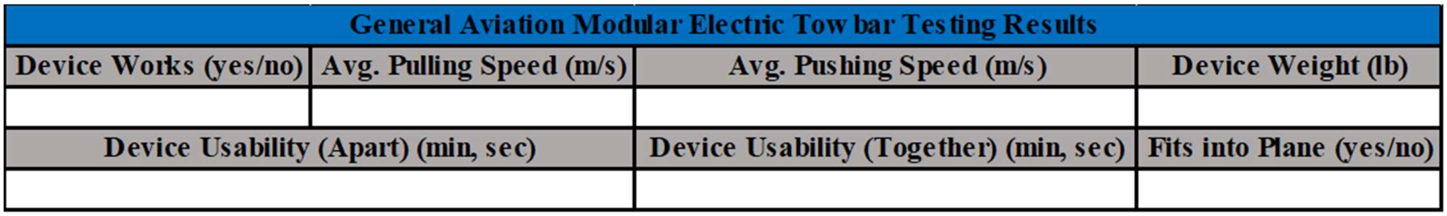
1. Ensure all five pieces of the device are aquired
2. Extend arms of tow bar by loosening fasteners and sliding the arms down, then retightening the fasteners.

3. Take the front support and slide the 4 fasteners on the front of the drive train into the openings of the support and tighten into place.
4. Take the Tow bar rear connection piece and loosen the nut on the bottom of the connection point and insert it into the top rear slide and tighten it in the middle of the horizontal bar.
5. Take the Tow bar piece again and slide the connection point onto the front support piece and tighten the fasteners.
6. Take the Shaft Support, and place it on the tow bar arms behind the shaft, and tighten the fasteners.
7. Once the tow bar is one, connect the rear support to the rear of the tow bar, and tighten fasteners.
8. For the final step, take the connection shaft and insert into the coupling, and tighten the fasteners, and the device is completed.

Appendix G2: Data Forms



Raw Data Records	
Device Works (yes/no)	
5 Yard Pulling time	
10 Yard Pulling Time	
5 Yard Pushing Time	
10 Yard Pushing Time	
Time to take apart	
Time to Assemble	
Device fits into plane	



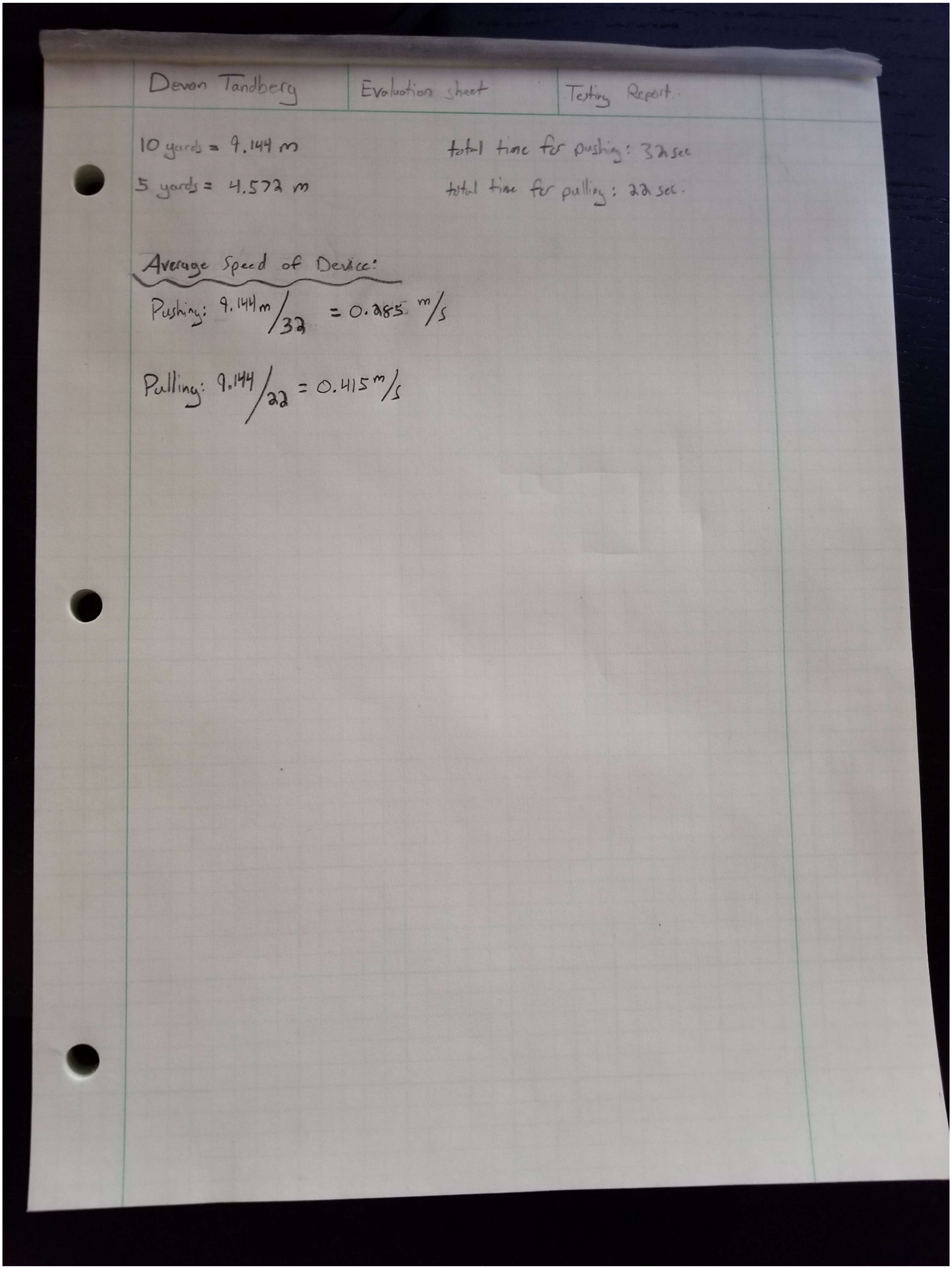
General Aviation Modular Electric Tow bar Testing Results			
Device Works (yes/no)	Avg. Pulling Speed (m/s)	Avg. Pushing Speed (m/s)	Device Weight (lb)
Device Usability (Apart) (min, sec)		Device Usability (Together) (min, sec)	Fits into Plane (yes/no)

Appendix G3: Raw Data

Raw Data Records	
Device Works (yes/no)	*Yes*
5 Yard Pulling time	*12 sec*
10 Yard Pulling Time	*22 sec*
5 Yard Pushing Time	*15 sec*
10 Yard Pushing Time	*32 sec*
Time to take apart	*4min, 41sec*
Time to Assemble	*9min, 18sec*
Device fits into plane	*Yes*

General Aviation Modular Electric Tow bar Testing Results			
Device Works (yes/no)	**Avg. Pulling Speed (m/s)**	**Avg. Pushing Speed (m/s)**	**Device Weight (lb)**
Yes	*0.415 m/s*	*0.283 m/s*	*31.5 lb*
Device Usability (Apart) (min, sec)		**Device Usability (Together) (min, sec)**	**Fits into Plane (yes/no)**
4min, 41sec		*9min, 18sec*	*Yes*

Appendix G4: Evaluation Sheets



Devon Tandberg	Evaluation sheet	Testing Report.

10 yards = 9.144 m

5 yards = 4.572 m

total time for pushing: 32 sec

total time for pulling: 22 sec.

Average Speed of Device:

Pushing: $9.144m / 32 = 0.285\ m/s$

Pulling: $9.144 / 22 = 0.415\ m/s$

Appendix G5: Gantt Chart

Project: Modular Electric General Aviation Tow Bar
Project Lead: Devon Tandberg
Schedule/Gantt Chart

TASK ID:	Description:	Est.	Actual:	% Comp.	September				October				November				December				January				February				March				April				May				June			
7	**Device Evaluation**																														⬛	⬛	⬛	⬛	◇									
a	Report Abstract	3	3																												🟩	🟩	X	X										
b	List Parameters	4	4																												🟧	🟧	🟧	X	X									
c	Design Test and Scope	4	4																												🟩	🟩	🟩	X	X									
d	Obtain Resources	2	2																													🟧	🟧	🟧	X	X								
e	Make Test Sheets	2	3																													🟩	🟩	🟩	X	X								
f	Plan Analysis	4	5																													🟧	🟧	🟧										
g	Instrument Robot	4	0																													🟩	🟩	🟩	X	X								
h	Test Plan	5	7																														🟧 X	🟧 X	🟧 X	X								
i	Perform Evaluation	5	8																														🟩	🟩	🟩 X	X								
j	Test ing Report	6	9																														🟧	🟧	🟧 X	X								
k	Update Website	4																															🟩	🟩	🟩	X								

Appendix H – Resume/Vita

Devon Tandberg

(253) 508-7058 | DevonTandberg2015@gmail.com

Education

Mechanical Engineering Technology | September 2018 - Present | Central Washington University

- Dean's List: Fall 2018, Winter 2019, Spring 2019.
- Anticipated Graduation Date: December 2020.
- Related coursework: AutoCAD, Solidworks, Fluid Dynamics, Plastics, Machining, Engineering Ethics, Mechanical Design, Computer Applications, and Business and Professional Speaking.

Mechanical Engineering | August 2015 – May 2018 | Montana State University

- Dean's List: Fall 2015.
- Related coursework: Calculus, Multi-Variable Calculus, Differential Equations, Statistics, Physics, Chemistry, Statics, Technical Dynamics, Materials, Mechanics of Materials, Application of Mechanics of Materials, Thermodynamics, MATLAB Programming, and Basic Electricity.

Experience

Host/Service Partner | Red Robin | May 2018 - Present

- Handle currency and credit transactions quickly and accurately.
- Build loyal clientele through friendly interactions and consistent appreciation.
- Take initiative to find extra tasks when scheduled duties were completed.
- Resolve complaints promptly and professionally.

Grounds Maintenance | Crest Airpark | May 2018 – September 2018

- Responsible for daily upkeep of airport grounds.
- Inspected fuel and fuel filters to ensure safety for all pilots.
- Recorded daily Tachometer readings for engine logs.
- Maintained airport runway, taxiways, and hangers.

Support Staff | Montana Aleworks | May 2017 – August 2017

- Responsible for maintaining the flow for the restaurant through various kitchen duties.
- Maintained high standards for customer service during high-volume, fast paced operations.
- Communicated clearly and positively with coworkers and management.

Leadership

Montana State University Football Team | NCAA Division 1 | August 2015 – December 2017

- Balanced practice and workouts to stay a strong student with a full-time academic schedule.
- Collaborated with teammates and coaches to build a successful program.

FIRST Robotics Competition | Team 2907 | January 2012 – May 2015

- Lead CAD Design: 2013, 2014, 2015.
- Mentored students to ensure continued growth of program.
- Helped design and build a world championship-level robot.

Skills & Abilities

- Autodesk AutoCAD – 9 years practical experience
- Solidworks – Certification & 1-year practical Experience
- Microsoft Office – Central Washington University, Computer Applications Class
- Private Pilot Certificate
- Excellent written and verbal communication skills
- Dynamic, results-oriented problem solver
- Thrive as team member as well as individually

Appendix J – Job Hazard Analysis

JOB HAZARD ANALYSIS
Operating a Miter Saw

Prepared by: Devon Tandberg	Reviewed by: Approved by:

Location of Task:	Central Washington University Machining Lab/Hogue 107
Required Equipment / Training for Task:	Safety Glasses, Proper Machining Practices, Proper PPE

Personal Protective Equipment (PPE) Required
(Check the box for required PPE and list any additional/specific PPE to be used in "Controls" section)

Gloves	Dust Mask	Eye Protection	Welding Mask	Appropriate Footwear	Hearing Protection	Protective Clothing
		X		X		X

Use of any respiratory protective device beyond a filtering facepiece respirator (dust mask) is voluntary by the user.

TITLE	TASK DESCRIPTION	HAZARDS	CONTROLS
Preplan the work	Gather proper tools Gather Proper PPE for the job and inspect it (safety glasses and safety shoes) Dress properly	Improper tools Improper PPE inspection/selection Loose clothes, jewelry or long hair can be caught in moving parts.	Using improper tools or parts can lead to lead to injury Improper PPE use and inspection can lead to unnecessary hazards created by wrong PPE or faulty PPE. Do not wear loose clothing or jewelry. Keep your hair, clothing and gloves away from moving parts.
Before the job	Don necessary PPE Check for misalignment or damage to the saw, binding of moving parts, function of guards, grounding plug and cord. Ensure switch is in the off position before plugging in	Improper Donning Eye Contact with debris Lacerations Hand Injury Electrical shock Injury from accidental starting Injury from loss of control of workpiece or from flying objects Injury from items interfering with saw operation. Injury from unseen hazards. Injury from	Ensure all PPE is on correctly and passed inspection DO NOT use and TAG OUT saw if it is misaligned, the grounding plug is missing, or the cord is damaged. Check switch position before plugging in saw Secure workpiece with clamps or other appropriate manner. Ensure there are no nails or foreign

	Secure and inspect workpiece Ensure work area is clean and well lit Check blade to ensure it is sharp and clean Select proper blade for application (i.e., metal, wood, etc.)	binding or loss of control during use Injury from using improper blade for application	objects in workpiece. Remove clutter and provide proper lighting prior to job. Ensure there is no debris between the workpiece and the table or fence. Replace blades that are dull. Clean dirty blades. Refer to operator manual or manufacturer for correct blade selection
Using the saw	Be sure to only use the easy grip handle when handling saw Keep proper footing and balance Adjusting tool or workpiece General cutting	Loss of control of the power tool Tripping/Falling Injury from contact with moving parts Injury from accidental startup Injury from using improper cutting method. Hand injury	Maintain firm grip on handle Do not overreach Do not adjust until the saw has come to a complete stop. Unplug from power supply before adjusting. Keep hands and fingers out of the “no hands zone” area marked on the saw table. Bring the saw blade down to the workpiece to see the cutting path of the blade. Squeeze trigger switch to start saw. Lower blade into workpiece with a firm downward motion. Release trigger when cut is complete. Keep the cut off piece free to move sideways after it is cut off.
Storage and Clean up	Properly cleanup work area. Make sure the saw is clean and properly stored.	Slips/trips/falls Improper Storage of Equipment/PPE	Remove tools and dispose of debris. Clean dust and debris from tool with damp cloth. Only use mild soap to clean. Store the saw in designated area.

Reference: https://ehs.unc.edu/files/2019/03/miter-saw.pdf

JOB HAZARD ANALYSIS
Operating a Cordless Drill

Prepared by: Devon Tandberg	Reviewed by: Approved by:

Location of Task:	Central Washington University Machining Lab/Hogue 107
Required Equipment / Training for Task:	Safety Glasses, Proper Machining Practices, Proper PPE

Personal Protective Equipment (PPE) Required

(Check the box for required PPE and list any additional/specific PPE to be used in "Controls" section)

Gloves	Dust Mask	Eye Protection	Welding Mask	Appropriate Footwear	Hearing Protection	Protective Clothing
		X		X		X

Use of any respiratory protective device beyond a filtering facepiece respirator (dust mask) is voluntary by the user.

TITLE	TASK DESCRIPTION	HAZARDS	CONTROLS
Preplan the work	Gather proper tools Gather Proper PPE for the job and inspect it (safety glasses and safety shoes). Dress properly	Improper tools Improper PPE inspection/selection Loose clothes, jewelry or long hair can be caught in moving parts	Using improper tools or parts can lead to lead to injury Improper PPE use and inspection can lead to unnecessary hazards created by wrong PPE or faulty PPE. Do not wear loose clothing or jewelry. Keep hair, clothing and gloves away from moving parts..
Before the job	Don necessary PPE Check for misalignment or damage to the drill, grounding plug and cord. Ensure switch is in the off position Secure workpiece Select proper drill bit or accessory for application	Improper Donning Eye Contact with debris Lacerations Hand Injury Electrical shock Injury from accidental starting Injury from movement of workpiece Injury from improper selection	Ensure all PPE is on correctly and passed inspection DO NOT use and TAG OUT drill if it is misaligned, the grounding plug is missing, or the cord is damaged. Check switch position Secure workpiece with clamps or another appropriate method Insert bit or accessory in chuck. Ensure bit or accessory is secure.
Using the drill	Be sure to only use the easy grip handle when handling drill	Loss of control of the drill Tripping/Falling Injury from accidental startup	Maintain firm grip on handle Do not overreach Ensure switch is in the off position before

	Keep proper footing and balance Adjusting tool or workpiece General Drilling	Injury from improper operation	adjusting To turn on drill, squeeze trigger switch. To stop the drill, release the trigger switch. Use forward/reverse button to control the direction of the tool.
Storage and Clean up	Properly clean up and dispose all debris Make sure the drill is clean and properly stored.	Improper housekeeping Improper Storage of Equipment/PPE	Maintain housekeeping Clean dirt out of air vents. Clean with damp cloth and mild soap, if needed. Store the sander in designated area

Reference: https://ehs.unc.edu/files/2019/03/cordless-drill.pdf

JOB HAZARD ANALYSIS
Operating a Metal Lathe

Prepared by: Devon Tandberg	Reviewed by: Approved by:

Location of Task:	Central Washington University Machining Lab/Hogue 107
Required Equipment / Training for Task:	Safety Glasses, Proper Machining Practices, Proper PPE

Personal Protective Equipment (PPE) Required

(Check the box for required PPE and list any additional/specific PPE to be used in "Controls" section)

Gloves	Dust Mask	Eye Protection	Welding Mask	Appropriate Footwear	Hearing Protection	Protective Clothing
		X		X		X

Use of any respiratory protective device beyond a filtering facepiece respirator (dust mask) is voluntary by the user.

TITLE	TASK DESCRIPTION	HAZARDS	CONTROLS
Preplan the Work	1. Obtain personal protective equipment before the job.	. None	1. Personal Protective Equipment (PPE) consisting of: -Safety glasses with side shields -Sturdy footwear -DO NOT wear jewelry or gloves that could get caught in equipment during operation. Long and loose hair must be contained.
Pre-operation Check	2. Perform an equipment preoperational check.	2a. Entanglement in unguarded moving parts. 2b. Injury due to improper machine operations	2a. Inspect guards prior to work. 2b. Locate and ensure you are familiar with all machine operations and controls.
Site Preparation	3. Inspect for unsecured tools and objects on the lathe.	3. Tools and objects can fall and be propelled at the operator.	3. Remove unsecured tools and objects from the lathe
Don PPE	4. Put on personal protective equipment before performing the job.	4. None	4. Personal Protective Equipment (PPE) consisting of: -Safety glasses with side shields -Sturdy footwear -DO NOT wear jewelry or gloves that could get caught in equipment during operation.

			Long and loose hair must be contained.
Operation	5. Mount chuck or collet	5a. Hand/finger contusion due to tool slippage from securing chuck or collet 5b. Foot injury from dropping chuck/tool 5c. Strain/sprain from transporting heavy and/or awkward chuck.	5a. Use correct tool to secure chuck or collet 5b. Wear recommended footwear 5c. Use mechanical lifting device or get assistance
	6. Set spindle speed	6. Damage to cutting tool and/or spindle drive system	6. Refer to operations manual and set proper spindle speed for material type/diameter to be machined
	7. Set lathe feed	7. Bodily injury and/or damage to workpiece from incorrect feed rate	7. Refer to operations manual and set proper lathe speed
	8. Select proper cutting tool and sharpened tool	8. Dull tools and improper height lead to bad surface finishes, out of tolerance parts and potentially a hazardous situation.	8. Use correct and properly sharpened tool
	9. Set up workpiece in chuck or collet	9a. Hand/finger contusion due to tool slippage from tightening chuck jaws or collet 9b. Damage to workpiece due to loose and/or off center installation of workpiece into chuck 9c. Strain/sprain from heavy and/or awkward workpiece 9d. Damage from chuck key flying off 9e. Long workpieces can bend and strike operator	9a. Use correct tool to secure chuck jaws and collet to workpiece 9b. Ensure workpiece is secure and evenly tightened into chuck or collet. Use dial test to center workpiece. 9c. Use mechanical lift or get assistance from coworker 9d. Never leave key in chuck. For newer models, use spring-loaded or self-ejecting chuck key 9e. Use workpiece of minimum length or use a bar feed tube to hold workpiece
	10. Lathe in operation	10a. Injury to exposed body parts at points of operation 10b. Eye injury from debris 10c. Heat damage to part and cutting tool 10d. Injury during measurements or adjustments	10a. Keep body parts and clothes away from the point of operation 10b. Wear PPE during operation 10c. Start at low speed and slowly increase to avoid overheating; use coolant 10d. Stop operation of lathe before performing measurements or adjustments
	11. Completing work	11a. Injury to exposed body parts at points of operation 11b. Strain/sprain from heavy workpiece 11c. Trip/fall on other tools/materials 11d. Foot	11a. Ensure equipment has stopped prior to placing hands near the point of operation 11b. Use mechanical lift or get assistance from coworker 11c. Clean work areas 11d. Wear

		injury from dropping workpiece	recommended footwear
Doff PPE	12. Remove personal protective equipment after completing the job	12. None	12. Personal Protective Equipment (PPE) consisting of: -Safety glasses with side shields -Sturdy footwear

Reference: https://ehs.unc.edu/files/2019/02/metal-lathe.pdf

JOB HAZARD ANALYSIS
Operating a Milling Machine

Prepared by: Devon Tandberg	Reviewed by: Approved by:

Location of Task:	Central Washington University Machining Lab/Hogue 107
Required Equipment / Training for Task:	Safety Glasses, Proper Machining Practices, Proper PPE

Personal Protective Equipment (PPE) Required

(Check the box for required PPE and list any additional/specific PPE to be used in "Controls" section)

Gloves	Dust Mask	Eye Protection	Welding Mask	Appropriate Footwear	Hearing Protection	Protective Clothing
		X		X		X

Use of any respiratory protective device beyond a filtering facepiece respirator (dust mask) is voluntary by the user.

TASK DESCRIPTION	HAZARDS	CONTROLS
Milling text blocks	Injury to hands from milling blades Hearing damage from noise of machine operation. Possible eye injury from wire stitches thrown out by milling blade. Crushing finger hazard from book clamp.	Never disconnect safety shields from milling blades. Wear hearing protection, such as ear plugs, if operation machine for periods extending more than 10 minutes. Wear safety glasses during operation. Do not hold book at spine when activation book clamp. Hold book at the face.

Reference: https://ehs.berkeley.edu/sites/default/files/jsa-library/ucpslbo04.pdf