FOX FACTORY BEARING ASSEMBLY RUNDOWN & TORQUE AUTOMATION PROJECT

Final Design Report

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Statement of Disclaimer

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Executive Summary

A machine design was created to partially automate the rundown and torque of a Fox Factory shock bearing housing, shown in Figure 0-1. This machine is needed at the factory to keep line associates safe by reducing ergonomic strains associated with this stage in the shock assembly process. Due to the lack of applicable torque drivers for this operation, an open ended, geared drivetrain was designed to allow for engagement of the bearing housing while allowing clearance for the shock shaft that the bearing rides on. This open drivetrain is held by a structure of linear rails and bearings to allow the line associate to guide the open gear into place on the bearing. A pneumatic cylinder and several rail brakes will be used to press the bearing housing into the shock body tube while beginning the rundown process. A control system consisting of a PLC, HMI, and torque driver controller was designed in terms of wiring & programming to control torque and pneumatic outputs. At each stage in the design process, safety and ergonomics were considered so the machine would satisfy the first and second design principle for the Fox manufacturing engineering department: safety and quality, respectively. Basic analysis for component strength and stiffness was performed where any concerns were present, and a maintenance schedule was created for any potential wear items. While the original intent was to manufacture and assemble nearly all machine components in house, parts were instead outsourced by Fox due to various factors stemming from the COVID-19 pandemic.

Figure 0-1. Bearing Housing

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1 Introduction

Fox Factory Inc. is looking to partially automate the assembly process of the shock shaft into the shock body, particularly the linear bearing that threads down into the body tube. One of the main goals of this project is line associate's safety, specifically concerning strains from poor ergonomics for the line associate performing this stage of the shock assembly process.

Currently the process utilizes a manual torque wrench with a modified spanner attachment to torque down the bearing housing, shown in Figure 1-1. This is a critical process because an incorrect torque on the bearing housing can cause premature failure of a shock. Prior to the torqueing stage, a separate rundown spanner is spun manually through roughly 10-15 revolutions in order to seat the bearing. Furthermore, a downward force must be applied to press the bearing into the shock body.

Figure 1-1. Manual rundown and torque process [1]

The goal of this automation project is to supply torque through an Atlas-Copco torque-sensing driver while running down the bearing housing into the shock body. To incorporate some of the team's mechatronics skills the process will be largely automated, utilizing an Atlas Copco controller in conjunction with existing PLC cabinets and pneumatic systems at the factory.

This report contains detailed information about the project and is divided 10 sections. Four of the major sections are described below:

The Background section contains the initial research that was performed for this project. Information on our first major sponsor interview, similar systems, and similar products can be found here. The Objectives section shows the goals, criteria, and descriptions of the project. Included in this section are the problem statement, boundary diagram, QFD house of quality, and project specifications. The Concept Design section contains the process used to generate and choose our final design, as well as preliminary analysis and predicted risks and hazards. The Final Design section describes our chosen design direction in depth. More technical data such as the final mechanical analysis, wiring diagrams, and software code example sections can be found here. Safety, maintenance and repair considerations, and final renders of the system(s) are also addressed in this section. Moving forward from this final design description, plans for testing and manufacturing have been included in the subsequent sections.

2 Background

This project contains several systems that must work together to successfully complete the required tasks. After the sponsor's requirements were fully understood, extensive research was performed on components that could potentially help to solve the problem at hand. This research was done to obtain a better grasp of the problem and provide a breadth of knowledge of potential solutions. The team later had to shift their project goals due to the outbreak of COVID-19, which caused campus to close forced the team to work in their respective homes.

2.1 Sponsor interviews

After reviewing the project proposal, we interviewed our sponsor, Will Crawford, over the phone on 11/07/19. Will is the manufacturing engineering manager who will oversee the implementation of our final design. The purpose of the call was to better define the problem statement and clarify his expectations of the final product. They are as follows:

- Focus more on safety and ergonomics than fully automating the process.
- The design must be easily adaptable so it can be used with other shock families.
- Reliability is more important than speed.
- It is preferable if the device is driven by an Atlas Copco or Ingersoll Rand torque driver.

The team visited the Watsonville factory on 1/3/20 to gain feedback on initial concepts. To gain first-hand experience, the team assembled two different shocks multiple times in the same manner as the operators. This helped the team better understand the nuances of the design challenge and familiarize them with the assembly process. After dropping the assembly tool multiple times and significantly scratching the anodizing on the bearing, the team came to the same conclusion as Fox; this assembly process is far from ideal and needs improvement.

After working on the factory floor, the team discussed our initial ideas with Will Crawford and Tom Mulrooney, a manufacturing engineer at Fox. Will assigned Tom to oversee the project from this point forward as well as assist the team with any PLC (Programable Logic Controller) related tasks. The main points from the discussion are listed below:

- Straight axle torque drivers are designed to be mounted into jigs and fixtures, so they would be a good fit for our application.
- The line associates need an easy visual way to know that all the driving pins and features are aligned before they activate the torque driver.
- Maintenance on the machine needs to be easy and well documented.
- The act of bringing down the driver should align the axis of the shock and driver without any external fixtures besides the body cap pallet.
- Everything in the factory is covered in oil and grease, and our design must accommodate that.
- Indexing the drive mechanism can be accomplished with an inductive sensor picking up a boss on a rotating element.
- The design must be able to drive the bearing in either direction.
- It is preferable to have most of the purchased components come from McMaster-Carr.

- Dowel pins or drill blanks can be used as pins to drive the bearing.
- Wear features on expensive components need to be replaceable.

2.2 Provided Supplies

Upon the first team visit to the Fox Watsonville factory, Will provided several key project elements: two shock absorbers from different shock families/styles, a body cap pallet assembly with inserts for both provided shocks, and two programable logic control boards. The main scope of this project concerns a special family of shocks shown in Figure 2-1. This style of shock has a relatively simple bearing which has a single, right-hand thread surface on the outside of the housing.

Figure 2-1. Fox Factory shock absorber

For clear notation throughout this report, a body cap pallet is a standard tooling assembly used at the factory which accommodates different sized/shaped shock body caps (component which main body tube and external "piggy-back" reservoir both thread into). Two Delrin inserts were provided (-004 component shown); one for each style of shock provided. This body cap pallet assembly is shown in Figure 2-2.

Figure 2-2. Body cap pallet assembly and pallet with shock loaded
(Left and right images, respectively)

As a stretch goal, a second style of shock was provided with the hope that the machine resulting from this project would be able to accommodate a more complicated bearing assembly. This shock from the second shock family, shown in Figure 2-3, has a bearing housing which left-hand threads into its respective body tube and is held in place while the internal section of the bearing housing right-hand threads down until reaching a predetermined torque spec. It should be noted that while this shock involves a more complicated rundown/torque procedure, line associates requested priority for the first family of shocks provided due to the large number of revolutions required during rundown.

Figure 2-3. Stretch goal shock

Also, two different Allen Bradley PLC were boards provided: a MicroLogix 1400 and Micro 820. They are discussed in section 2.4.

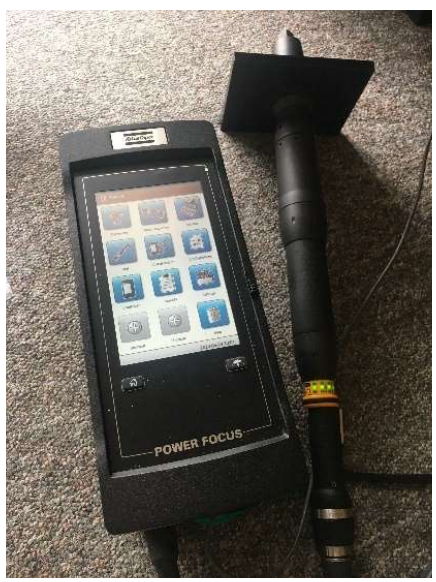


Figure 2-4. Atlas Copco Power Focus and Torque Driver

Finally, FOX provided the team with an Atlas Copco Power Focus 6000 Controller (PF6000). The controller physically connects to the torque driver via a data/power cable, which is shown in Figure

2-4. The PF6000 is used to program rundown and torqueing operations for the driver. It can also be used to track and record data about the operations that are run and save the results from those operations.

2.3 Existing Systems

To not to re-invent the wheel, the team spent time to researching existing systems in place that solved similar problems. The team looked at systems that addressed entire problems as well as mechanisms that solved a single problem that could potentially be implemented into an entire solution.

2.3.1 El Cajon Fox Factory:

A similar automated version of this project is in use at the Fox El Cajon factory, as seen in Figure 2-5. An Atlas Copco torque driver is mounted on a structure made of linear rails. One rail is placed vertically and two are placed radially. This allows the torque driver to be freely positioned while being constrained from rotating in any direction. The weight of the system mitigated by a tool balancer.

The line associate positions the torque driver using two handles attached to the driver mounting plate. Once in position, the line associate presses two thumb buttons on top of the handles to activate the torque driver. The torque driver automatically runs down and torques the bearing. If a shock needs to be disassembled, the system can run the torque driver in reverse using the thumb button controls.

This system is not fully compatible with the needs of our project. Unlike the shocks assembled in El Cajon, we do not have easy access to the bearing from the top because the eyelet, boot, and end cap are already installed on the shock shaft. A large and long tool would need to reach around those parts to drive the bearing from the top. In addition, such a system cannot easily accommodate longer shocks without becoming excessively tall.

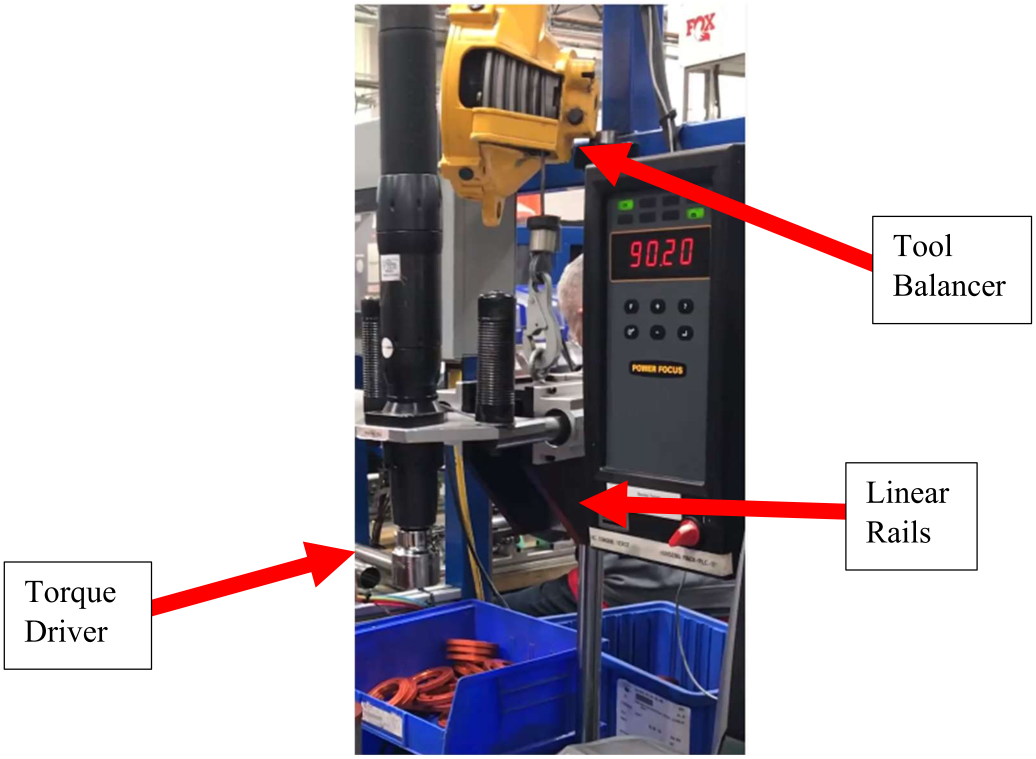


Figure 2-5. Fox Factory El Cajon automated rundown and torque machine [1]

2.3.2 Atlas Copco LTO/LTC Angle Nutrunner:

Atlas Copco sells pneumatic nut drivers with open ended rotating spanners [2]. This allows the tool to drive nuts without the need to fit over the end of a shaft or pipe. An example of one can be seen below in Figure 2-6. We will most likely design a scaled-up version of this tool's drive mechanism for our final design due to the lack of this style of driver in a large size enough for our application.

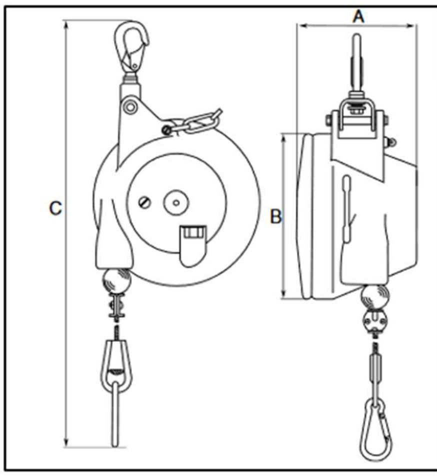
Figure 2-6. Atlas Copco LTO/LTC Angle Nutrunner [2]

2.4 General Component Research

General component research was done to build a data base of knowledge in which the team could use in the design and brainstorm of a full system. This research was done on components the team knew they would use but did not have a specific model number for. Research was also done on components that the team was trying to get a better idea of to decide if the wanted to use it in the system.

2.4.1 Tool-balancers

Upon visiting the factory to discuss initial design ideas, Will suggested using a tool-balancer to hold the weight of the rundown and torque automation tool. These tool-balancers are used in several locations in the Watsonville factory for limiting line associate fatigue when using power delivery tools such as torque drivers for different operations in the shock assembly process. From video footage of a similar system used for a semi-automated rundown machine in FOX's El Cajon factory, we saw that tool-balancers are already used for a very similar process, with Atlas-Copco being the preferred brand used at FOX due to the proven cable reliability over Ingersoll-Rand or other balancers. These balancers are purchased for a certain load range with a limited span of adjustment which increases the as the load capacity of the balancer increases. The tool-balancer section of the 2019 Atlas-Copco is shown below in Figure 2-7.



Model	Capacity range kg	Capacity range lb	Cable length m	Weight kg	Weight lb	Dimension A mm	Dimension B mm	Dimension C mm	Ordering No.
WP 10 - Standard									
WP 10-3	3-5	6.6-11	2	2.9	6.4	130	188	521	8202 0779 00
WP 10-4.5	4.5-7	10-15.4	2	3.1	6.8	130	188	521	8202 0779 01
WP 10-6	6-10	13-22	2	3.2	7.0	130	188	521	8202 0779 02
WP 10-9	9-14	20-31	2	3.4	7.5	130	188	521	8202 0779 03
WP 10-13	13-17	29-37	2	3.6	8.0	130	188	521	8202 0779 04
WP 10-16	16-21	35-46	2	3.8	8.4	130	188	521	8202 0779 05
WP 10 - Extended Cable - A									
WP 10-3-A	3-5	6.6-11	5.5	2.9	6.4	130	188	521	8202 0779 06
WP 10-4.5-A	4.5-7	10-15.4	5.5	3.1	6.8	130	188	521	8202 0779 07
WP 10-6-A	6-10	13-22	5.5	3.2	7.0	130	188	521	8202 0779 08
WP 10-9-A	9-14	20-31	5.5	3.4	7.5	130	188	521	8202 0779 09
WP 10-13-A	13-17	29-37	5.5	3.6	8.0	130	188	521	8202 0779 10
WP 10-16-A	16-21	35-46	5.5	3.8	8.4	130	188	521	8202 0779 11
WP 20 - Standard									
WP 20-15	15-25	33-55	2	7.8	17.2	152	218	521	8202 0780 00
WP 20-25	25-35	55-77	2	8.9	19.6	152	218	521	8202 0780 01
WP 20-35	35-45	77-99	2	9.5	21.0	152	218	521	8202 0780 02
WP 20-45	45-55	99-121	2	9.8	21.5	152	218	521	8202 0780 03

Figure 2-7. Atlas-Copco tool balancer catalog with capacity ranges [3]

Looking at McMaster-Carr for a rough pricing estimate for tool balances, there are large jumps in cost between balancer capacity ranges. For an 18-25lb range, balancers can be purchased under $200, but for a 235-250lb range the cost is a much higher at $2,300+. The price doesn't increase linearly with capacity, so the total weight of any tool assembly being held by one of these balancers would need to be carefully monitored during the design process to avoid tipping the needed capacity into the next price bracket. If a tool-balancer is chosen as part of the design direction to avoid automation of positioning in the vertical direction, quotes will need to be sourced from Atlas-Copco when a final tool weight is found.

2.4.2 Torque Wrenches

The device supplying the force required to tighten the bearing housing into the shock body will be a torque wrench. Our sponsor recommended two companies to potentially purchase a torque wrench from: Atlas Copco and Ingersoll Rand.

Ingersoll Rand has three models of torque wrenches, the QXN, QXC and QXX. Some of the more relevant features are shown in Table 2-1.

Table 2-1. Some Features of the Ingersoll Rand QX Torque Wrench Family

Features	QXN	QXC	QXX
Number of tightening configurations	1	8	8
Displays quantitative result of actual torque	No	Yes	Yes
Programming directly from back of tool	No	Yes	Yes
Supports remote access	No	No	Yes

Atlas Copco has a family of torque wrenches called the Tensor ST Electric Nutrunners. This family is built to provide higher levels of torque and are offered in different configurations. One of the configurations is called straight where the rotating bit is in line with the handle of the rundown tool. This configuration is made to be easily integrated with machinery or a fixture.

Atlas Copco also has rundown tools that are specifically designed to be mounted, called fixed nutrunners. These machines are not made to be held by a human line associate, but only to be mounted to a machine.

Two promising nutrunners are the QST50-150CT-T50-L137-H13 (QST) and the ETD ST101-150-20 (ETD). The QST is a fixed nutrunner and the ETD is a straight electric rundown tool. They both can supply 22-110 ft-lb of torque but differ in speed and torque. The two nutrunners are briefly compared in Figure 2-8.

Figure 2-8. Comparison of two Atlas Copco nutrunners [2]

2.4.3 Controllers

Both Atlas Copco and Ingersoll Rand have controllers for their torque wrenches. The controller allows for data collection and customization for the connected tool. Controllers are typically boxes that are mounted near the assembly station and often provide visual information to the worker about the current assembly process, such as which operation is happening and if specific requirements are met.

The Ingersoll Rand controller is called the INSIGHTqc Controller. It connects to a single tool and the virtual station can be reached from any device through an internet connection. Atlas Copco has two controllers, the Power Focus 6000 and 4000. The PF6000 can connect to up to six tools and run a virtual station for each. It allows for programming of multi-step tightening and fastening for both wired and wireless tools. The 4000 can only connect to one tool at a time but is cheaper and our sponsor may have one on hand.

The controller will need to not only start and stop the machine but do so after receiving user input as well as be able to index the output gear. If the output gear is not indexed, it will not be possible to remove the shock from the machine. From the PF4000 manual, there is a function called "Home Position." This function remembers a spindle position and will rotate to that position when that function is called, which will solve the indexing problem. The PF4000 also has the capability to use "Function Buttons" as well as incorporating a safety button. The safety button must be pressed within ±.5 seconds of the operating button for the machine to start. This ensures that both of the operator's hands are occupied when operating the machine. The function buttons can be set up to trigger after a single push or double push and can be linked to different functions.

2.4.4 Belts and Belt Driven Systems

One drivetrain option considered is a belt driven system. A belt driven system offers a potential for infinite points of contact for the driven adapter which needs at minimum a 7/8" gap for clearance of the shock shaft. A belt would allow the adapter to be spun around its axis without fear of the adapter losing contact with the driven system.

There are 3 different belt types considered: flat belt, V-belt, and synchronous belt (timing). Each have their distinct advantages over one another, and each have been improved to minimize their disadvantages. Table 2-2 illustrates the general properties of the different types of belts.

Table 2-2. General Properties of different belting [4]

Belt Type	Jointed	Size Range	Center Distance	Comments
Flat Belt	Yes	t = 0.03-0.20 in	No upper limit	Can be driven out of plane
V Belt	No	b = 0.31-0.91 in	Limited	Low initial tension
Timing Belt	Yes	p = 2mm and up	Limited	Synchronous mvmt.

Flat belt can be obtained in thicknesses between 0.03 and 0.20 inches and in all widths starting at 0.2 inches. They are jointed which allows them to be purchased in any length and are useful in systems with large distances between centers. The pulleys are friction driven and have an efficiency of up to 99.9% in some cases. Due to the small cross section, belt drives are also beneficial in systems with higher manipulation of direction. Being friction driven, power and torque are transmitted through the grip provided by the initial tension in the system. The general load case of our system is 50 ft-lbs of torque. Basic calculations on a 6-inch pulley would require approximately 150lbs and a built-up tension of approximately 300lbs. These numbers are on the high side for the capability of a flat belt but are plausible by increasing thickness and width of the belts. A concern, however, is being able to provide the initial tension consistently and easily in routine maintenance procedures. These numbers are directly proportional to pulley size and can be manipulated into lower forces at the expense of system size [5].

V belts are the least flexible in terms of flexible mechanical elements (belts and chains) due to their larger cross section. They work best in applications of direct power transmission, even avoiding the use of idlers. They have been proven to still work in cases of unideal application such as the system which drives a car alternator, but useful life is said to go down significantly by an unquantified amount. V belts are 2-3% less efficient than flat belts but boast an advantage in terms of initial tensioning requirements. The wedge shape of the belt allows a mechanical advantage in terms of friction build up. Tensioning these belts creates large sidewall forces to build up along the V, creating the frictional build up with a much lower tension [5]. Initial calculations on a 6-inch pulley would require an initial tension of approximately 10lbs. The tension in load would still however be close to 250 lbs. The low initial tension would allow for much simpler mechanisms to tension the belt initially.

Timing belts are the final option in the belt category. A timing belt works similar to a chain in that it uses teeth to provide synchronous timing. This aspect is highly desired for our use because the teeth provide the same positive engagement as gears or a chain drive. Timing belts guarantee positioning, a constant speed ratio, and therefore a constant torque ratio. In our case it would guarantee a constant torque 1:1 ratio. They excel in low speed high torque applications because they do not depend on initial tension and built centripetal tension to operate efficiently. Teeth in a timing belt can have many different shapes depending on the application.

For high torque applications like the problem presented, curvilinear and modified curvilinear tooth profiles are desired. Curvilinear tooth profiles offer better load distribution and are less likely to shear teeth or jump upon shock loading [6]. The largest issue with a timing belt system is that as loads get high, the standard belts and pulleys available become less and less broad and severely constrain design or require custom machining. Timing pulleys are difficult to custom machine and typically require special casting forms and equipment because the tooth profile is continuous around the perimeter of the pulley.

Timing belts are straight forward in calculations. Initial tension on a low speed timing belt can be approximated to 80% the design tension of the belt for operating tensions with a factor of safety of 1.3 or greater [6]. Utilizing a 6 inch pulley the design tension would be 150lbs and the operating tension would be 270lbs. Table 2-3 below displays different belt types and the tension allowed for each belt type per inch of width. The GT3 and HTD style belts are desired as their tooth profiles are curvilinear and better for high torque applications.

Table 2-3. Allowable working tension of different belt constructions [6]

	Belt Type	Pitch		Allowable Working Tension Per 1 Inch of Belt Width					
				Neoprene		Urethane/Polyester		Urethane/Kevlar	
		Inch	mm	lbf	N	lbf	N	lbf	N
19a	MXL	0.080	2.03	18	80	20 to 32	89 to 142	32 to 70	142 to 311
19b	40DP	0.0816	2.07	—	—	20 to 32	89 to 142	32 to 70	142 to 311
19c	XL	0.200	5.08	28	125	32	142	40	178
19d	L	0.375	9.525	49	218	—	—	—	—
—	H	0.500	12.7	135	601	—	—	—	—
19e	HTD	0.118	3	64	285	—	—	—	—
19f		0.197	5	102	454	—	—	—	—
—		0.315	8	178	792	—	—	—	—
19g	GT3	0.079	2	25	111	—	—	—	—
19h		0.118	3	114	507	—	—	—	—
19i		0.197	5	160	712	—	—	—	—
—		0.315	8	380	1690	—	—	—	—
—		0.551	14	650	2891	—	—	—	—
19j	T	0.098	2.5*	70	312	—	—	—	—
19k		0.197	5*	209	930	—	—	—	—
19*l*		0.394	10*	405	1800	—	—	—	—

The 8mm GT3 belt best fits application because it comes in standard widths of 20mm and 30mm. Issues with GT3 belts arise in detailed design of a belt driven system as standardized parts become less available. This was a driving characteristic of belts that led the team to reconsider gears as gears are much more available in a variety of sizes.

2.4.5 Gears and Gear driven Systems

Like timing belts, gears are synchronous and can provide a one to one drive ratio. A gear driven system can utilize two idler gears, which are controlled by the driven gear, to always maintain a mesh with a C shaped gear. Pitch and number of teeth can be modified to change the strength of the teeth and increase the diameter of the gear, decreasing load. After identifying the desired pitch and number of teeth, face width can be modified to ensure that the gears are strong enough to convey the design torque of 50 ft-lbs. There are two main gear types when gears are not trying to change the axis of rotation: helical and spur gears. Helical gears excel in overall efficiency. They are also quieter, but they are harder to maintain and replace due to the nature of the way that they mesh.

Spur gears still maintain high efficiency and the straight cut gear mesh allows for easier maintenance of the overall system. Considering the nature in the way gears convey power and torque, they inherently provide a more robust system than a belt driven system with less maintenance. Gears have a similar issue with sizing as a belt driven system. As the gears get bigger to deal with higher torque, they become less standard and more necessary to machine or special order. Unlike timing pulleys, gears are much easier to custom machine because their tooth profile is involute and not continuous.

A five-inch spur gear must withstand a tangential gear load of 240 lbf and a radial force of approximately 62 pounds according to standard gear calculations. Large safety factors must be considered for the C shaped driven gear for 3 main reasons. First there will be at minimum a 7/8-

inch cut through the gear which will affect its integrity. Secondly, the stress flow through the gear will be non-standard as it will not be transmitting to a shaft, but to a component underneath the gear. Lastly, because the gear will not be constrained by its axis of rotation, the mesh on the teeth will not be ideal and may cause excessive wear.

2.4.6 Pneumatics

To provide the downward force required to compress the bearing housing O-rings and drive the housing into the shock body tube while beginning the bearing rundown process, pneumatic cylinders immediately came to mind. They would enable a repeatable downward force to be applied at controllable times without fatiguing the machine line associate. To minimize the volume height that air cylinder would add to the machine in the event it is mounted in line with the shock, round body air cylinders for narrow spaces (or pancake cylinders) were found on McMaster-Carr. These narrow cylinders were found to be in a range available with a one square inch piston area to give a 1:1 ratio between line pressure and output force at the ram. Considering the roughly 80lbf initial load needed on the bearing housing and the component weights which would be supported by the cylinder, this 1:1 ratio would be ideal for the 105-120psi line pressure at the Fox factory. From the thread length on the bearing housing, a minimum of ½" of travel would be needed on the cylinder to keep the drivetrain and bearing housing engaged. This style of narrow cylinder is shown below in Figure 2-9.

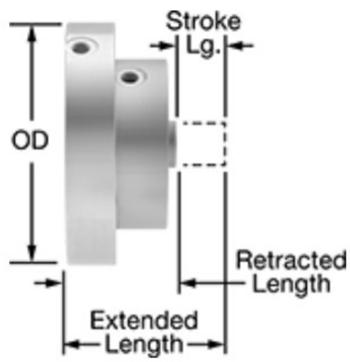


Figure 2-9. McMaster-Carr narrow-space air cylinder [7]

To keep either the drivetrain or the shock stationary while the bearing is threaded into the housing under load to begin the thread engagement, air brakes were suggested by Will during an early project discussion. These air brakes are already utilized in numerous machines around the Fox factory and could be used to lock the linear slide structure once the torque/rundown cycle was initiated. Air brakes, otherwise known as pneumatic rod locks, were found on a Fox dynamometer from Advanced Engineering and Machining Co. from the "Amlok RLA" model line. The RLA line doesn't appear to still be in production, but has been replaced by a new RLN line of pneumatic rod locks shown in Figure 2-10. This series of rod locks is available for relatively few rod diameters, so another brand of rod locks may need to be sourced if none of the available sizes match available linear bearing sizes. Furthermore, these rod locks would need to facilitate a rod large enough to limit deflection at the drivetrain adapter to a reasonable magnitude.

Figure 2-10. Amlok RLN series pneumatic rod locks [8]

2.4.7 Structures:

The mechanism that drives the bearing needs a support structure to allow it to be positioned and restrained during operation. Two systems were considered for this project: a FlexArm torque reaction arm and linear rails.

The FlexArm torque reaction arm is a beam-based tool balancer designed to support the weight of a torque driver as well as resist the torque it generates. A schematic of the arm is shown in Figure 2-11. Their largest model can support a torque of up to 800 ft/lbf with a tool weight of 65 lbf at an 84" radius [9]. This is more than enough for our needs. However, the bearing must be pushed down with 80lb of force to get past the first O-ring before the threads can be engaged. Will requested that our device provide the downward force, and the FlexArm is not capable of locking itself to allow another mechanism to provide the downward force.

Figure 2-11: FlexArm Torque Reaction Arm [9]

Linear rails with mounted linear ball bearings in a similar configuration to the system in El Cajon can be used to support the driving mechanism, as seen in Figure 2-5. A tool balancer can be used to support the weight of the driving mechanism. Due to the structure riding on a liner motion shaft, shaft brakes can be used to fix it in place to provide the downforce needed to push the bearing into the shock body past the O-ring. An overall layout of the system is shown in Figure 4-11.

2.4.8 Programmable Logic Control (PLC) Systems:

A PLC will be used to communicate between the torque controller and the rest of the system. The team received two Allen-Bradley PLC controllers from Fox: a Micro 820 and a MicroLogix 1400. These can be seen below in Figure 2-12.

Figure 2-12. PLC Controllers- Micro 800, MicroLogix 1400 left to right [10]

The two controllers allow communication and automated control throughout the system: communicating with the Torque controller, safety switches, pneumatics, and whatever needs to be controlled. The main differences between the two controllers is the number of input and output ports, the speed at which the ports react, and the voltage that the ports output. The software for both controllers can be installed for free off the Rockwell Automation website [11].

The Micro 800 has 12 input/output ports and 4 high amperage outputs that eliminate the need for external relays in a system [12]. The MicroLogix 1400 has 120 inputs and 72 outputs, all varying in speed, voltage, and amperage capabilities. The 1400 is also expandable with up to 7, 1762 input output modules [10]. The choice between the two modules will come down to the number of items that need to be controlled in the final design.

2.4.9 HMI Screen and Program

Many stations in FOX use an HMI (Human Machine Interface) screen to give the operation information about the status of the station and the process being worked on. An HMI is a small display, around 8” diagonally, that is often a touchscreen. This allows the operator to interact with the machine digitally and can provide an elevated point from which to troubleshoot. Figure 2-13 shows a simulation of one of the FOX HMI programs. The software used to code and simulate the HMI is called C-more and was provided by our sponsor.

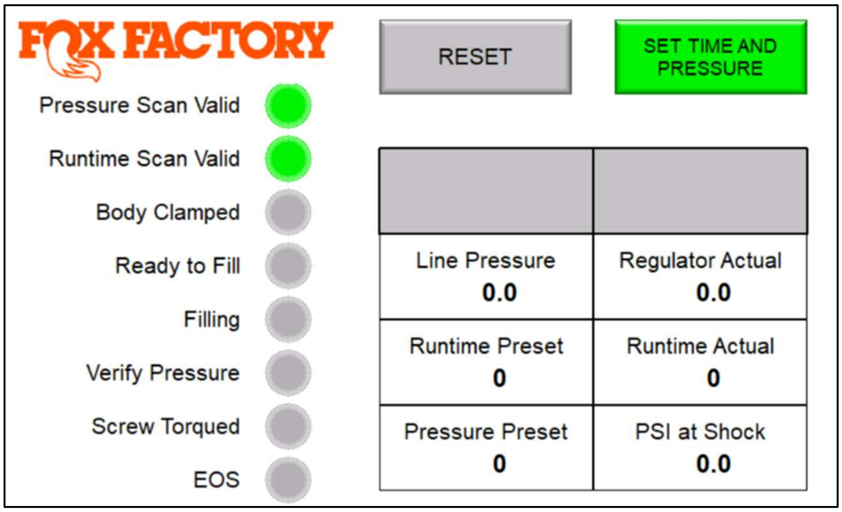


Figure 2-13. FOX HMI Main Screen

There are some notable components that make up this HMI screen. On the left is a strip of indicators that are referred to as the runway or Christmas lights. This strip of indicators will ideally light up in order as the machine's process continues nominally. The HMI also has a section that shows the digital output of various sensors and presets. These values are given to the HMI from the connected PLC which is, in turn, directly connected to those sensors. There is also a maintenance mode, shown in Figure 2-14, that can be accessed through a hidden button that requires a password.

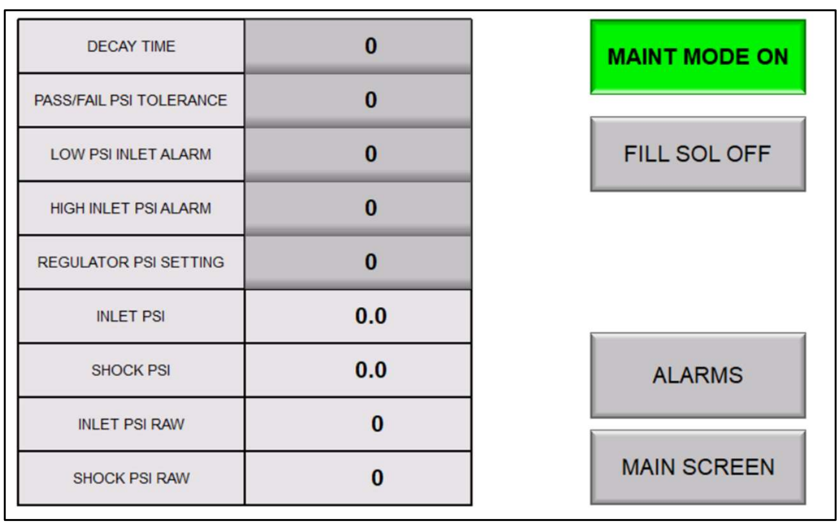


Figure 2-14. FOX HMI Maintenance Screen

In this page, maintenance mode can be toggled on and off. Once on, the operator can edit and set values that effect the machine. This allows the operator to troubleshoot if any problems with the machines arise.

2.5 Patent Research

Patent searches early in the design process for this machine were relatively unsuccessful because of poor terminology being used during the initial searches. After learning about the open-ended nutrunner (Atlas Copco LTO/LTC), a patent search was performed with similar key words which resulted in many useful resources for drivetrain design. One particularly interesting patent was an "off-set geared nutrunner attachment" [13] which looked nearly identical to the end of the Atlas Copco offset driver shown above in Figure 2-6, and the internals of the mechanism were exactly in line with the geared design the team was already working on. A summary of this patent is included in Appendix A along with other results such as belt/chain drive open-ended nutrunner, a combination ratcheting nutrunner and manual torque wrench, and an Atlas Copco torque controller for pneumatic nutrunner.

2.6 COVID-19 Response

During the spring break of 2020, Cal Poly announced that they would shut down the campus and all classes would be presented in an online format. This had several implications for this project. One implication is that the team can no longer meet physically as a group. The physical meetings were substituted with virtual zoom meetings. Virtual meetings with the sponsors from Fox and the advisor form Cal Poly have also been held virtually through WebEx and Zoom. The biggest implication from the outbreak was that the machine shops would also be closed, and the team would be unable to machine any parts for the project. The original plan was to machine a large majority of the parts over spring break and in the early weeks of the spring quarter. With the machine shops closed this was no longer possible. Because of this all the pieces need to be outsourced to a third-party manufacturer, adding more cost to the project. Another problem is that a lot of the pieces in the machine are designed to be waterjet. These pieces were intended to be cut with the Cal Poly waterjet in Mustang 60, but that is no longer possible. This is another problem because the third-party manufacturer used by Fox does not have a waterjet, so some of the pieces were re-designed.

Because a third-party manufacturer was needed to complete the project, the project timeline had to be shifted. As a result, the team has spent a portion of the spring quarter re-designing the machine to be lighter and sleeker. During the spring quarter the team has also worked on the controls aspect of the project; writing software for the HMI display screen, the PF6000, and for the Allan Bradley PLC. Though a fully functional machine will no longer be the final deliverable for the team, the team is hoping to have a test machine ready for Fox by the end of the quarter.

3 Objectives

After preforming extensive background research, the team worked to define the goals and specifications for the project. A boundary diagram was used to help visualize which aspects of the problem the team has control over, and which aspects they did not. After this, a house of quality was used to help quantify criteria and assign it numerical importance. Finally, a table of specifications was generated allowing the team to show if the goals were validated and met.

The main principles of consideration are safety, quality, and getting shocks out the door. With these principles in mind the team intends on developing a semi-automated procedure for pressing, screwing down, and torqueing the bearing housing. To define what the team was building a boundary diagram was made in order to create a better understanding of the process.

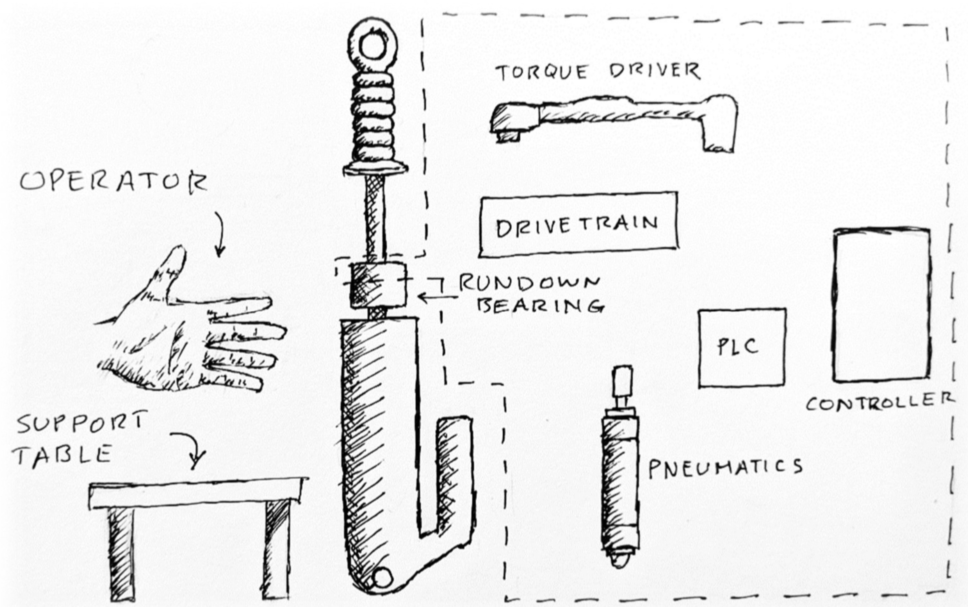


Figure 3-1. Boundary Diagram describing the specific elements the team has control over

As outlined by the boundary diagram, the team has control over the tooling, surroundings, and process involved in pressing, screwing and torqueing down the bearing housing to the shock body. This can be done in any feasible way to improve the consistency of assembly while maintaining line associate safety and assembly quality. There however is no control over the actual bearing housing, the shock itself, or the operator. The machine should be built to withstand torques between 50 and 100 ft-lbs.

The process is for the shock family first shown in Figure 2-1, and the automation tool should be easily adaptable to all shocks within that family. Scalability should be taken into consideration because many shock families share similarities in the assembly process.

A stretch goal for this project is to create a system that is easily adaptable to other shock families, such as the one shown in Figure 2-3. These shock families typically consist of a bearing housing that is hand tightened into the shock body counterclockwise, a snap ring is placed into the assembly, and then the internal section of the bearing is tightened clockwise against the snap ring.

Resulting from COVID-19 the team will not be responsible for machining/ final assembly or testing of the machine. A final design and resulting documentation will be provided to Fox to be built as desired. A controls system and program will be specified and programmed for the assumed operation of the machine. Fox will have access to all files and documentation to modify to their final desired purpose. Fox will design, outsource parts for, and assemble a test rig to build and test the drivetrain portion of the full system as a proof of concept.

3.1 QFD House of Quality

Project wants and needs were distinguished in order to determine how to consider the project successful, all while weighing in what would be possible to provide within the course of a year. The team categorized "Needs" as something necessary in order to successfully complete the project. "Wants" would be categorized as design considerations that may achieve what is needed but are not necessary for a successful project outcome. The wants and needs utilized can be seen below in Table 3-1.

Table 3-1. Wants and Needs

Needs	Torque Repeatability	No Witness Marks
	Operator Safety	Reliability
	Ergonomic	Maintainability
	Manufacturability	
Wants	Scalability	80/20 Rule
	Minimize Foot Print	McMaster Heavy
	Cost	

With the problem defined, the team sought to choose the best course for solving it. A Quality Function Deployment (QFD) chart was utilized to define the most important aspects of the problem. With this the team will have a better idea of how to make decisions when solving the problem at hand. To do this the wants and needs were listed and weighted by their importance to both the customer's and to what contributes most to full automation. A list of quantifiable engineering specifications used to define and test for successful implementation of any specific want or need was made. The QFD can be seen in Appendix B. The QFD is necessary to constantly assess and iterate the in-progress design. It will ensure the team stays on track of the goals we have set such that we do not waste time developing a product that does not fit the needs of the customer.

3.2 Specifications

Engineering specifications were developed from the QFD in order to quantify the wants and needs and decide whether we have achieved the set goals. The house of quality can be found in Appendix B. The current 13 engineering specifications developed, their importance in completing the project, how they will be measured, and the risk involved with each specification are displayed in Table 3-2. The risk is important to note, because the higher the risk the harder it will be to meet that specification.

Table 3-2. Engineering Specifications; outlining specification targets, importance, and method of checking for compliance (Inspection (I), Test (T), Analysis (A), and Similarity (S))

Spec #	Specification Description	Requirement	Tolerance	Risk	Compliance
1	Torque Repeatability	Within 5%	Max	M	I,T
2	Foot Print	1.5*Current	Max	L	S
3	Safety	Safe	–	H	I,T,A
4	Cycle Time	1.5*Current	Max	L	S,T
5	Setup Time	1.5*Current	Max	L	S,T
6	Adaptability	within 9XX-50-0XX	Min	H	T,A
7	80/20 DFMA Rule	50% Standard	Min	L	A,S
8	Machinability	DFM guidelines	Min	L	I,T
9	Cost (internal goal) (neglecting controls systems)	$25,000	Max	M	S
10	Time before maintenance/failure	90 Days	Min	M	S
11	Failure Modes	2	Max	L	S
12	Ease of Maintenance	1Hour DT	Max	M	T,S
13	Line associate Intervention	Minimal	-	L	S,I

Each specification listed in Table 3-2 above has a certain level of risk associated with it. [14] The team is most concerned about safety, and it was identified as one of the high-risk specifications. The machine will be operated nearly continuously, and unlikely causes of an unsafe environment can quickly compound and make the machine unsafe. This is not desirable as line associate safety is the top priority. This will be the most difficult specification to meet as it will require a good amount of inspection, testing, and analysis in order to ensure safety [3]. The design will be made and analyzed as much as possible through solid modeling and scenario analysis. A controls system will be designed and programmed to meet safety specifications of moving machinery.

The other high-risk specification is adaptability of the machine inside and outside the main shock family for this project, shown in Figure 2-1. This specification is high risk due to subtleties of each shock within a family that may cause an issue with the automated assembly process. A robust and versatile machine will be developed to avoid running into problems between shocks.

Medium-risk specifications are also of concern because there is a large amount of them. Torque repeatability was listed as a medium level risk. A torque driver will be implemented into the design of the automated assembly process and must by itself meet the listed specifications. The concern comes from implementing the driver into a device that possibly has loss or uncertainty of its own. Testing and analysis of the driver and the machine to be implemented should be done by Fox in order to achieve good results.

Resulting from COVID-19, cost also was listed as a medium risk specification. The halt in manufacturing slowed cashed flow through the factory and has required justification of cost to build new machines. Originally the cost included controls equipment and cost for material that would be machined at Cal Poly. All parts will now be machined through Fox and require quotes and part revisions to reduce cost of machining.

The other medium-risk specifications go hand in hand. Maximizing time before maintenance and ease of maintenance are both crucial to factory production. The team aims to maximize the time before maintenance by overbuilding the machine and building in specific points where the machine will wear such that other parts do not. This will narrow down points of maintenance which will allow the team to make these points of maintenance more accessible.

Testing possibilities were considered for each specification in order to make sure each specification was achieved. Table 3-3 below lists out each specification and the method in which it will be tested.

Table 3-3. Specifications and Testing Methods

Spec #	Specification Description	Testing Description
1	Torque Repeatability	Current torquing method will be tested against the new method
2	Foot Print	Footprint would be volumetrically measured in comparison to original
3	Safety	Safety procedures will be implemented in order to ensure proper use of the equipment where safety cannot be implemented into the design. Hazards will be minimized through risk and hazard assessment.
4	Cycle Time	Measured with a stopwatch and compared to original
5	Setup Time	Measured with a stopwatch and compared to original
6	Adaptability	Done through analysis of Fox standardized parts
7	80/20 DFMA Rule	Measured comparison of new versus standard components
8	Machinability	Done through following DFM guidelines
9	Cost (internal goal) (neglecting torque driver)	Perform cost analysis and cost breakdown of the entire assembly
10	Time before maintenance/failure	Utilize fatigue analysis to estimate time of failure and schedule maintenance prior
11	Failure Modes	Design the system to wear/break in specific accessible regions
12	Ease of Maintenance	Utilize DFA to make the points of failure easily accessible
13	Line associate Intervention	Compare to the line associate intervention against the current method

4 Concept Design

After performing research on relevant topics and similar machines, as covered in section 2 Background, enough information was gathered to begin working towards a design direction. The team used various design tools and techniques to help narrow down ideas and quantify results.

4.1 Design Process

The first tool used was functional decomposition. The main problem was split into unique categories that were further split into components. These components described basic and unique aspects that were required by the design problem. A short list of possible solutions for each component was generated.

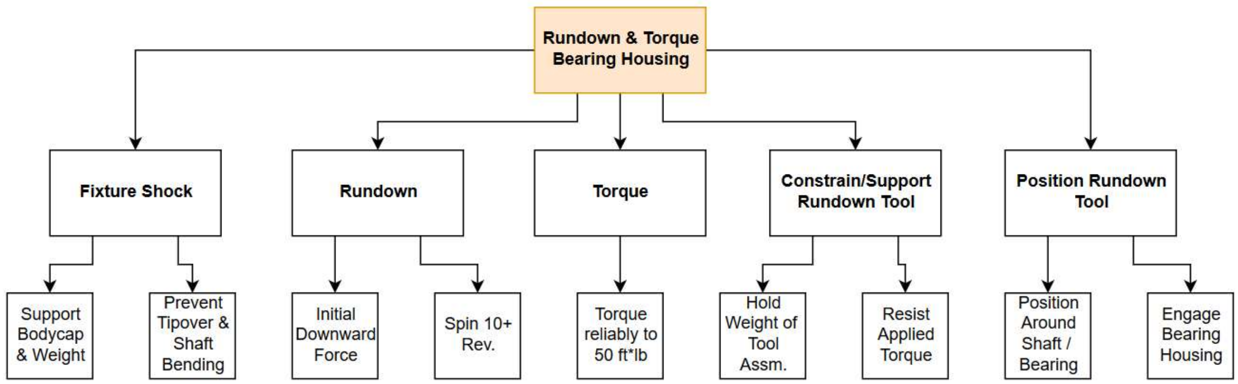


Figure 4-1. Functional Decomposition Diagram

The lists of solutions from the functional decomposition were then put into a series of Pugh matrices (one per function) which can be found in Appendix E. For each matrix, one of the solutions was chosen as the baseline solution and all other solutions were compared against it using the needs section as criterial from the house of quality. The results were tallied and used to indicate which solutions would be more effective. The effectiveness of the solution was based off how much it was better than the baseline, but bonus points were offered to solutions that would be more capable of achieving the stretch goal.

The top three results from each matrix were then put into a Morphological matrix, shown in Table 4-1. The purpose of this matrix was to generate potential design directions that have unique combinations of problems. Four different initial design directions were generated from the matrix, each made up of a different combination of solutions. The four potential solutions were each chosen to have different strengths and to be unique. Note that a fifth concept direction off the morphological matrix is shown below to account for feedback received during the team's factory visit in early January, which will be discussed further in section 4.3.

Table 4-1. Morphological Matrix

	Concept			
Function	I	II	III	
Downward Force	Self-Weight	Pnuematics	Fixture Pushed-Up	
Spin/Drivetrain	Belt Spanner	Geared Spanner	Spin Shock	
Hold Tool Weight & Tool Position	Tool Balancer & Linear Rails	Flex-Arm	Manual Tool Support	
Engage Bearing Housing	Hex Adaptor	Friction Engagement	No Adaptor, Pin-Spanner	
Resist Torque	Rotational-Locked Linear Slides	Dual Handle (Operator)	80/20 Post (Full rigid)	(Flex Arm)
Prevent Tipover	Pnuematic Softjaws	U-shape w/ latch	Taller bodycap / extension	

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Will feedback, pre-factory-visit:	**blue**	
Flex-Arm system:	**purple**	
Low automation system:	**red**	
Spin shock system:	**green**	
Will &Tom feedback, post-factory visit:	**orange**	

It should be noted that each initial solution shown chooses a belt driven spanner, shown in Figure 4-2. Initial design discussions showed that gears would have more design challenges for no more benefit than the belt spanner. In designing a belt driven spanner, it became apparent that a gear driven spanner would in fact have less challenges to overcome in terms of manufacturability and maintenance intervals.

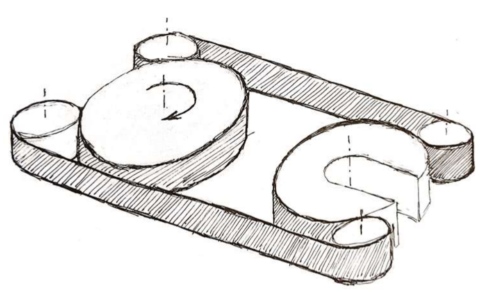

Figure 4-2. Belt spanner concept

4.2 Concepts Generated

Sketches of the four top concepts are shown below, sketched based off the solutions chosen in the Morphological Matrix.

The first concept chosen is called "Will feedback, pre-factory-visit". It was generated from the morphological matrix by choosing solutions that the project sponsor, Will, would most likely be in line with. The concept uses a belt drive to rotate the spanner tool and the structure utilizes a tool balancer and linear rails, as shown in Figure 4-3.

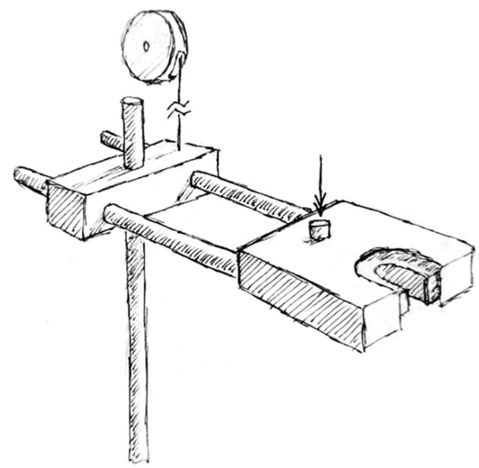

Figure 4-3. "Will feedback, pre-factory-visit" system

This concept also uses a hex adapter used to interface between the spanner tool and the bearing, as shown in Figure 4-4. The adapter has a slot cut into it, matching the slot in the spanner tool. The top of the adapter is cut to a hex shape that fits into a hex cavity in the spanner tool. The bottom of the adapter tool has four pins that fit into the bearing housing. This piece avoids the problem of leaving witness marks on the bearing housing as it is to be put in place, and then the rotating spanner tool will spin and engage with the adapter.

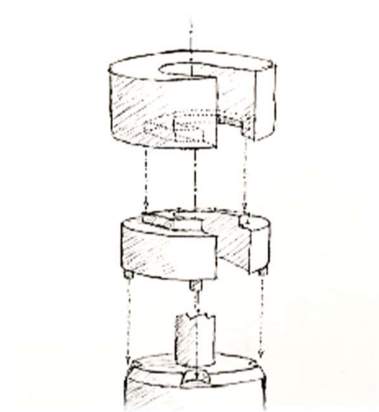

Figure 4-4. Spanner hex adapter

Another concept in line with some initial input from Will that was generated was a FlexArm drivetrain support system. This concept direction would utilize a FlexArm Torque Reaction Arm, mentioned during the discussion of general component research, to provide easy positioning of the drivetrain assembly around the shock and bearing housing without needing to design a structural system. The FlexArm in question was designed with the intention of holding an inline torque driver, so this system would be well equipped to withstand the torque reaction at the bearing housing / spanner interface while holding the weight of the drivetrain system without need for a tool balancer. Using a similar hex-drive spanner adapter as the above mentioned system, this FlexArm design concept is shown in Figure 4-5 along with pneumatic soft-jaws fixturing the shock body-tube to prevent tip-over.

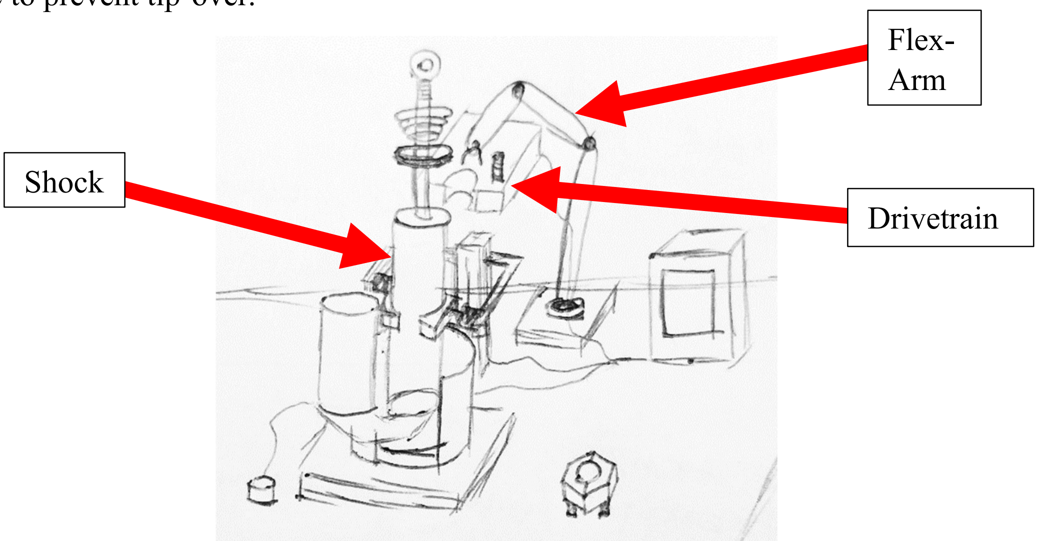

Figure 4-5. FlexArm drivetrain support system

A potential issue foreseen with this FlexArm system is the lack of vertical constraint preventing the drivetrain from being pushed up while attempting to drive the bearing housing down into the shock body tube while looking for the initial thread. With the above-mentioned linear slides utilized as structures, pneumatic braking can be performed on the linear slides to lock the drivetrain assembly from moving vertically while the bearing is pressed into the shock body.

Another option from the initial morphological matrix was a minimal automation system shown in Figure 4-6. This system would utilize the body cap pallet and a U-shaped latch to support the shock. The belt driven spanner would be manually placed onto the shock with the help of a tool balancer. The torque of the machine would be resisted through the line associates grip on two handles attached to the drivetrain. Like the other designs the belt driven spanner would utilize a spanner adapter in order to engage with the bearing housing. This option came in last on the weighted decision matrix mainly because of the need for line associate intervention that can cause fatigue and is a potential safety risk.

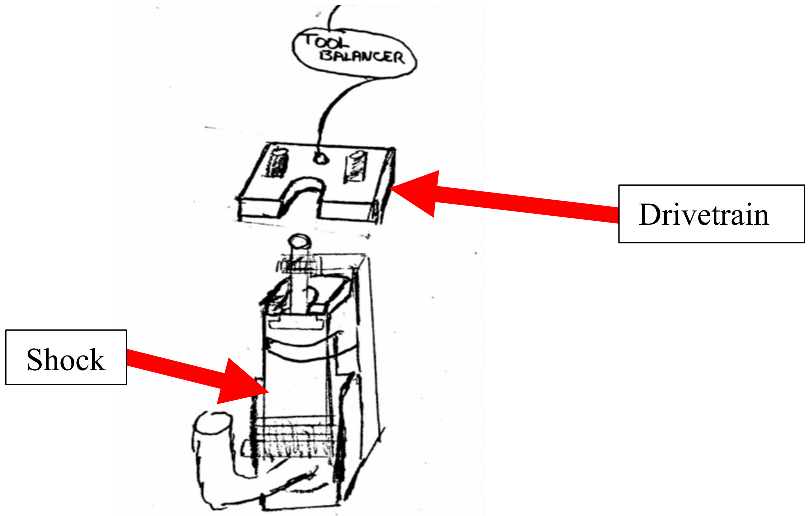

Figure 4-6. Minimal Automation System

One concept involves spinning the shock in place to run down the bearing, as shown in Figure 4-7. A spanner wrench similar to one used currently, can be held in place by linear slides and prevent the bearing from rotating with the shock. Pneumatic cylinders are used to provide the initial force to get the bearing threads pass the O-ring. The spinning mechanism underneath the shock is powered by an external motor. This eliminates any complex driving mechanism on the bearing side, but it introduces several other problems. Because this system isn't driving the bearing directly it will be more difficult to quantify the losses throughout the system to ensure the bearing is properly torqued. In addition, a large spinning shock poses a significant safety hazard if the shock comes out of its fixture.

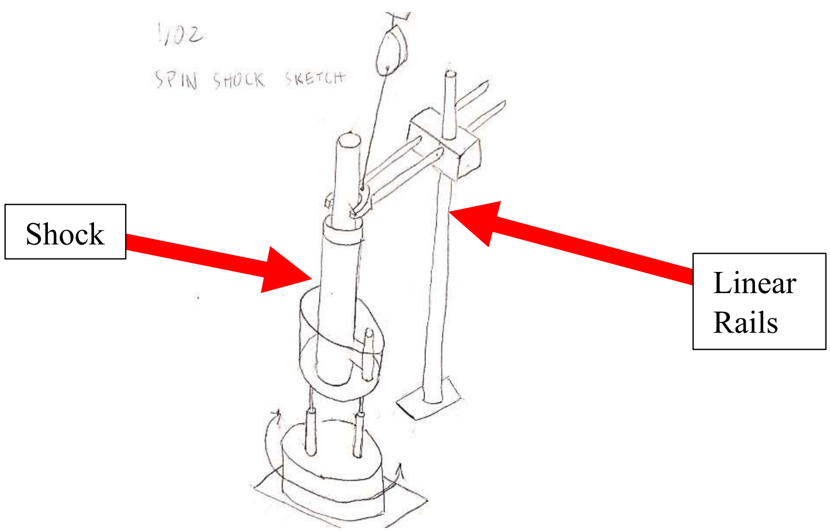

Figure 4-7. Shock spin system

4.3 Concept Selection

After the four concepts were generated and discussed, they were put into a weighted decision matrix (located in Appendix F), using criteria from the previously mentioned house of quality. The team discussed how each concept might perform for each criterion and assigned points accordingly. After totaling the points, it was shown that the concept "Will feedback, pre-factory visit" scored the best.

Before deciding on a final design, most of the team visited the Fox factory and spoke with Will and Tom. Some of the feedback that was given was about the idea of using an adapter to interface between the spanner tool and the bearing housing. In order to constrain the adapter around the axis of rotation, it was suggested that the adapter pick up on the sides of the cylindrical bearing housing. Similarly, it was suggested that the rotating spanner tool had a circular step on its top or bottom that would constrain it to rotate about the desired axis of rotation. Concerns about providing a downwards force on the bearing housing were discussed, from how the force would be provided to how the resulting forces would affect the structures of the machine.

Some final research was also performed. After seeing a patent that showed an open-ended crow foot adapter, very similar to our spinning spanner tool, the team realized that using gears may still be a viable option. Gears were initially ruled out because of machining and safety concerns regarding the mesh of the gears. As mentioned before, using belts seemed to be the best option and would provide less problems, so using gears to transmit torque was unimplemented in our top four concepts. Changing between the two would not affect any other subassemblies other than the drivetrain assembly that it is housed in.

4.4 Selected Concept Description

The team opted to move forward with the design described by the 5th option in **Error! Reference source not found.**. After doing analysis detailed out in section 4.5 the team decided the belt driven system would not allow for standardized parts to be utilized to their fullest.

Using the functional decomposition, the team broke down the project into 3 main categories: drivetrain, structures, and fixturing/downward force. Drivetrain's responsibilities include choosing the torque driver, interfacing the driver with the driven system and interfacing the driven system with the bearing housing. The structures category works on the design and mechanics of supporting the shock and drivetrain. Structures will interface with the drivetrain to allow it to move freely for positioning and keep it static during operation. Fixturing/downward force oversees securing the shock and applying the force necessary to push the bearing housing past the O-ring. These categories were chosen such that each category could design freely within constraints to endpoints which are easily interfaceable with one another.

4.4.1 Drivetrain

The drivetrain consists of a main C-shaped gear (open gear) that interfaces with a bearing adapter to drive the bearing housing into place. The open gear will be driven using two idler gears which ensure that at least one gear will remain in mesh with the open gear at any point in time. Lastly, the two idler gears will be driven by a gear of the same size as the open gear to maintain a 1:1 torque ratio. The idler gears will likely be smaller than the other two gears, allowing for different alignments of the gear mesh. This driving gear will be attached directly to the torque driver of choice. The main drive shape is shown below in Figure 4-8.

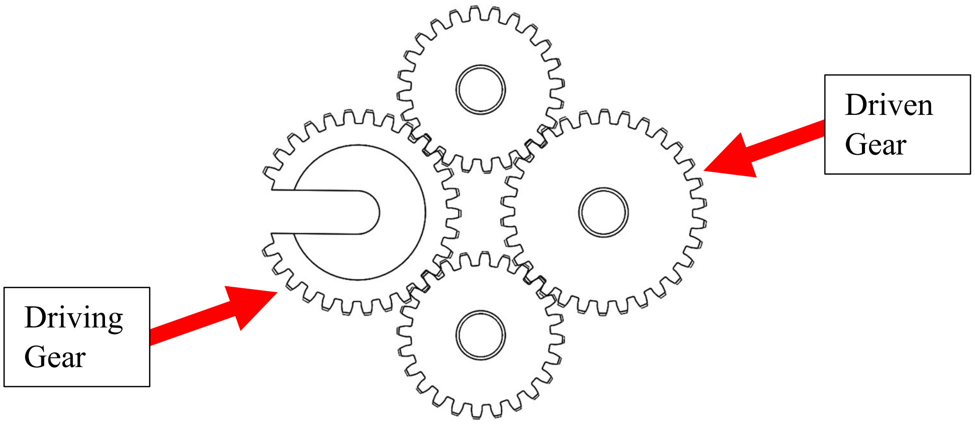

Figure 4-8. Drivetrain gear layout

The open gear cannot be constrained from its axis of rotation. The drivetrain housing will have a consumable wear part that cups the open gear around as much of its diameter as possible, allowing the gear to remain in place positionally. Figure 4-9 shows a concept of what the consumable part would look like:

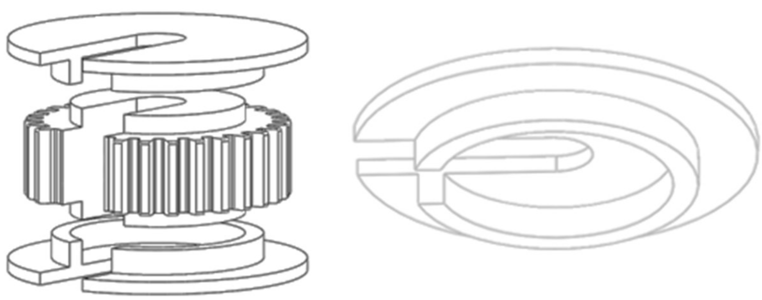

Figure 4-9. Sectional view of open gear and its method of constraint

4.4.2 Adapter

One of the major design requirements is to maintain quality. One way this manifests itself is the avoidance of leaving witness marks on the shock, specifically on the bearing housing. The adapter solves this problem while allowing the drivetrain to quickly and easily transmit the required torque to the bearing. The adapter is placed on the bearing by the line associate. Because this placement is performed by a human and not an automated process, there will be no excessive forces or misalignment that could leave a scratch on the bearing. Once placed, the line associate will turn on the machine and lower it over the adapter. The hex extrusion on the adapter will fit into the matching hex recess in the drivetrain and thus the system will be connected, and torque will flow from the drivetrain, through the adapter, into the bearing. The adapter itself it made up of two main components. The first is the tool steel body that is machined to have the hex extrusion and will have pins inserted into it. This component will transfer all of the torque into the bearing. The second component is a Delrin piece that will attach to the bottom of the tool steel and will fit up against the bearing housing. This allows a softer contact and it allows the adapter to pick up on the geometry of the bearing, which will maintain the adapters co-axiality.

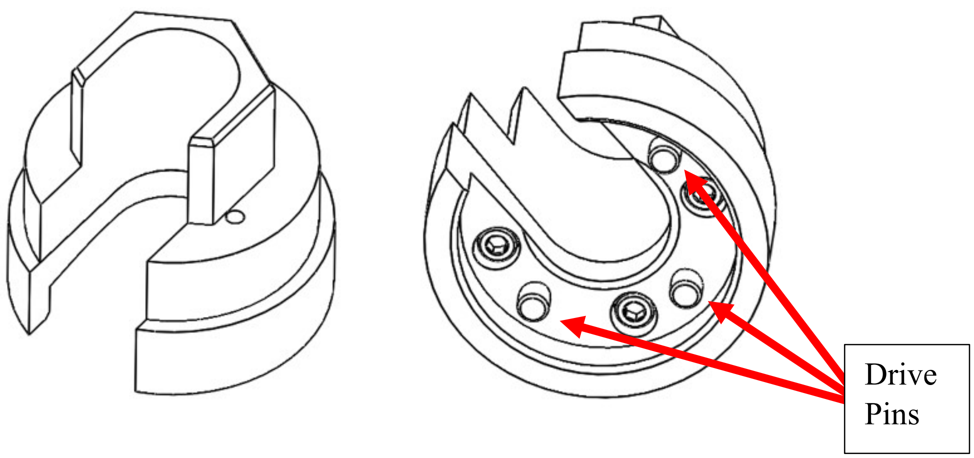

Figure 4-10. Top and bottom view of the adapter assembly
(Left and right images, respectively)

4.4.3 Structures

Motion in the structures with be achieved by using linear shafts and linear shaft bearings. A single vertical shaft will be used to provide axial motion to the drivetrain and allow it to rotate about the vertical axis. Two horizontal shafts will be used to allow the drivetrain assembly to be positioned radially and resist the torque generated by the torque driver. These kinematics allow the system to position the drivetrain wherever needed as well as allow for any minor misalignment between the drivetrain and shock. The layout of the system is shown in Figure 4-11.

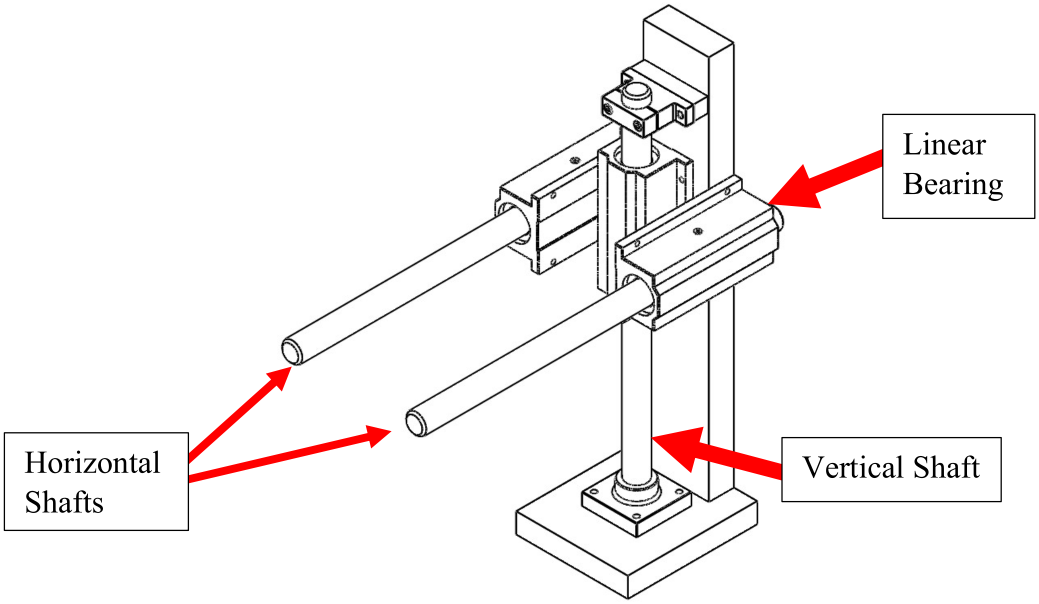

Figure 4-11. Structures Layout

4.4.4 Pneumatics (Downward Force)

To simplify the mechanism providing downward force on the bearing housing, which is to compress the O-rings and slip the housing into the body tube while looking for the first thread, a low-profile air-cylinder will be placed directly underneath the body cap pallet. This keeps the linear force directly in line with the shock and bearing axes and avoids the need for the mechanism to travel with the moving drivetrain. Utilizing the press-fit drill bushings already assembled with the body cap pallet base plate, vertical posts will be attached to the machine base plate and used to locate the body cap pallet in the plane of the workbench while allowing vertical freedom. A third, rectangular support will be placed behind the body cap pallet to keep the base plate parallel to the workbench and avoid any bending in the vertical posts. Potential material choices for these supports include Delrin or 6000 series aluminum due to ease of machining and low cost, but frictional effects during the vertical travel of the body cap pallet will need to be investigated. This lower pneumatic assembly is shown in Figure 4-12.

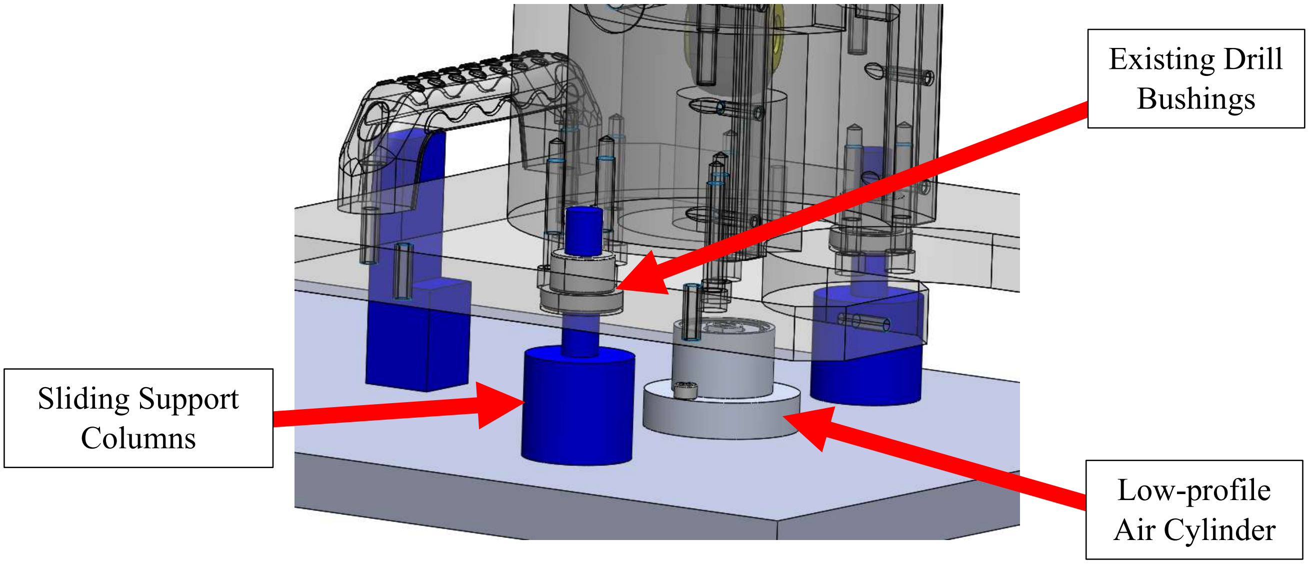

Figure 4-12. Lower pneumatic assembly with low-profile cylinder

This vertical force from the body cap pallet will be resisted at the drivetrain mechanism by pneumatic linear rail brakes on the structural rails. Moving forward, compromises between the structural design and rail braking system will need to be made to ensure that rail brakes are available for a shaft size which limits deflection of the drivetrain assembly to an acceptable amount.

Some uncertainty remains about the need for need for upper fixturing of the shock body tube in order to prevent shock tip-over towards the line associate. If the drivetrain housing bumps the shock shaft and knocks the shock out of the body cap pallet, a U-shaped support at the highest point of the body tube would go a long way towards ensuring machine line associate safety. However, the body cap pallet is stable in holding the shock and would likely provide enough stability when the shock is clamped by the pneumatic cylinder between the pallet and the drivetrain housing. If this secondary shock support is found to be a necessity, a pneumatic latch to close the U-shaped support could be used to keep the shock fully fixtured until the machine torque cycle is complete.

4.4.5 Full assembly

The full assembly consists of the aforementioned subsystems. The structures work in conjunction with the tool balancer to support the weight of the drivetrain system. The drivetrain will be connected to the structures via the linear rails. The linear rails do not currently have detailed connections to the drivetrain but will be pinned and locked in with shaft collars. The drivetrain currently consists of only the drivetrain gears and the c-shaped bearing. Moving forward, the housing will be built around the gears, the torque wrench will be attached to the top, and handles attached to the bottom. Currently the fixture assembly only fixtures the shock at the bottom. The linear rails and pancake piston allow the shock to be forced upward, but a second fixture point will most likely be added to the shock body to further prevent tip over.

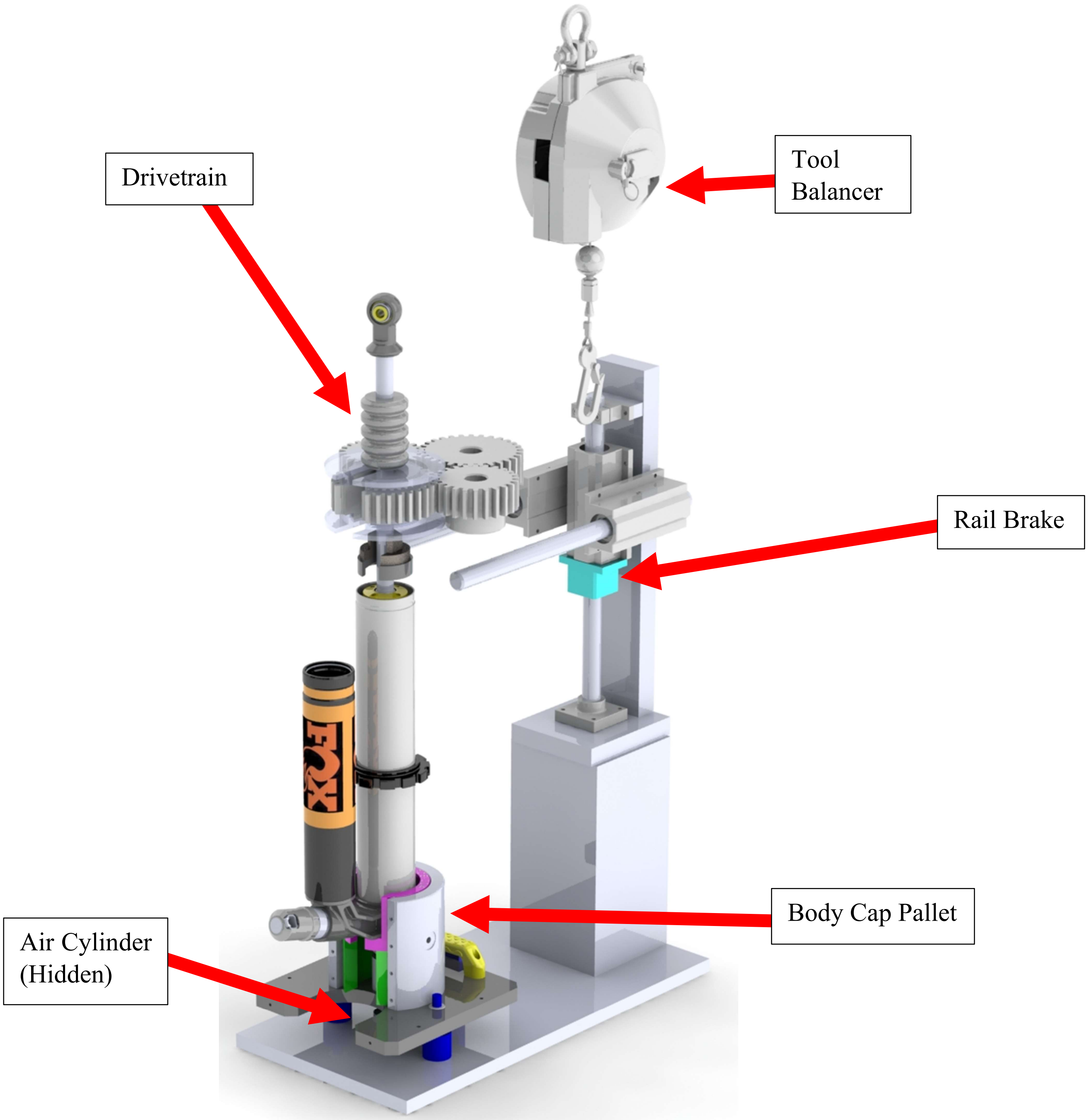

Figure 4-13. Render of full assembly

4.5 Preliminary Analysis

As the team generated concepts and ideas for the machine, various forms of analysis were required to validate and further define the ideas. Hand calculations were used to estimate forces and reactions and quick experiments to simulate factory conditions when assembling a shock. While simplifying assumptions were occasionally used to prevent over-complication of the calculations, they provided initial values to help drive the design.

4.5.1 Bearing housing O-ring compressive force

To quantify how much linear force is needed to compress the bearing housing O-rings while engaging the first thread in the body tube during the rundown process, some preliminary tests were performed using the scale outside the Mustang 60 machine shop. The shock was placed in the center of the scale and carefully balanced to estimate the pre-oil weight for the shock assembly, which was recorded. Next, the top of the bearing housing was loaded until it dropped into the shock body and bottomed at the start of the first body tube thread. The scale's readout was monitored, and the peak weight noted. This was repeated several times, and the peak value to hold the bearing housing at the thread beginning was found to be roughly 80lb (shock weight was subtracted from the scale readout value). This procedure is shown below in Figure 4-14.

Figure 4-14. Shock weighing and preliminary O-ring compression quantification (Left and right images, respectively)

Due to some concern about the shock potentially not being loaded completely vertically on the scale and any impact effects on the scale output, this test would have been repeated with the shock in its appropriate body cap pallet assembly. However, when the body cap pallet was brought to campus on a following day, the scale appeared to be broken and subsequent tests to verify the 80lb magnitude could not be performed during the preliminary analysis stage. This compressive force will certainly be confirmed to a greater level of certainty before any structural or pneumatic components are purchased.

4.5.2 Continued Bearing Load Quantification:

As mentioned above, the initial findings for the downward force needed to compress the O-rings on the bearing housing needed to be revisited due to problems with the scale. With the scale once again working and the body cap pallet on hand, the loading test described previously was repeated several times. The results of this repeated test indicated a much higher force required than the original 80lbs, with values upward of 120lbs needed to engage the first thread on the bearing. Both the magnitude displayed on the scale and the effort required in order to engage the thread seemed excessive compared with experience on the manual process from the original factory visit. When difficulty arose for simply pulling the shaft assembly out of the body tube, it was realized that all the assembly grease from the original application at the factory had been worn away. To fix this issue, a tube of Slickoleum light grease, shown below in Figure 4-15, was ordered to replicate factory conditions.

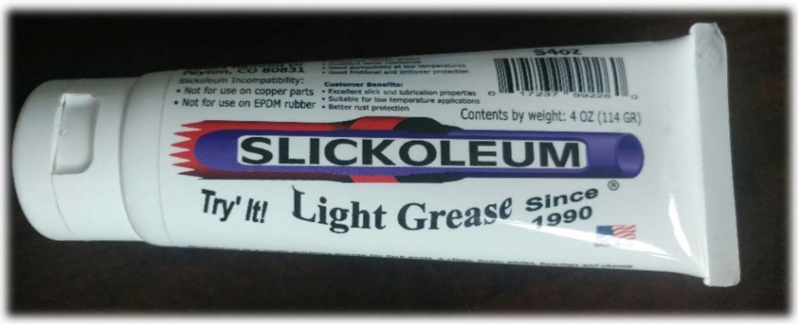

Figure 4-15. Slickoleum grease used for assembly at the Fox Watsonville factory

With the bearing housing and O-rings re-lubricated, assembly of the bearing into the shock body felt once again in line with factory conditions, and the final downward force value was found to be roughly 50lbs. This provides a high confidence in air cylinder sized, and potentially leaves room for downsizing the pneumatic cylinder to decrease costs if desired.

4.5.3 Gear Analysis

The strength of a gear is related primarily to pitch, face width, material, and hardness. In general, the number of teeth increase the life of the gear because pitch diameter is increased. Pitch and face width are directly proportional to the strength of the gear. Material is proportional based off its ultimate strength and hardness is directly proportional to the wear characteristics of the gear. To utilize McMaster-Carr as much as possible, calculations were done on different gears readily available from their website; modifying pitch, face width, and material only based on what can be purchased directly off the McMaster-Carr Website.

Gears can fail in two separate ways, from bending, and from contact wear. Due to the unknown nature of the c-shaped gear the team aimed for a bending factor of safety of 2 and a wear factor of safety of 1.5 at one million cycles.

On gear analysis there are several factors that modify the life expectancy of gears. Table 4-2 below shows the most important modifiers. These values were chosen based off recommendations and tables in the from Shigley's Mechanical Engineering and Design textbook [4]. Justifications for the modification factors can be found in Appendix G.

Table 4-2. Modification Factors

Modification Factor	Symbol	Units	Value
Overload Factor	Ko	-	1.50
Dynamic Factor	Kv	-	1.37
Temperature Factor	Kt	-	1.00
Reliability Factor	Kr	-	1.002
Surface Condition Factor	Cf	-	1.00
Geometric Factor for Contact	I	-	0.054

Calculations were done on several different gears in the McMaster selection. All used the same or similar modification factors. Table 4-3 below show different gears available and the corresponding factors of safety. Sample calculations for this table can be seen in Appendix G as well.

Table 4-3. McMaster Standard Gear Factors of Safety

Pitch (teeth/in)	Number of Teeth	Face Width (in)	Bending F.O.S	Contact F.O.S.
10	20	1.25	1.3	2.3
10	40	1.25	1.7	3.1
8	24	1.5	2.0	2.1
8	28	1.5	2.3	2.4
6	24	1.5	3.4	2.1
6	30	1.5	4.8	2.5

Given the large standard face widths of the 6 and 8 TPI gears, the team is considering custom machining gears to better fit the needs and constraints of the design.

4.5.4 Structures Analysis

Static analysis and beam deflection calculations were performed to confirm that the structure layout of the El Cajon factory in Figure 2-5 is suitable for our applications in terms of load capacity and stiffness. A loading case of 100lbs upward from the drivetrain was evaluated. The schematic for the system is shown below.

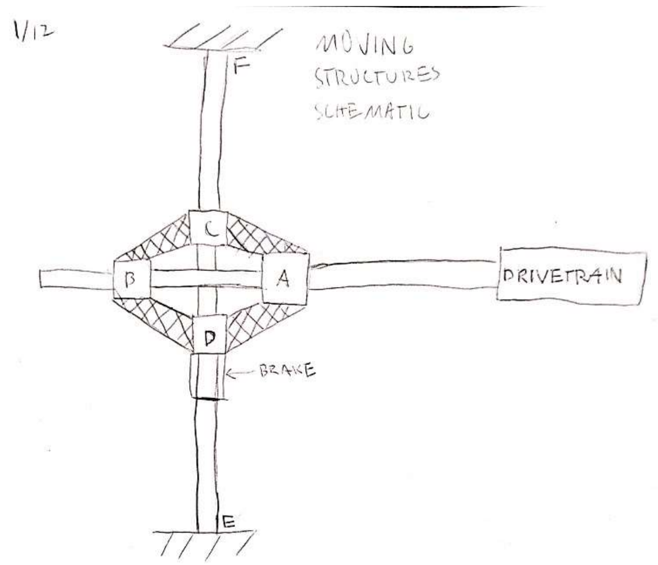

Figure 4-16. Moving Structures Schematic

Linear bearings are located at A, B, C, and D. The structure connecting them is assumed to be much stiffer than the shaft the bearings are on.

The free body diagrams for the horizontal arm, bearing plate, and vertical shaft are shown below in Figure 4-17, Figure 4-18, and Figure 4-19. The loading case was evaluated with the parameters shown in Table 4-4.

Table 4-4. Structure Loading Parameters

Inputs	Variable name	units	Value
Upward force	F	lbf	100
Length from front bearing to applied load	L_1	in	8
Distance between bearings	L_2	in	6
Number of horizontal shafts	n	n/a	2
Horizontal shaft diameter	d_h	in	1
Distance between bearings	L_3	in	10
Distance from floor to bottom bearing	L_4	in	2
Height of shaft	L_5	in	18
Vertical shaft diameter	d_v	in	1

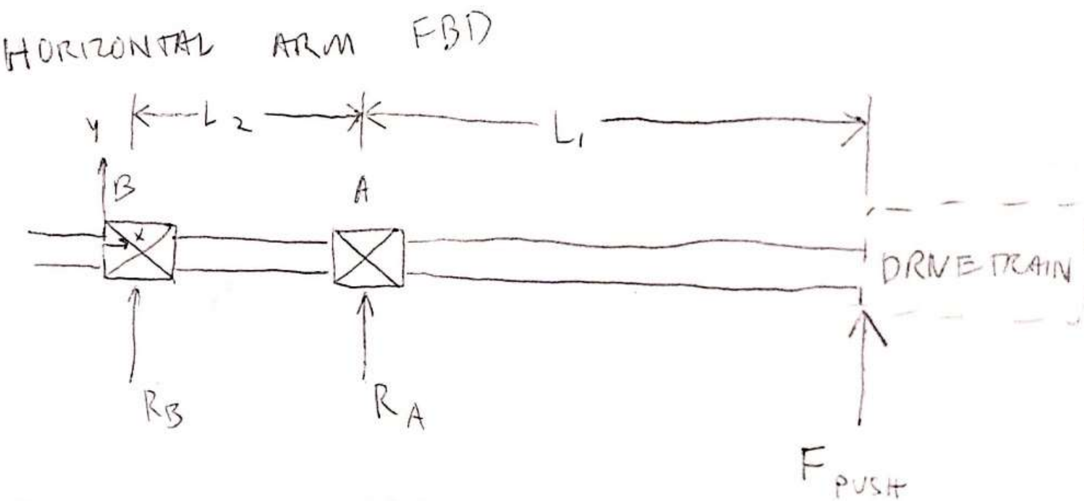

Figure 4-17. Horizontal Arm Free Body Diagram

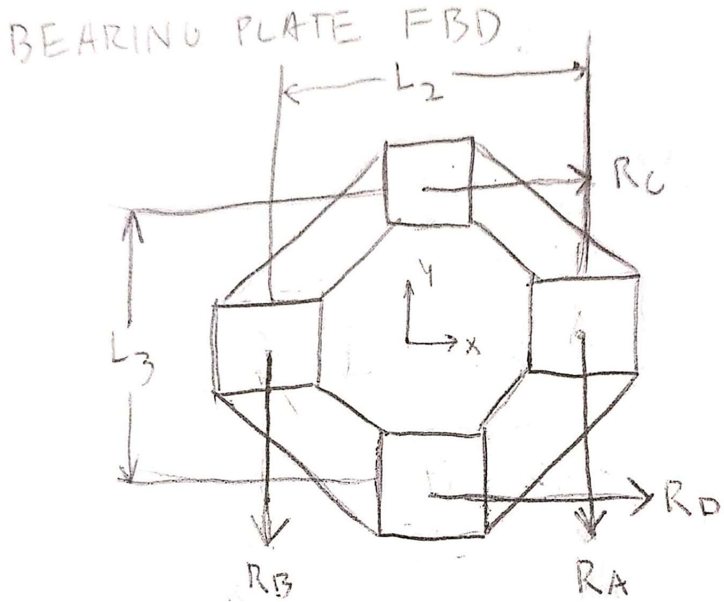

Figure 4-18. Bearing Plate Free Body Diagram

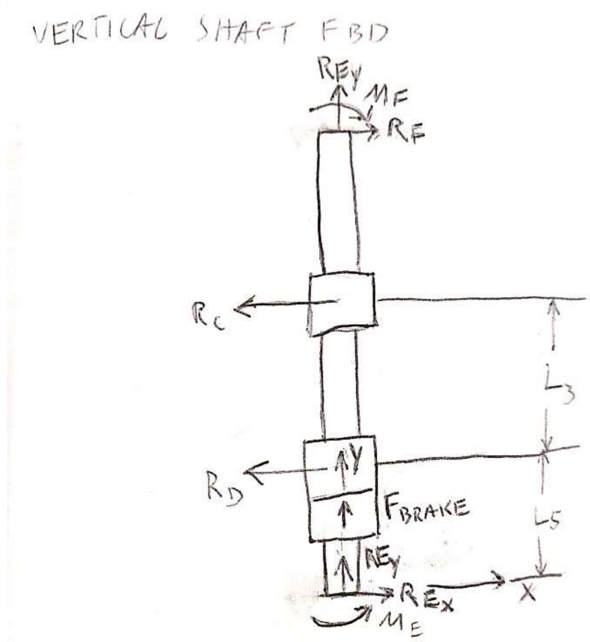

Figure 4-19. Vertical Shaft Free Body Diagram

The resulting deflections and reactions are shown below in Table 4-5. Equations for beam deflection and reactions were obtained from Shigley's Mechanical Engineering and Design textbook [4].

Table 4-5. Structure Results

Reactions and deflections	Variable name	units	Value
Forward bearing	R_A	lbf	-116.67
Rear bearing	R_B	lbf	66.67
Max horizontal arm deflection	D_h_max	in	0.010
Top bearing	R_C	lbf	-110.00
Bottom bearing	R_D	lbf	110.00
Top fixture Point Horizontal Reaction	R_F_x	lbf	-77.71
Bottom fixture point horizontal Reaction	R_E_x	lbf	77.71
Top fixture Point Moment	M_F	in lbf	73.33
Bottom fixture point moment	M_E	in lbf	271.60
Max deflection	D_v_max	in	0.000

The reactions are sufficiently low enough to be negligible compared to the capacity of the linear bearings for a 1" shaft from McMaster-Carr. The bearing has a static capacity of 2100 lbs [15]. The deflection is low but may need to be reduced based on the needs of the drivetrain. Further analysis will be conducted on the loading case where the structure is experiencing the torque from the drivetrain.

4.6 Potential Risks and Hazards

As far as line associate safety is concerned, the initial clear hazards involve pinch points at the drivetrain opening, large machine weight / stability on a relatively small base plate, and pneumatic lines near areas with grease, oil, and various cleaning solutions. To avoid a pinch hazard with the open gear, both hands will need to be kept occupied away from the drivetrain opening, with either two hands guiding the drivetrain assembly or one hand on a safety switch at the base of the machine. Either way, two buttons will need to be pressed for the machine to be powered. Concerning a machine tipping hazard, limits can be placed on the structural rails if moving the drivetrain in any direction is found to shift the center of gravity of the machine off the base plate. For the risk of pneumatic lines failing and propelling any chemicals towards the line associate, the standard Fox safety glasses policy should be enough. Finally, the general ergonomics of the machine operation will be monitored closely as the CAD assembly becomes more detailed since ergonomics were a large factor in the need for this project.

The largest perceived challenge moving forward in the design will be learning enough about PLC systems to effectively integrate the torque driver control system with the pneumatic systems for providing downward force and constraining the shock. Since Cal Poly does not include PLC systems in the mechanical engineering control systems curriculum, a formidable gap in design knowledge will need to be overcome in the next few months. Ideally, during the final quarter of this project, several of the team members involved with this project will be enrolled in a PLC / manufacturing automation course offered through the manufacturing engineering department at Cal Poly which should help significantly in this area.

One issue perceived with the hex-drive adapter is that the current design direction calls for vertically locking the drivetrain once the rundown cycle begins. However, the open gear needs to drop down onto the adapter to engage the pins in the bearing housing, and likely some amount of drivetrain rotation will need to happen under power until the hex drive aligns. This current design flaw will need to be resolved, possibly with a longer travelling pneumatic cylinder or an inductive sensor to alert the control system when the hex drive has been engaged.

5 Final Design

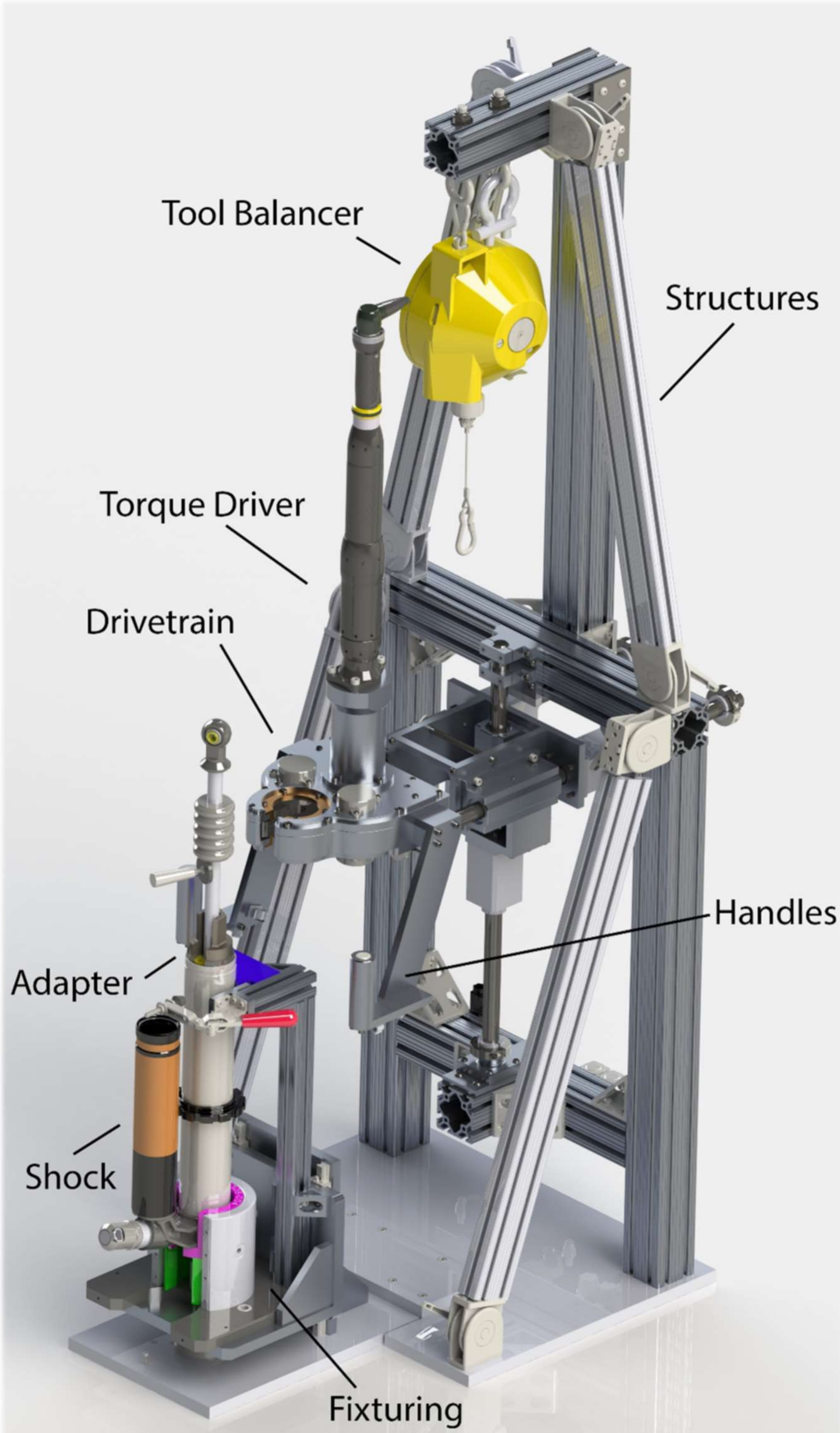

Figure 5-1. Annotated Full Assembly

5.1 Full Assembly

The full assembly, shown above in Figure 5-1, consists of 6 main subassemblies, which will briefly be described in the following paragraphs. More detailed descriptions will be given for each individual subassembly in the sub-sections of this section.

The drivetrain assembly is the most complex assembly of machine. The purpose of this assembly is ultimately to transfer the torque from the torque driver into the adapter piece. The drivetrain assembly achieves this through a spur gear train with one input gear, one output gear, and two idler gears. The output gear has a female hex cut into it which is how it interfaces with the adapter assembly.

The adapter assembly is made up of two main pieces. The first piece is made of 4140 chromoly steel and has a male hex that fits into the female hex of the drivetrain output gear. The second piece of the adapter is a Delrin piece that is machined to fit the geometry of the bearing housing. The adapter has dowel pins that fit into the bearing housing and is how the torque is transferred into the bearing housing.

The handle assembly is attached to the bottom of the drivetrain. The handles are attached to the drivetrain with pieces of aluminum plate. The handles each have a button where the operator's thumbs will be located, and the overall handle location is designed with the operator's ergonomics in mind. The buttons communicate with the PLC cabinet which communicates with the PF4000 controller.

The controller is a necessary component of the machine not just because it controls the torque driver, but because it gives feedback to the operator about the status of the current job. The PF4000 is mounted on an 8020 frame that is mounted onto an aluminum plate, separate from the main base plate. This allows the controller to be moved wherever convenient for the operator.

The structures assembly holds the weight of the drivetrain and provides a reaction to the downward force. The structure is made primarily of 8020. Linear rails are used to allow the drivetrain to be positioned by the operator and linear brakes are used to lock the drivetrain in place. The structure also contains a tool balancer, used to make the positioning of the machine less of an ergonomic strain on the operator. A polycarbonate shield is mounted around the 8020 frame for safety, preventing any objects or human extremities to come in contact with any potentially dangerous areas.

The fixtures assembly has two primary functions. The first is to secure the shock in place. A body cap pallet, a standard assembly component from Fox, is used to secure the base of the shock. This alone provides ample support, but a second fixture point was added for safety reasons. The upper fixture point consists of a Delrin V-block and a toggle clamp. This locks the shock body into place and prevents it from tipping towards the operator. The second function of the fixture assembly is to provide the required downward force onto the bearing housing. A pneumatic "pancake" cylinder is located below the body cap pallet and pushes the shock into the drivetrain. Linear rails are used to constrain the shock to vertical movement only.

Finally, a panel of pneumatic components is attached to the back of the main structure. This panel will allow airflow to the machine, filter the air, regulate the pressure, and hold the solenoids which will supply air to the rail brakes and pancake cylinder as needed.

As mentioned before in this report, the team had the opportunity to perform a round of re-design on the machine.

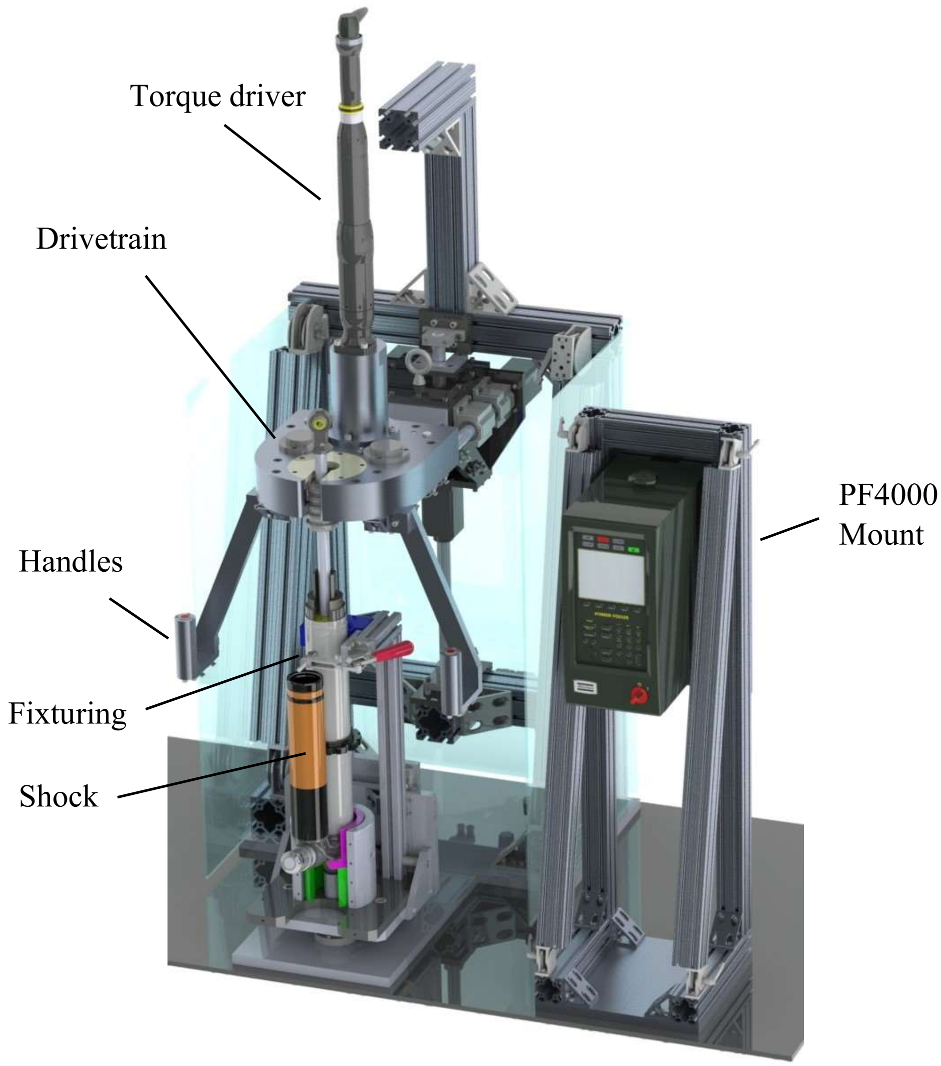

Figure 5-2. Outdated Full Assembly

Figure 5-2 shows what the design looked like before the re-design. This design is what was presented in the CDR presentation. From visual inspection it is obvious that there were changes made to the drivetrain, handles, and the controls 8020 structure. Many of these changes were made for simplicity of the overall design and are mentioned in the following subsections.

5.2 Drivetrain Assembly

As mentioned previously the drivetrain assembly is a complex assembly consisting of 1 driven gear, 1 drive gear, and 2 idler gears. The rest of the components are support components necessary to maintain the rotation of these gears as well as allow for the adaptation of the Atlas Copco torque driver onto the drive gear. Because of COVID-19 the team worked on a redesign that made the moving mass more lightweight. Figure 5-3 below shows a rendered version of the drivetrain assembly before and after being reduced in weight.

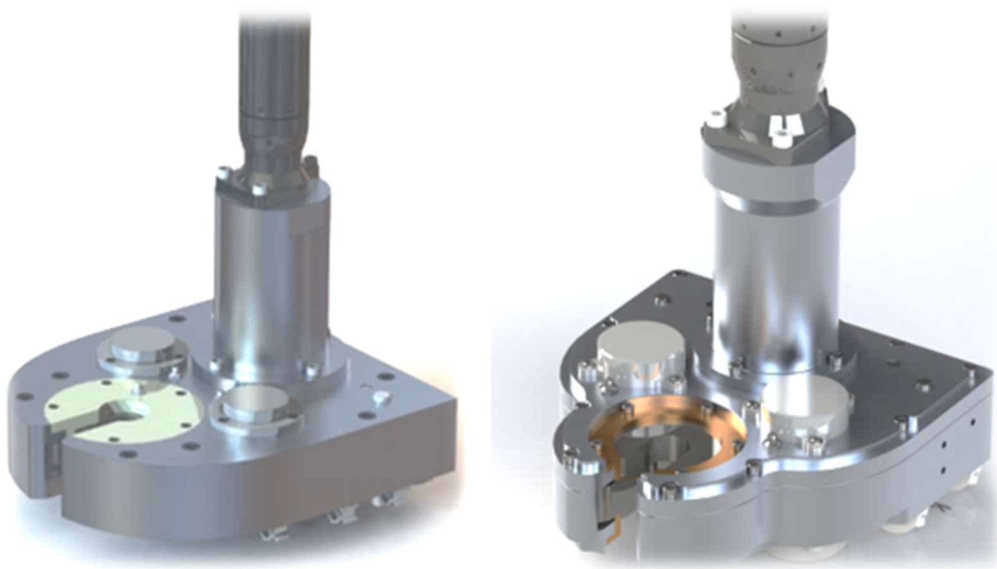

Figure 5-3. Rendered Drivetrain Subassembly

The drivetrain lost over 20lbs, going from a bit over 70lbs to being 42lbs. The drivetrain's main component is the set of gears shown in Figure 5-4. These gears are machined to a face width of 1 inch from McMaster standard gears. They have a pitch of 8 teeth per inch and the drive and idler gears have 30 and 24 teeth, respectively. The slotted gear will be from the same type of gear as the drive gear but the diameter of part of the gear will be turned down such that the turned diameter can ride on the slotted bearing. The gears will be made from 1144 steel and case hardened to 40-45 HRC for wear resistance. As part of the effort to become more lightweight, more studies into gear sizing was done. The hardness was increased allowing gears to be reduced in size. The gears were then machined out in a conservative manner based off of rim thickness calculations in Shigley's [4].

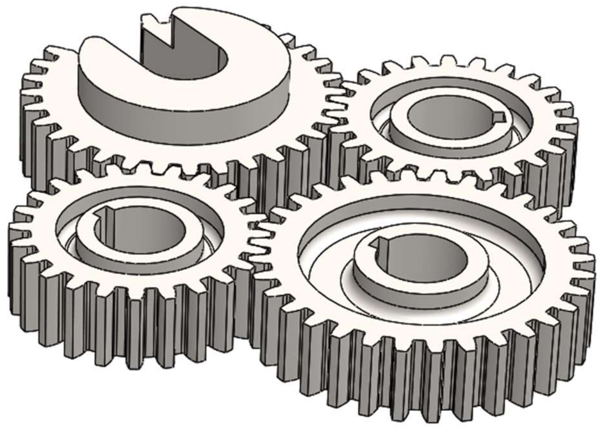

Figure 5-4. Drivetrain Gears

These gears are designed for a life of 1 million cycles or approximately 50,000 shocks at 130 ft-lbs of torque and designed with a factor of safety of 1.3. These calculations were done using an Excel sheet written for gear design. Sample calculations for this can be found in Appendix G. These calculations are very conservative for two main reasons. First, for most instances a single gear tooth will only be experiencing half of the design load due to two idlers transmitting the torque for as long as they are both in mesh with the gear. Second, 50,000 shocks was achieved under the assumption that it takes 20 revolutions at a 130ft-lb load per shock assembly, however from manual assembly experience the rundown of the bearing housing experiences very little torque until the very last revolution, when the bearing housing bottoms out on the shock body thread. With this in mind, one could confidently say that the gears will last upwards of 500,000 shocks.

The team was also concerned that the slotted gear would not work as expected due to excessive bending and deflection from the lack of material. A finite element analysis was done to compare the gear deflection and stress from a standard gear to the slotted gear. Figure 5-5 shows the deflection of the slotted gear in comparison to a standard gear, this was done for the worst-case load of 130 ft-lbs.

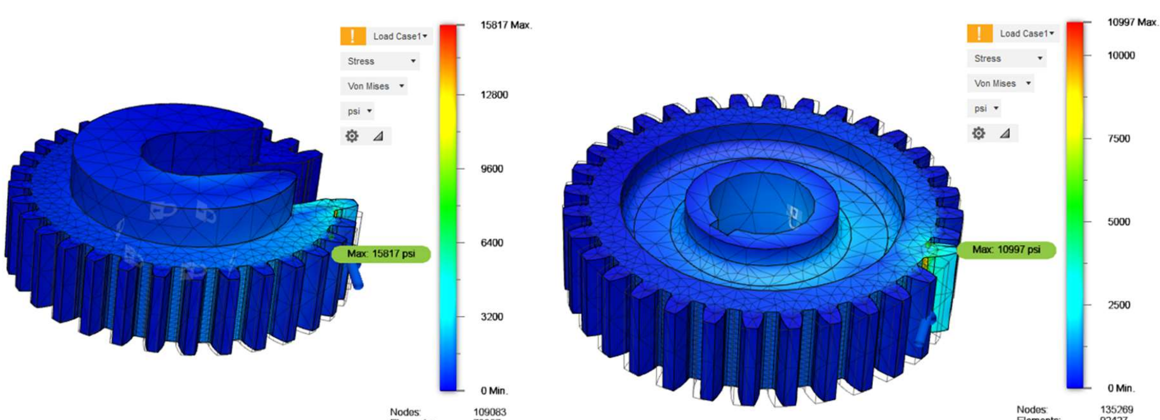

Figure 5-5. FEA Deflection

The results of the deflection FEA show that the maximum bending case for the slotted gear is 0.0004 inches while a standard gear of the same size is nearly half that at 0.0002 inches. While this is concerning, the deflection is still within the limits of the gears. Figure 5-6 shows the stress analysis comparison of the two gears.

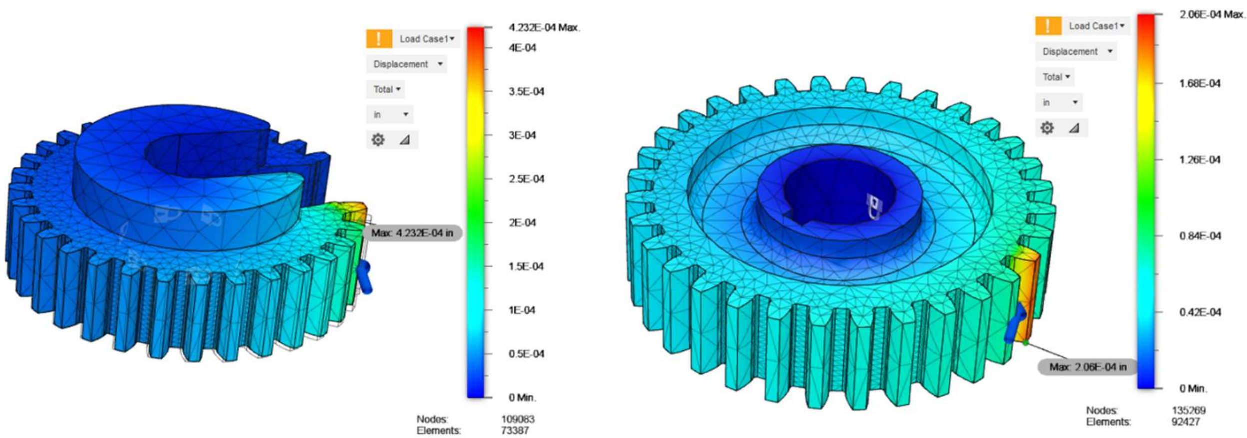

Figure 5-6. FEA Gear Stress

The gear stress analysis at first showed concerning results with increased stress in the gear. The increased deflection at the gear tooth was indicative of increased stress at the gear teeth. This however was not the case as stress stayed nearly the same at the gear teeth. The increased stress was due to stress concentrations at the hex cut into the slotted gear and was not of concern to the team because it would see much less cyclic loading. The increased deflection of the slotted gear tooth was not from increased stress and bending specifically at the tooth, but from bending from the slot.

The next major function in the drivetrain assembly is that of the slotted bearings which constrain the slotted gear. An exploded view of the slotted gear and bearings can be seen below in Figure 5-7. The bearing rides on the top/bottom of the gear and the sides of the turned down diameter. The sides of the slotted bearing act as a normal bushing and the top acts as a thrust washer. These slotted bearings will be made from 841 bearing bronze and machined from a standard McMaster part to save on material cost. It is desired that the slotted bearings will wear and be replaced while maintaining the integrity of the slotted gear's bearing surface.

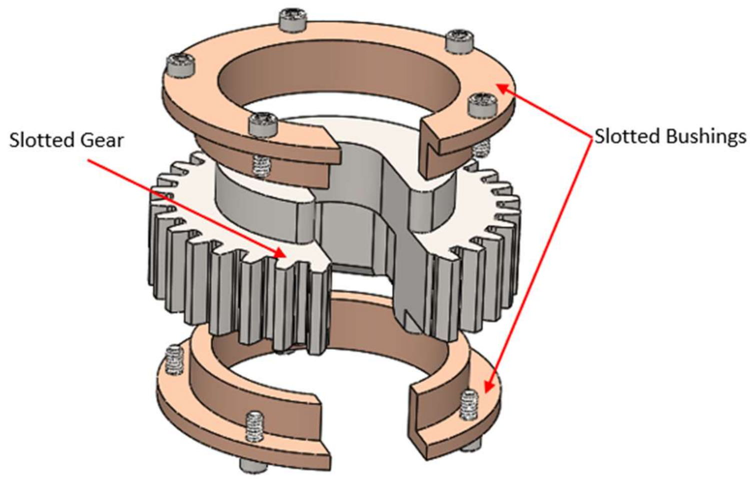

Figure 5-7. Slotted Gear and Bearings

In order to estimate the life of the slotted bearings, a hydrodynamic bushing analysis was used from Shigley's Mechanical Design textbook [4]. Utilizing the standard assumptions and a wear factor sourced from a study on sliding wear of 841 bearing bronze, it was calculated that the bearings will last for 2220 hours of use for a diametral wear of 0.0015 inches, which is when it is recommended that they be replaced [16] [4]. 2220 hours of use should account for approximately 200,000 shocks.

A major sub-assembly within the drivetrain assembly is the shaft assembly which maintains the gears axially and vertically. There is a shaft assembly for the idler gears and another one with only minor changes that constrains the drive gear. An exploded view shown in Figure 5-8 depicts the components within the idler gear assembly. They consist of several components such as tapered roller bearings to withstand radial and axial loads and retaining rings to hold the gear in place. There is also a combination of a retaining ring and a bearing nut to preload the tapered roller bearings, and a key to mate the gear and the shaft together.

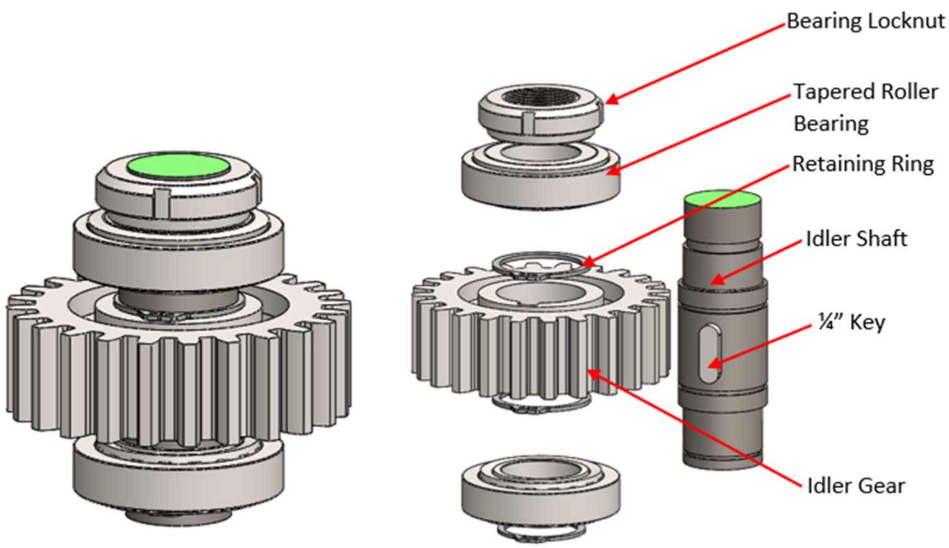

Figure 5-8. Idler Shaft Assembly

The drive shaft assembly is very similar to that of the idler shaft. The main change for the drive shaft is that it has a tapped hole at the top in order to include a ½"-13 x 1" heavy duty bolt such that a socket, attached to the torque driver, can drive this bolt and therefore drive the drive gear. Figure 5-9 shows how the drive shaft will be driven by the torque driver.

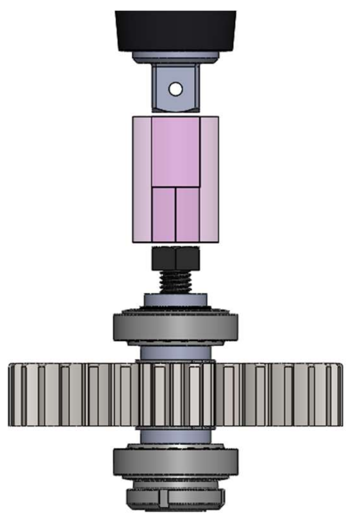

Figure 5-9. Drive Shaft Drive Method

The bolt was used to drive the drive shaft and wear an easily replaceable component rather than rounding a hex cut into the shaft itself. Quick calculations showed that the bolt could easily withstand being torque down to 100ft-lbs, and with the use of Loctite it would ensure that the bolt would not back out even with shock disassembly. Figure 5-10 shows another view of the drive shaft assembly and how it is driven by the torque driver.

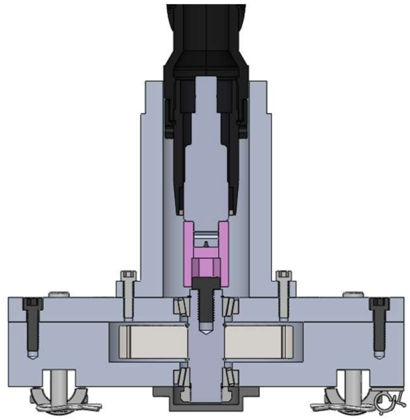

Figure 5-10. Cross Section of Drive Gear

The remaining pieces of the assembly are all housing and support pieces. Figure 5-11 shows the two drivetrain housing halves. These halves house the tapered roller bearings from the shaft assemblies shown above. The bottom half of the housing has pressed in dowel pins used for precise alignment of the upper half of the housing. This is done to maintain shaft alignment. The bottom half of the housing also has slots cut into the bottom that are used to mount the structures system to the drivetrain. The housing has minimal clearance for the gears to keep the grease contained in the system as much as possible.

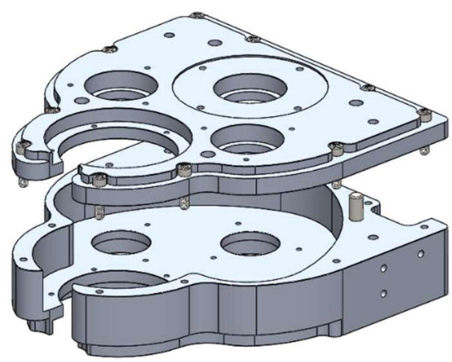

Figure 5-11. Drivetrain Housing Halves

Shown above in Figure 5-3 and directly below in Figure 5-12 is the torque driver adapter piece. This piece is used to mate the torque driver to the top half of the drivetrain housing so torque can be transmitted through the driveshaft. This piece was made to be manually machinable to reduce costs.

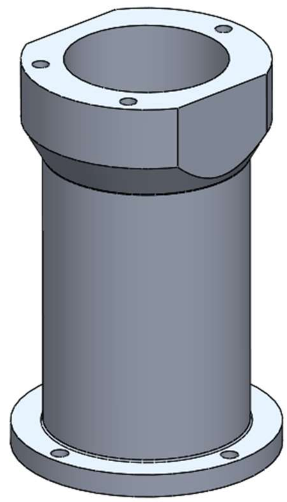

Figure 5-12. Torque Driver Adapter Piece

One of the last pieces, the shaft cap, is shown in Figure 5-13. The shaft cap is a Delrin piece designed to cover the exposed rotating shafts at the top and bottom of the drivetrain assembly. This is purely a safety feature to keep line associates safe. Due to space constraints on the drivetrain this needed to be made on a CNC to fit it on the drivetrain. Fortunately, due to the ease of machining, this will remain a relatively lo

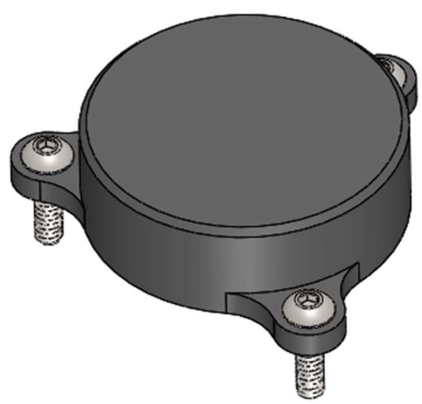

Figure 5-13. Shaft Cap

The final piece of the drivetrain is the torque driver. The torque driver that will be used is an Atlas Copco Tensor ST. This driver has a torque capacity range of 36 ft-lbf to 146 ft-lbf, well encompassing the required torque for this project. The decision to have a torque range so far above requirement was made so that the machine could be scalable and could still work with higher torque requirements if needed in the future. As seen in Figure 5-14 the selected torque driver is completely straight. This style of torque driver, called a “straight model” is predominantly used as an integrated piece in a machine, which is why this style was chosen. The Tensor ST has three mounting holes that allow it to be connected to the previously mentioned torque driver adapter piece. The torque driver connects to the controller though a cable that attaches to the end of the torque driver. This cable will be routed around the back of the structures and connect to the controller. The PF6000 will not only control the torque wrench but will take data during the operations and store them locally. This data can be used to further refine the operation and aid with troubleshooting.

Figure 5-14. ST Tensor Torque Driver

For a full list of components used in the drivetrain assembly see Appendix L for the bill of materials. For assembly drawings see Appendix U assembly drawings. As discussed later in the report Fox will be manufacturing the drivetrain and a few other components for preliminary testing before manufacturing the entire machine. Figure 5-15 and Figure 5-16 below show some of the machine parts that arrived before the end of the senior project timeline.

Figure 5-15. Slotted Bearings and Gear

Figure 5-16. Gear Train Assembly

5.3 Adapter Assembly

The adapter is the intermediary between the output gear of the drivetrain and the bearing housing. There are several requirements that drove the design of this piece. The overarching goal is to transmit torque and rotational displacement to the bearing housing from the drivetrain. As shown in Figure 5-17, the adapter is made up of two main pieces. The top made of steel and the bottom of Delrin.

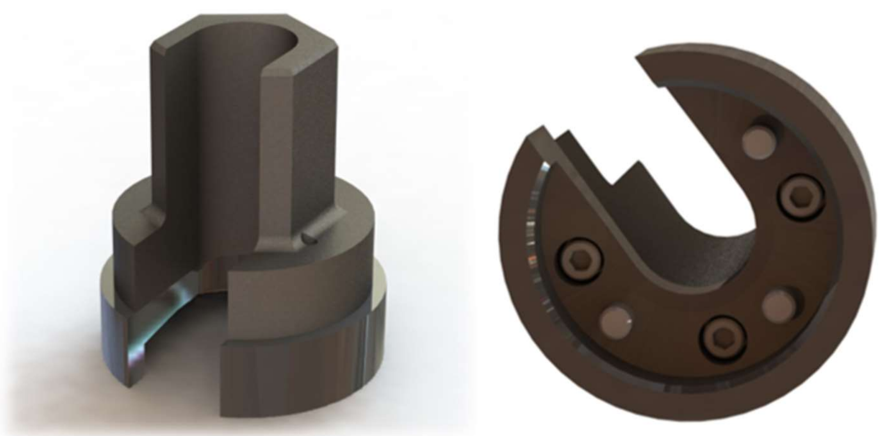

Figure 5-17. Adapter render

The top piece, shown in Figure 5-18 is made of machined 4140 chromoly steel. 4140 steel was chosen for its low stock cost, machinability, and hardness lower than that of the heat treated 1144 gear. The gear that it's fitting into has a hardness of approximately 45 HRC while the adapter can be hardened to approximately 40 HRC. Thus, the adapter will be the wear piece, not the gear. This is because replacing and remaking the adapter piece is much easier and less expensive than replacing and remaking the drivetrain gear. To aid the alignment of the adapter into the drivetrain gear, a 30° chamfer is cut into the top edge. This angle was chosen because it is typically used to align two pieces, as opposed to a 45° chamfer which is typically used to break sharp corners that operator may hit or handle. A fillet has also been added to the base of the hex feature. This was added to mitigate a stress concentration that would be present at the otherwise sharp internal corner. This fillet will not interfere with the drive hear because the hex feature is sized so that it is slightly taller than the cavity it fits into. This means there will be some stick out of the adapter and that the only horizontal face that will come into contact with the drive gear will be the topmost face of the adapter.

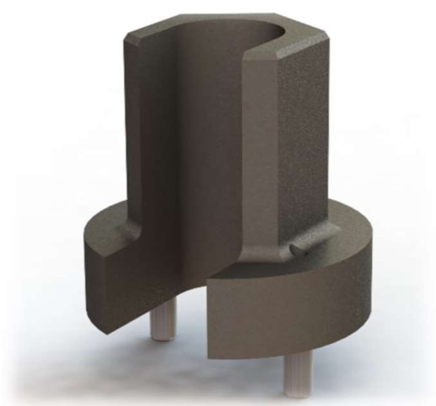

Figure 5-18. Steel Adapter Piece with Pins

The steel piece also has 3 dowel pins press fit into it. Figure 5-19 shows a cut away view of the dowel pins and hole. The pins will be pushed fully into the hole and there is a smaller diameter hole that continues through the part. This hole allows the pins to be removed and pushed out from the top.

Figure 5-19. Section view of adapter with pins

The second half of the adapter piece is machined Delrin, shown in Figure 5-20. This piece will not be transmitting torque but will be used to aid in positioning. The piece will be machined to match the outer geometry of the bearing housing so that it fits snugly. Additionally, the outer diameter of the piece will be machined to fit within the shock body. This will prevent the adapter from wiggling relative to the bearing and shock during the rundown and torque process. It also prevents the adapter and bearing from wiggling relative to the shock body.

Figure 5-20. Adapter Delrin piece

Another problem the adapter solves is preventing witness marks. Because the adapter is a separate piece, it can be manually and carefully placed by the line associate to prevent any scratches on the bearing housing. The softness of the Delrin with also aid with scratch prevention. The adapter piece was also one of the parts that was machined as part of Fox's plan to test the drivetrain. Figure 5-21 below shows the final product that has yet to be tested.

Figure 5-21. Machined Adapter Piece

5.4 Handle Assembly

To interface with the operator, our machine will have two handles to grab on to, shown in Figure 5-22. The handles are used to position the drivetrain around the shock and onto the adapter. The handles are currently made of an aluminum cylinder, and some padding or rubber may be added on the surface for user comfort. Each handle has a button at its end, which is intended to be pressed by the operator's thumbs. The buttons are used to cycle between the machine's operating states. For safety reasons, both buttons need to be pressed for the machine to operate. This ensures that the operator's hands are on each handle and not near any pinch points on the machine. If any button is released while the torque driver is in operation, it will immediately stop.

The handles connect to the drivetrain through two aluminum plates, one 0.5" and the other 0.75" thick. The plates are to be waterjet, tapped, and fastened together with ¼-20 screws. The handles are also one of the few assemblies in the machine with electronic components and adhesive cable ties are to be mounted on the back plates of the handles to route the wires from the handles to the drivetrain. The wires will be wrapped together with some outer wrapping that will both protect them and make wire management easier.

The handle position is also not necessarily finalized. It has gone through numerous iterations both for ergonomic reasons and to avoid interference with other parts of the drivetrain. Due to it's simple geometry, modifying the handle's locations would not be difficult. Changing horizontal distance is achieved by adding or removing aluminum spacing plates, and the handles' heights and distance from the drivetrain can be made by modifying the aluminum plate.

Figure 5-22. Handle Assembly and transparent view

5.4.1 Handle Stiffness

One potential cause for concern is the amount of deflection present in the handles. They are relatively far away from their fixturing point and a large moment could easily be applied by the operator. The following calculations were performed on a previous version of the handles but can still be confidently applied to the current version. This is because the current handle version is shorter and now has a much higher moment of inertia. Both increasing the handle stiffness. Now the following calculations will represent an incredibly liberal situation and provide the handles with a conservative factor of safety.

Two methods were used to evaluate the stiffness of the handle. The first method is a simple hand calculation, shown in Appendix R. The handle is modeled as a cantilever beam, with a 20 lbf load applied at the bottom. Using table A-2 from Shigley's [4], the maximum deflection was calculated to be $2.45*10^{-2}$ in; well below the maximum allowable value. The second method is to run FEA on the back plate of the handle assembly. The top surface of the plate is fixed and a 20 lbf load is applied at the bottom edge of the plate, shown in Figure 5-23. To further validate the results, a convergence diagram was generated. The maximum displacements were recorded over a series of runs with increasingly finer meshes. As the element size decreased, the maximum displacement value converged to a single value, shown in Figure 5-24. The FEA results show that the maximum displacement is 0.035 in. This does not exactly match the hand calculations, but this is because the hand calculations used a simplified model of the plate. The two values can be considered close enough.

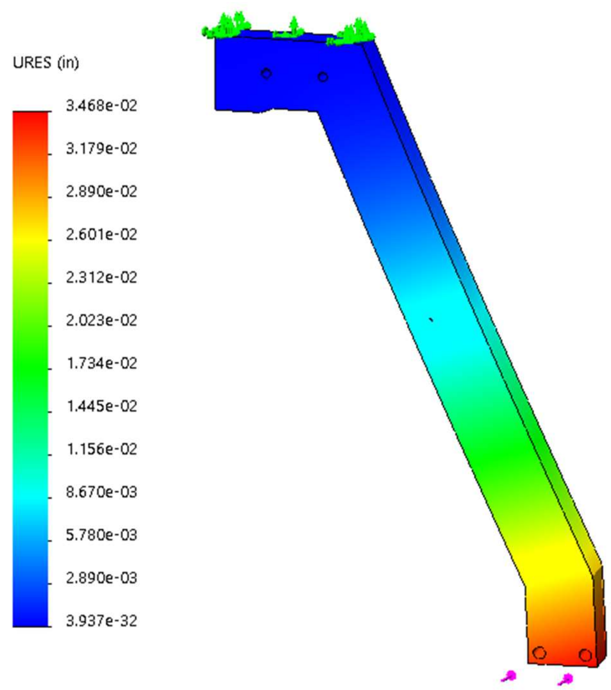

Figure 5-23. Results of FEA on Handle Plate

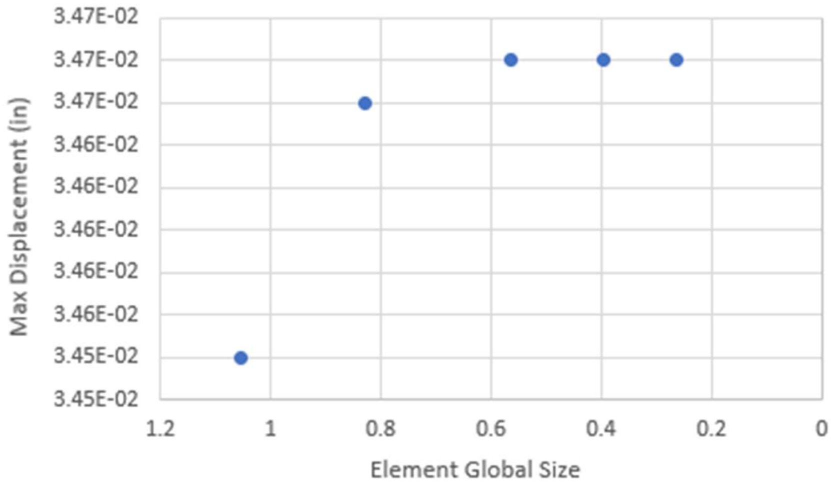

Figure 5-24. Convergence diagram from FEA on Handle Plate

5.5 Structures Assembly

The purpose of the structures assembly is to allow the operator to position the drivetrain wherever they need as well as resolve any reactions from the drivetrain into the table. The static portion of the assembly is constructed of 3x3 8020 aluminum t-slot framing. The use of 8020 greatly reduces the fabrication time of the assembly because the t-slot extrusion can easily be fastened together after it is cut to length. In addition, 8020 is extensively used at Fox, so spare parts for the assembly are readily available. The 3x3 inch profile was chosen to provide the maximum stiffness.

Figure 5-25. Structures assembly

The moving portion of the assembly, as shown in Figure 5-26, is constructed of half inch aluminum plate. All parts are designed to be cut on a waterjet or laser cutter and finish machined on a manual mill. Aluminum was chosen to reduce the amount of weight the tool balancer needs to support.

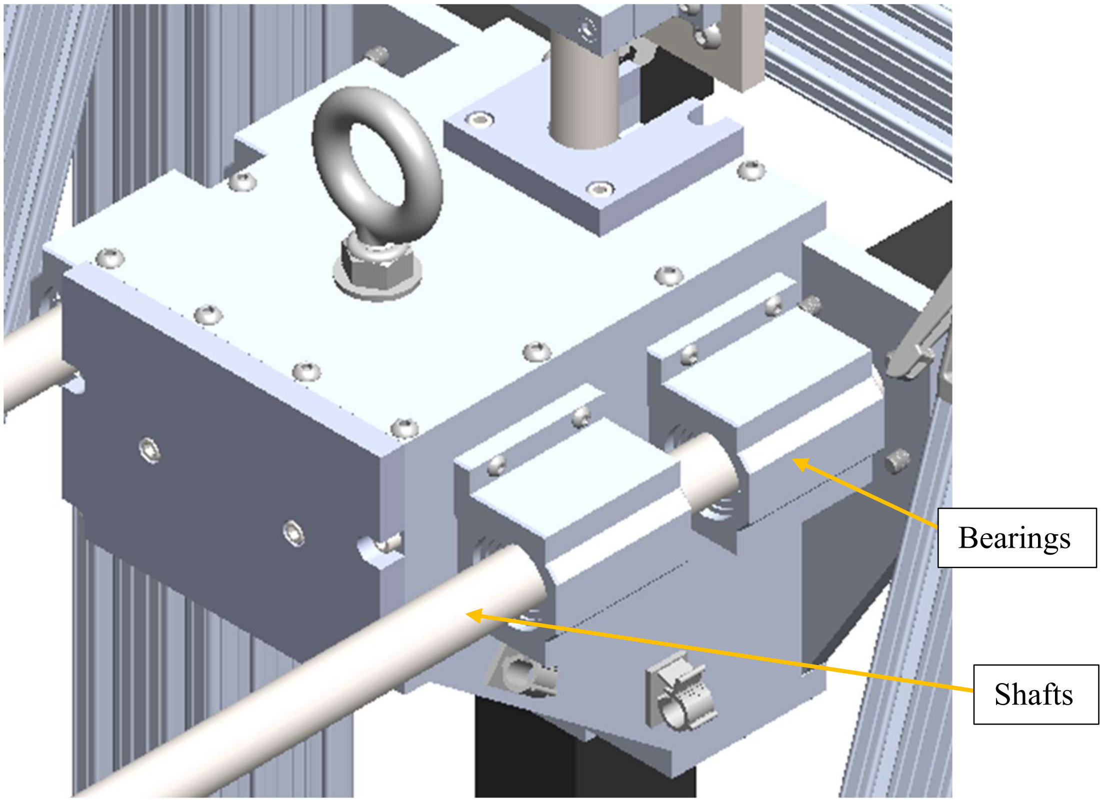

Figure 5-26. Structures moving components

Motion is provided using linear motion rails. Two 1-inch hardened steel shafts are used horizontally to provide radial motion. A single 1-inch hardened steel shaft is used to provide axial motion and rotation. Two bearings on each shaft are used to prevent moments from developing in the bearings. An underside view of the bearings is shown in Figure 5-27. The bearings are highlighted in green.

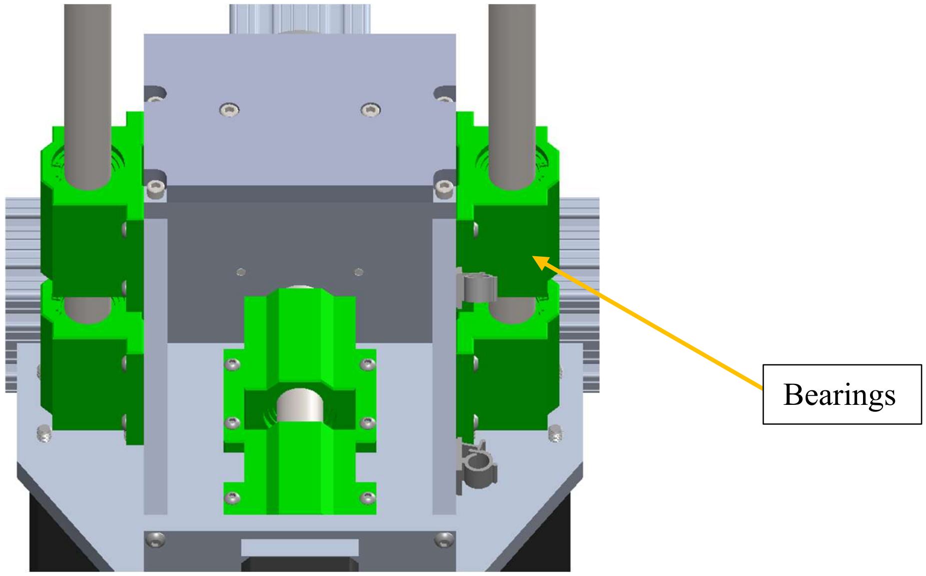

Figure 5-27. Linear bearing layout

Amlok rail brakes, shown in Figure 5-28, are used to hold the moving components static during the bearing run down cycle. Each brake has a holding force of 300lbf, and there is one mounted on each shaft. The brake on the vertical shaft resists the force of the stock body being pushed into the shock shaft bearings, and the two on the horizontal shafts resist the reaction from the bearing as it is being torqued down. All brakes are normally closed and need air pressure to release, so in the event of a loss of air, the system will lock up instead of releasing.

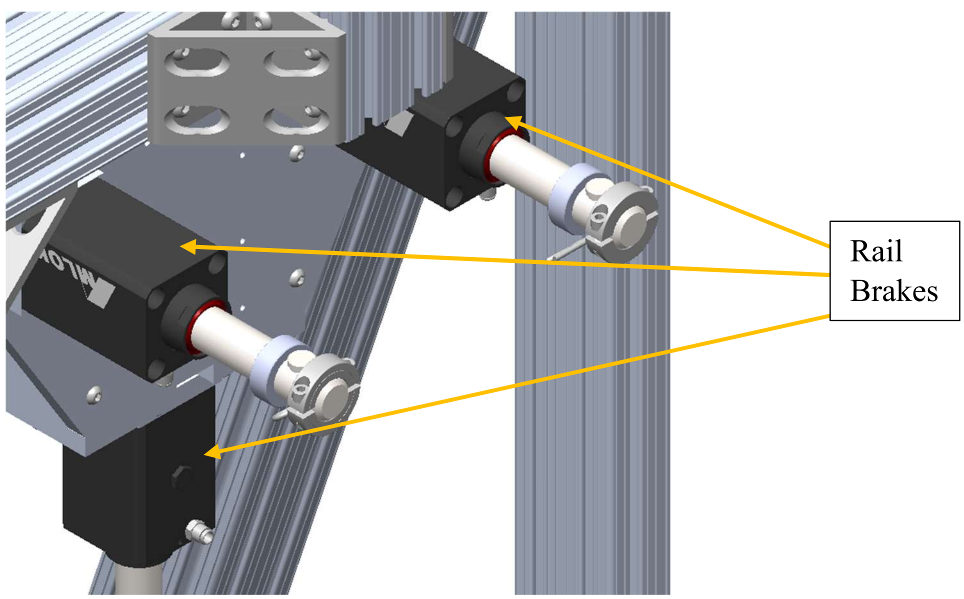

Figure 5-28. Amlok rail brakes

Delrin wear pads are placed at all surfaces where moving components can contact each other. They will serve as wear items that will be replaced as needed. The wear pads are show in Figure 5-29 in green.

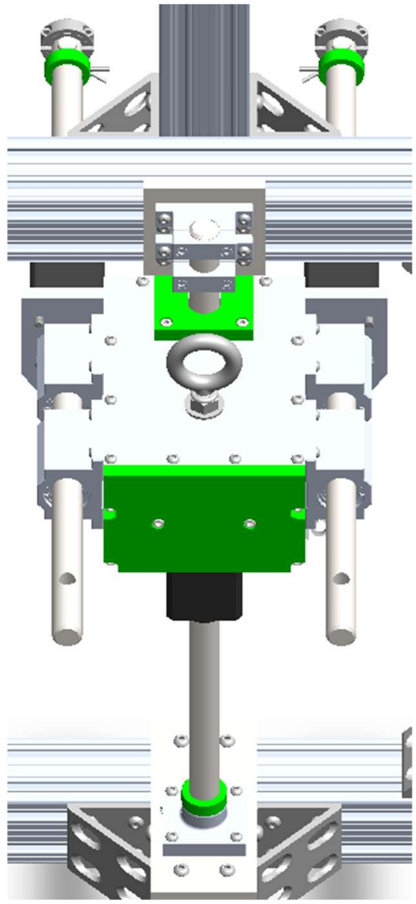

Figure 5-29. Structures Delrin wear pads

A tool balancer, which acts like a constant force spring, is used to support the weight of the drivetrain and the moving portion of structures when the rail brakes are released. It is hung from the structures assembly above the drivetrain and secured to the moving portion of structures. As shown in Figure 5-30, it is secured with a hook on one eyebolt and a secondary chain on another eyebolt.

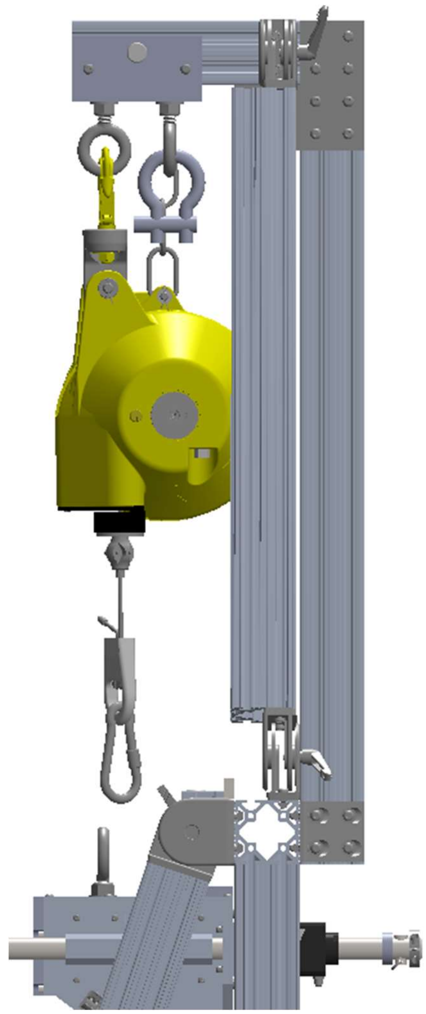

Figure 5-30. Tool balancer mounting

For safety, all moving components are fastened with positive retention. The horizontal shafts have half inch pins through both ends to prevent the shafts from coming out of the linear bearings and the drivetrain from coming off the shafts. This is shown in Figure 5-31. In addition, the eyebolts securing the tool balancer are fastened with nylock nuts, and the tool balancer mount is secured to the 8020 with a three-quarter inch pin, as shown in Figure 5-32.

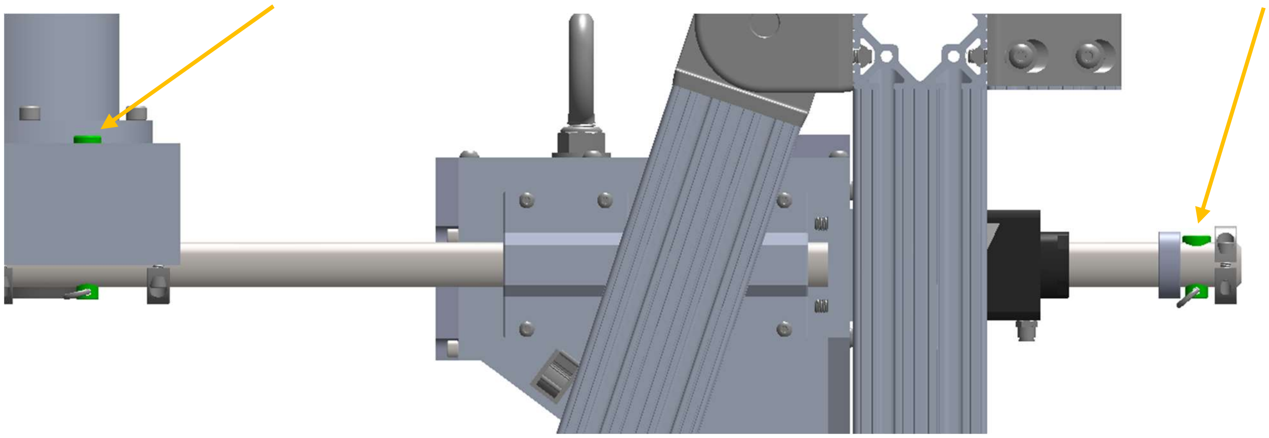

Figure 5-31. Horizontal shaft pins

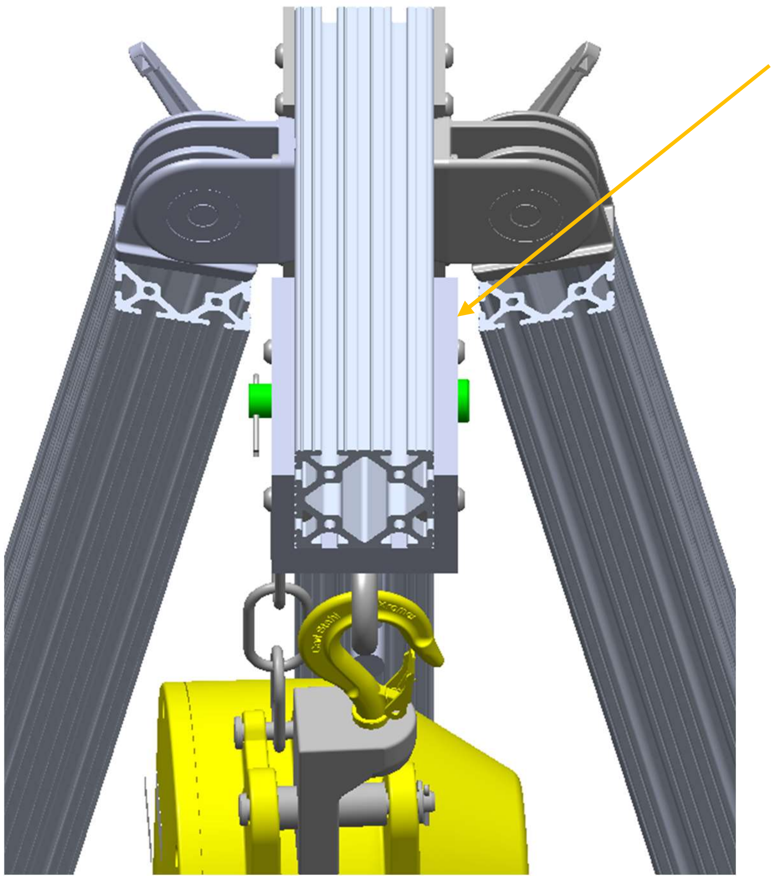

Figure 5-32. Tool balancer mount pin

5.5.1 Static Analysis

The static analysis in section 4.5 was reevaluated once the final dimensions of the assembly were chosen. The two areas of interest were the reactions in the linear bearings and rail brakes.

The free body diagram of the two horizontal shafts is shown below in Figure 5-33. The linear bearings are located at points C and D.

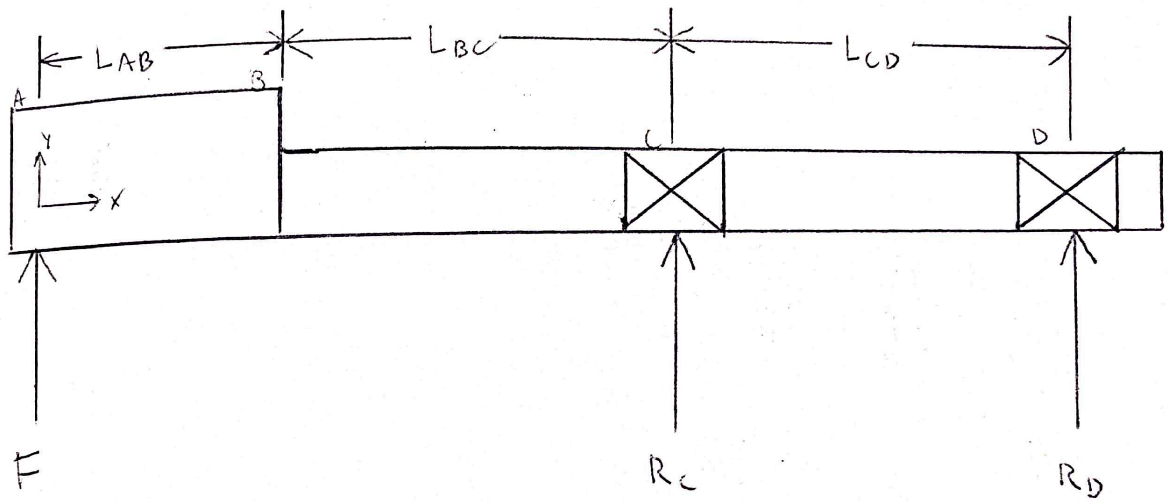

Figure 5-33. Horizontal shaft free body diagram

The following dimensions in Table 5-1 were used to obtain the reactions at C and D. The stiffness of the drivetrain is assumed to be much higher than the stiffness of the shafts. This loading case is assuming the air cylinder is outputting double the normal force of 50 lbf. An upward force of 100 lbf is balanced by the weight of the drivetrain and torque driver (70 lbf) to give a net load of 30 lbf upward.

Table 5-1. Horizontal shaft loading parameters and reactions

	Name	Variable	Units	Value
Inputs	Drivetrain length	L_AB	in	10
	Length from bearing to drivetrain	L_BC	in	7
	Horizontal bearing spacing	L_CD	in	4
	Load	F	lbf	30
Results	Front bearing reaction	R_C	lbf	-78.8
	Rear bearing reaction	R_D	lbf	63.8

The bearings chosen have a static load capacity of 1000 lbf [17], which gives a factor of safety of 12.8 for the front bearings and 15.7 for the rear bearings.

The reactions on the horizontal linear bearings are resolved through the plates on the moving portion of the structures assembly into the bearings on the vertical shafts. The free body diagram for this system is shown in Figure 5-34. The plates are hidden for clarity. The horizontal bearings are located C and D, and the vertical bearings are located at F and G.

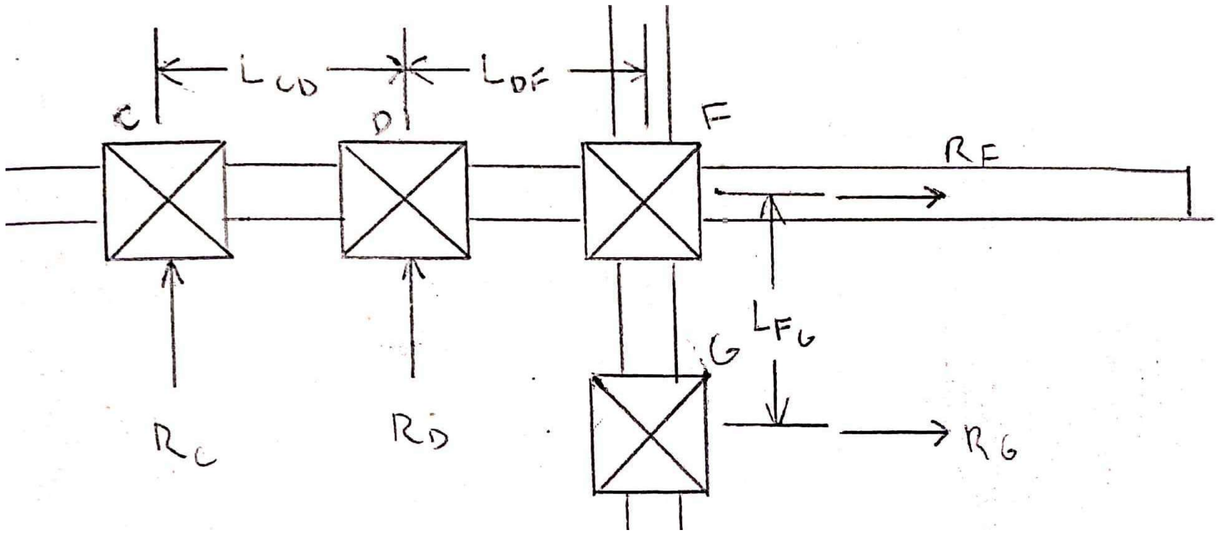

Figure 5-34. Free Body Diagram for Vertical Bearing Reactions

The following dimensions in Table 5-2 were used to obtain the reactions for the vertical linear bearings.

Table 5-2. Vertical bearing loading conditions

	Name	Variable	Units	Value
Inputs	Distance from rear Horizontal bearing to top Vertical bearing	L_DF	in	0.65
	Vertical Bearing Spacing	L_FG	in	4
Results	Reaction at Top bearing	R_F	lbf	-30.6
	Reaction at Bottom bearing	R_G	lbf	30.6

The same bearings on the vertical shafts are used as on the horizontal shafts. This gives a factor of safety of 27.3.

The final loading case analyzed was the reaction in the rail brakes on the horizontal shafts due to the torque from the c-shaped gear. The free body diagram is shown in Figure 5-35, and the loading parameters are shown in Table 5-3.

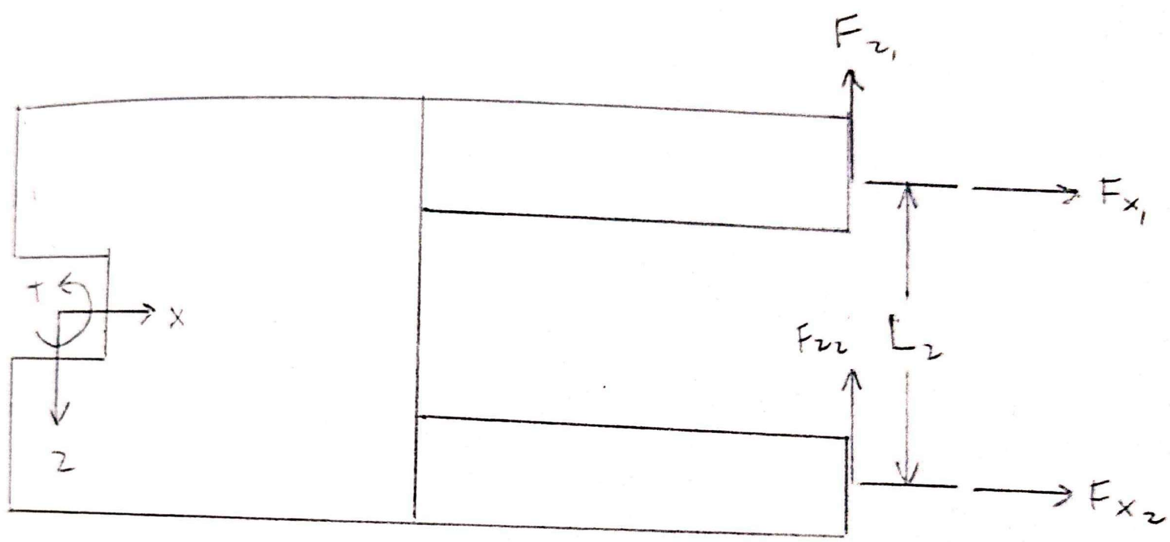

Figure 5-35. Applied torque free body diagram

Table 5-3. Applied torque loading parameters

	Name	Variable	Units	Value
Inputs	Distance between rails	L_2	in	9
	Applied Torque	T	In-lbf	600
Results	Force exerted by horizontal rail brake	F_2	lbf	66.7

The rail brakes chosen can exert at static force of 300 lbf. This give a factor of safety of 4.5. If the torque driver were required to run at its highest torque, 1800 in-lbf, the rail brakes would still have a factor of safety of 1.5.

5.5.2 Structure Redesign

Due to the novel Corona virus pandemic, the manufacturing timeline of the project was delayed. This allowed the team to undertake a redesign of each system to address the concerns brought up by the project sponsors. One of the main concerns was the weight of all the moving components. Many components were overbuilt to an unnecessary degree. This excessive weight required the use of a larger and more expensive tool balancer, as well as making the machine more difficult for the end user to control.

For the structures assembly, many of the components on the moving carriage were skeletonized to reduce weight but still maintain adequate stiffness. An overview of the new carriage is shown below in Figure 5-36. About 13 lbs was cut out of the carriage.

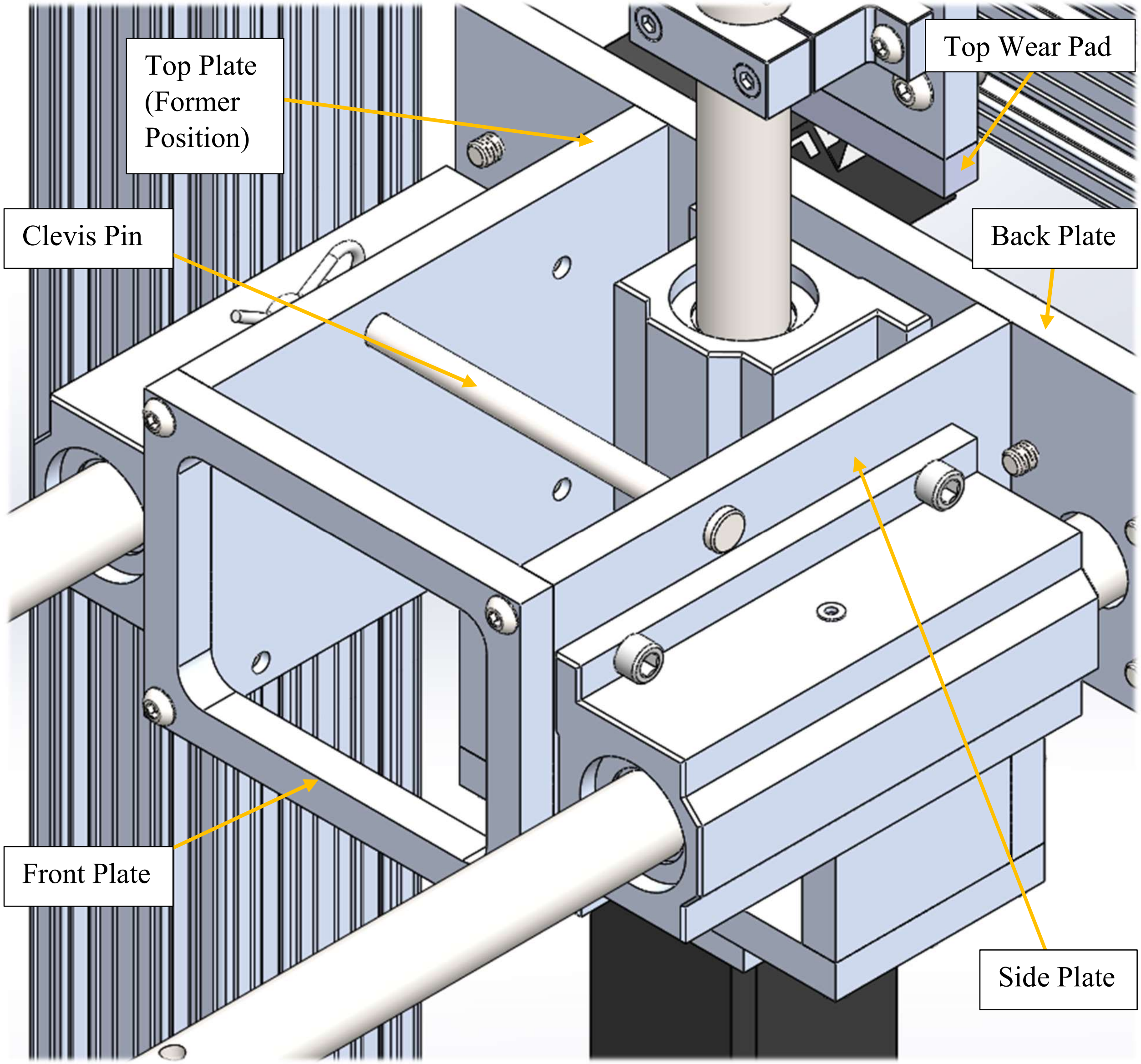

Figure 5-36. Redesigned Structures Carriage

Most of the weight loss was from the horizontal shafts, front plate, and top plate. The horizontal shafts were changed from solid (1” OD) to hollow (1” OD .6” ID). This resulted in a 56% reduction in mass with only a 15% loss in stiffness. The top plate was hollowed out in a similar manner to the front plate, however it was realized that in doing so it was no longer providing any meaningful stiffness to the carriage, and was eliminated. This allowed the top wear pad to be moved off the carriage and the large eye bolt to be eliminated. They eyebolt was replaced with a clevis pin which goes through both side plates. Some, but not a significant amount, of mass was removed from the back plate and size plates because these parts contribute the most to the stiffness of the system. The front wear pad was changed from a large pad that took up the entire area of the front plate into two small pads attached to the back of the drivetrain. This is shown in Figure 5-37.

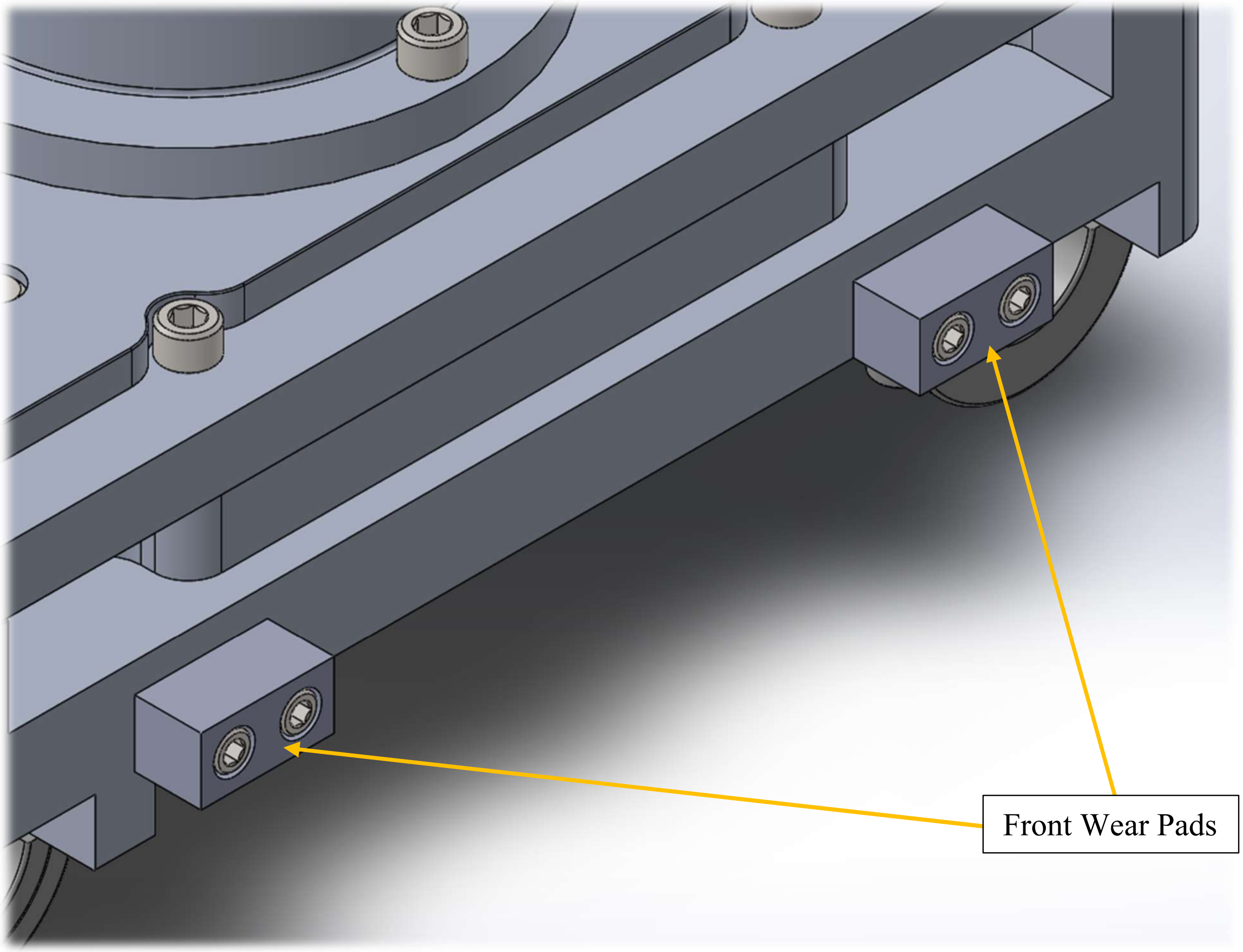

Figure 5-37. New Front Wear Pads

In addition to weight loss, there were simplifications made to the static portion of the assembly. A custom part to hold the eyebolts for the tool balancer was eliminated and replaced with longer eyebolts and nylocks, as shown in Figure 5-38.

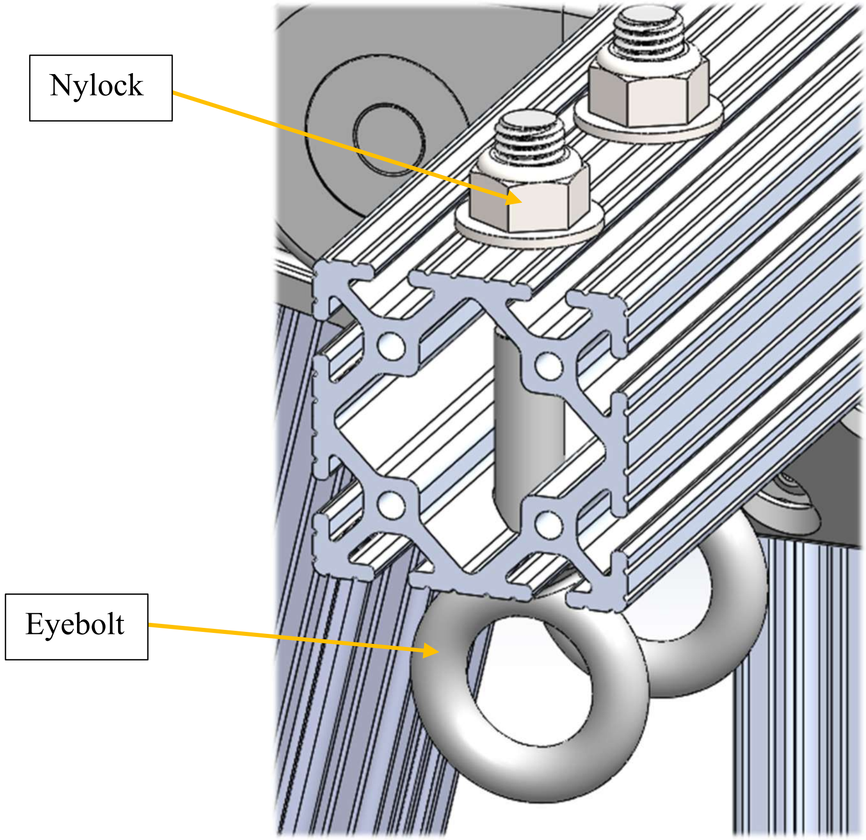

Figure 5-38. Simplified Tool Balancer Mounting

The lowest horizontal member of the 8020 structure was eliminated in favor of bolting the vertical members and the locking joint directly to the main baseplate. The original layout is shown in Figure 5-25, and the new layout is shown in Figure 5-39.

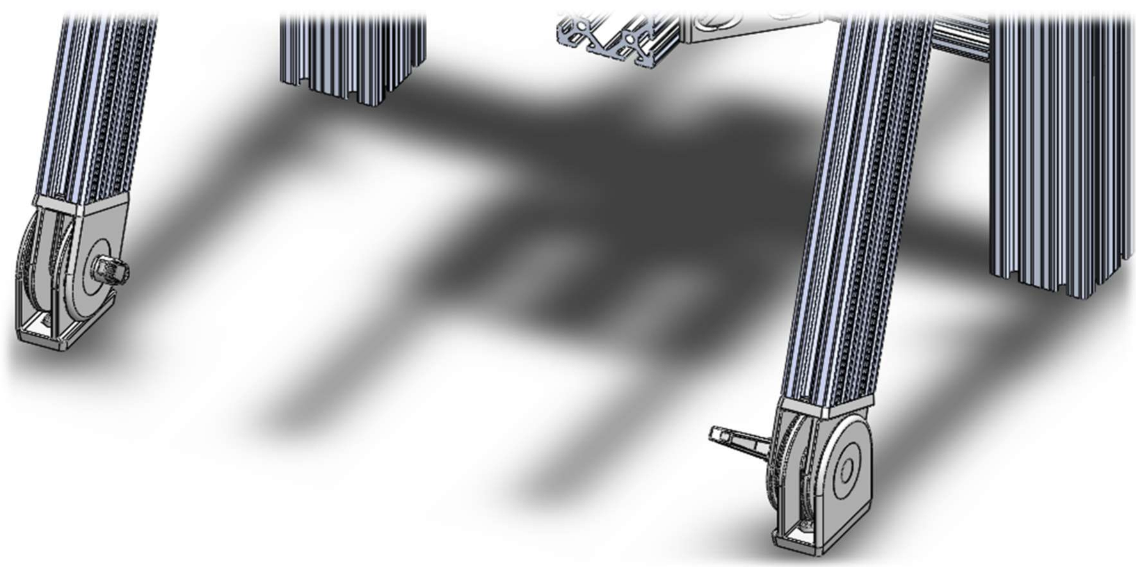

Figure 5-39. Simplified Structures 8020

5.6 Fixturing Assembly

As mentioned at the beginning of section 5, the fixturing assembly secures the shock in place, prevents it from tipping towards the operator or rotating with the bearing, and allows vertical motion of the shock body as the linear bearing housing on the shaft is rundown into the body tube. The complete fixturing assembly is shown below in Figure 5-40. The fasteners protruding from the base plate are for attaching the body cap pallet assembly to the fixture, and a pneumatic cylinder and ram will push on the bottom of the base plate directly in line with the shock axis.

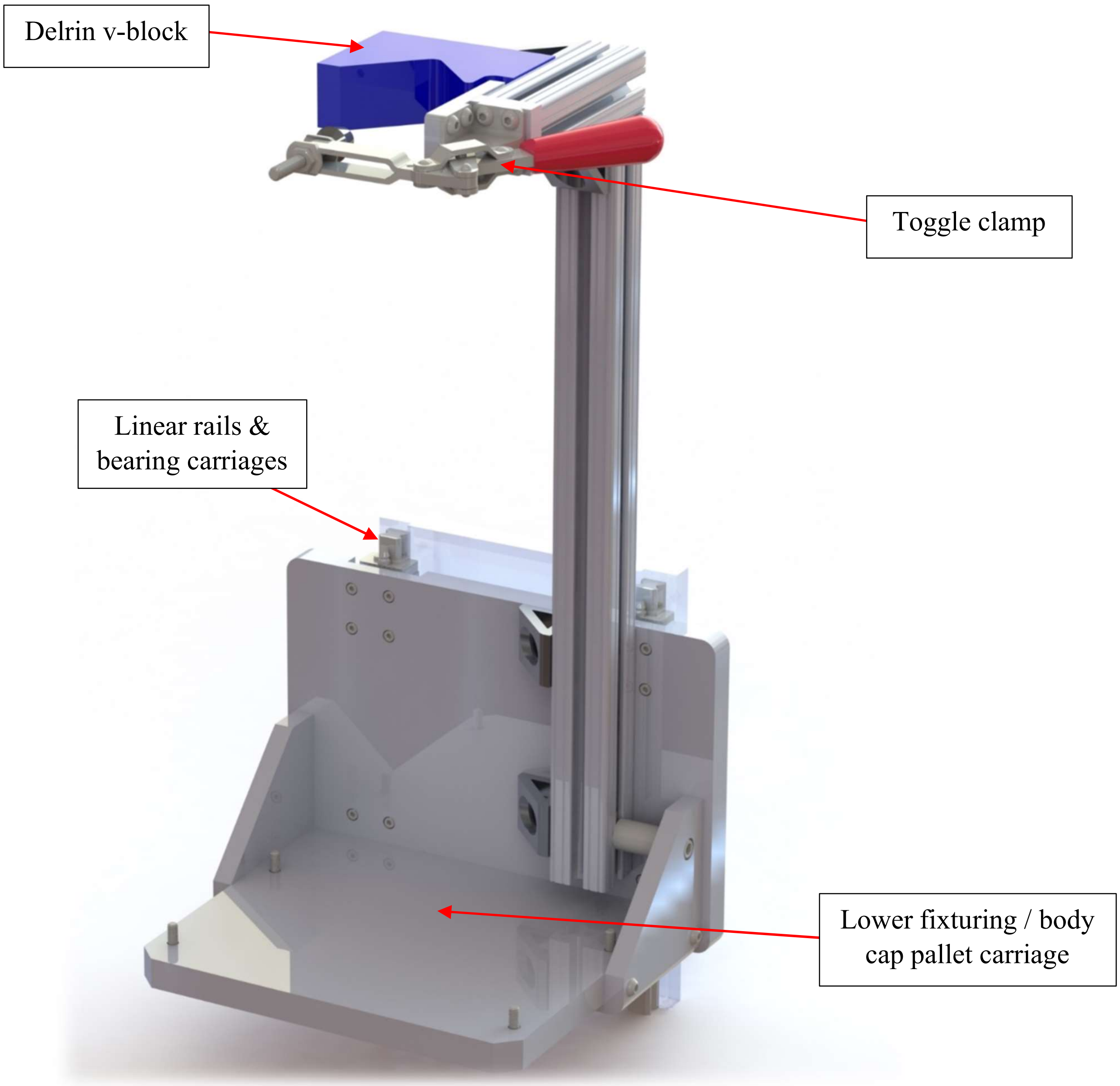

Figure 5-40. Fixturing assembly (pre-redesign)

To accomplish the motion required for the body cap pallet to travel parallel to the shock axis (one degree of freedom), linear rails and ball bearing carriages were chosen. This switch from the simple post solution used in the preliminary design was in response to concerns about having the body cap pallet base plate potentially bind throughout its range of travel and potentially damage components. To prevent binding in this transition to the parallel rail and carriage method, parallel shoulders will be machined into the rail backing plate, and the carriage plate will only have a shoulder cut for one rail's carriages. This will ensure smooth travel of the rail system without over-constraining any of the components. While this method is not generally used for high accuracy in mounting location, rail supplier HIWIN's methods for high accuracy involve adding significant complication in the form of tapered gibs and rows of set screws [18]. Since the minimum size rail available on McMaster-Carr was found to be overbuilt for this application by a huge margin, this minimal mounting method should be more than sufficient. The rail system described is shown below in Figure 5-41.

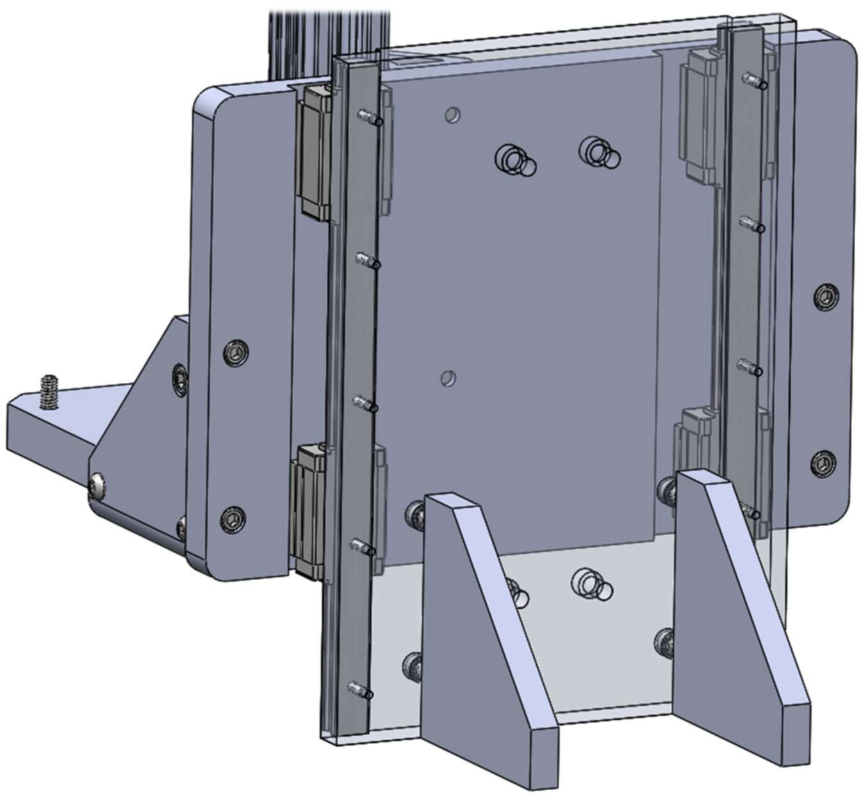

Figure 5-41. Fixturing linear rails and ball bearing carriages

To size rails and carriages, an equivalent load at each carriage was needed. Methods for finding these loads were given for a variety of loading cases in HIWIN's linear guideway catalog, with the case most similar to this machine's application shown below in Figure 5-42. At most times, the weight of the body cap pallet, shock, and upper fixturing assembly are supported by the pneumatic cylinder and ram beneath the fixturing base plate. Even during downward force application, nearly all the linear force will be resolved between the cylinder and the drivetrain above it. Because of this, the worst load case scenario assumed for the rails was a sudden drop of the cylinder from the fixturing base plate. This would expose the bearing carriages to roughly 80 lbf of shock and fixture assembly weight. This assumption is also fairly conservative due to the ignored downward acceleration of the fixture. A preliminary spacing of carriage centers being 10” apart and the shock weight 5” off the front of the rails resulted in a 20 lbf equivalent load at each carriage. Considering the minimum size, 15 mm rail available on McMaster-Carr is rated for a 2,450 lbf dynamic load capacity, this massive factor of safety of 120+ justifies a large degree of freedom in carriage placement. Hand calculations for this sizing method are available in Appendix N.

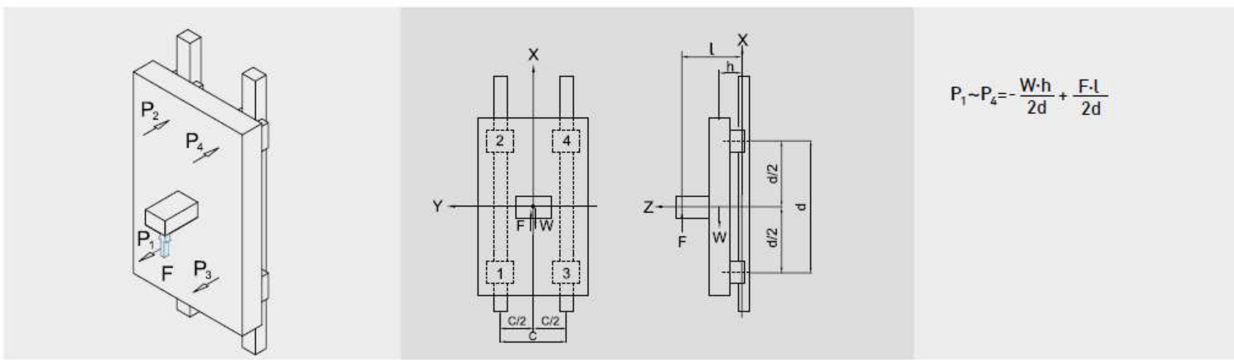

Figure 5-42. HIWIN linear rail carriage equivalent load rating for applicable case [18]

Due to safety concerns about the shock potentially tipping out of a worn body cap pallet insert and a need for added stiffness in case of a lack of torsional rigidity from the vertical rail brake, a simple upper fixture was added to the design. This upper support consists of a Delrin v-block and a standard dual-fixturing toggle clamp, which will grab the shock between the end of the body tube and end of the piggyback reservoir tube. By using Delrin and a rubber foot on the toggle clamp, no witness marks will be left on the shock body. The toggle clamp, a McMaster-Carr component, is identical to clamps used on several other machines around the factory and should help new operators adjust quickly to the rundown machine. This upper fixture is shown with the shock below in Figure 5-43.

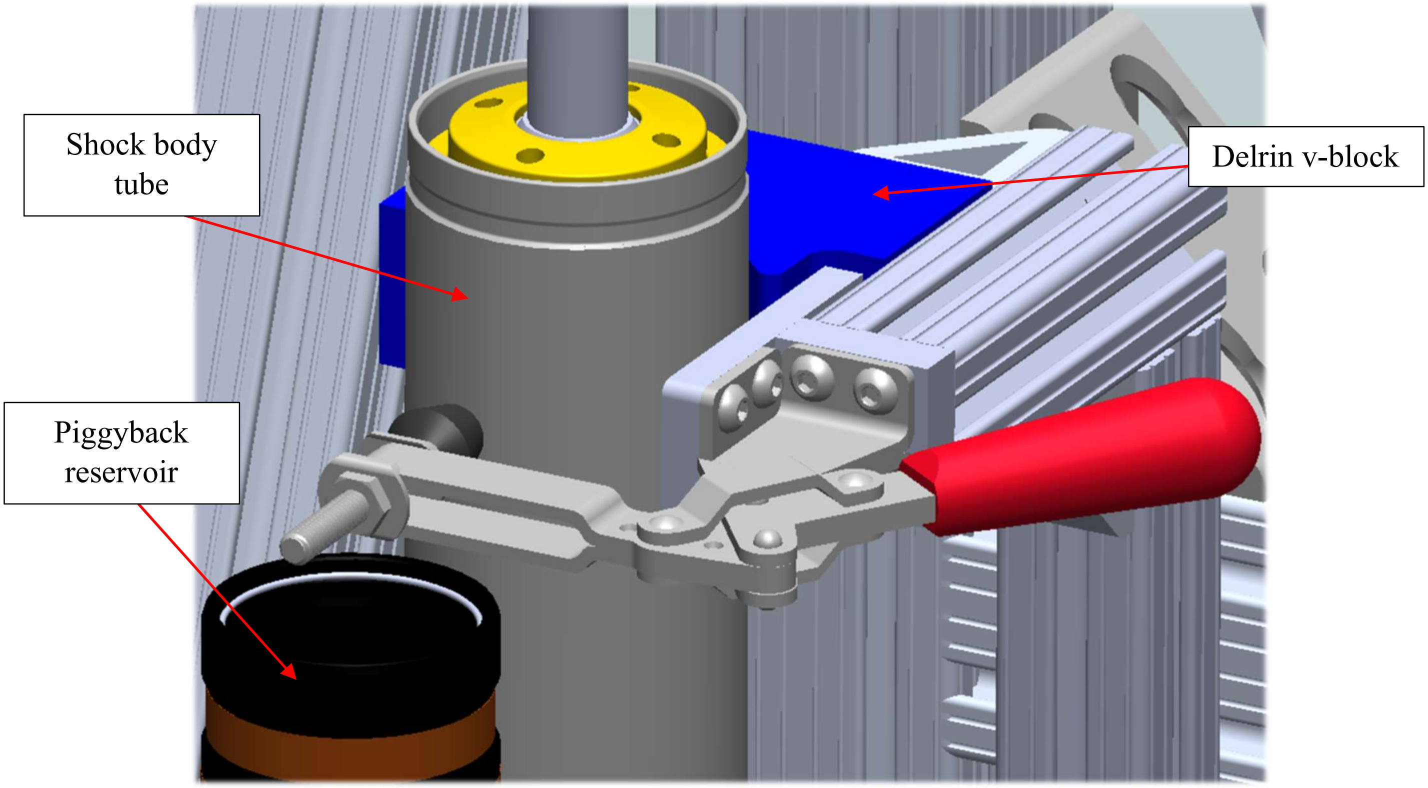

Figure 5-43. Upper fixturing Delrin jaw and toggle clamp

As discussed in the load conditions for the linear guideways, the shock should be well supported between the drivetrain / structures and the body cap pallet during normal operation. The two perceived concerns are (1) the shock shaft being hit by an incoming drivetrain and knocked forward before the drivetrain can be engaged, and (2) a lack of torsional support from the vertical rail brake on structures, which could cause the drivetrain to kick the hex-adapter out of the bearing pin holes. As of the time of writing this report, engineers at AME have yet to confirm the torsional holding capabilities of the Amlok rail brake selected for this project. However, the collet style frictional hold the brake provides, as shown in Figure 5-44, should provide a non-negligible rotational constraint to prevent the drivetrain from rotating about the vertical shaft. The numbered items on the brake cut-away are in explained in further detail on the Amlok technical data sheet online [8], but note the coil springs (3) that hold the collet closed normally through the locking mechanism (2).

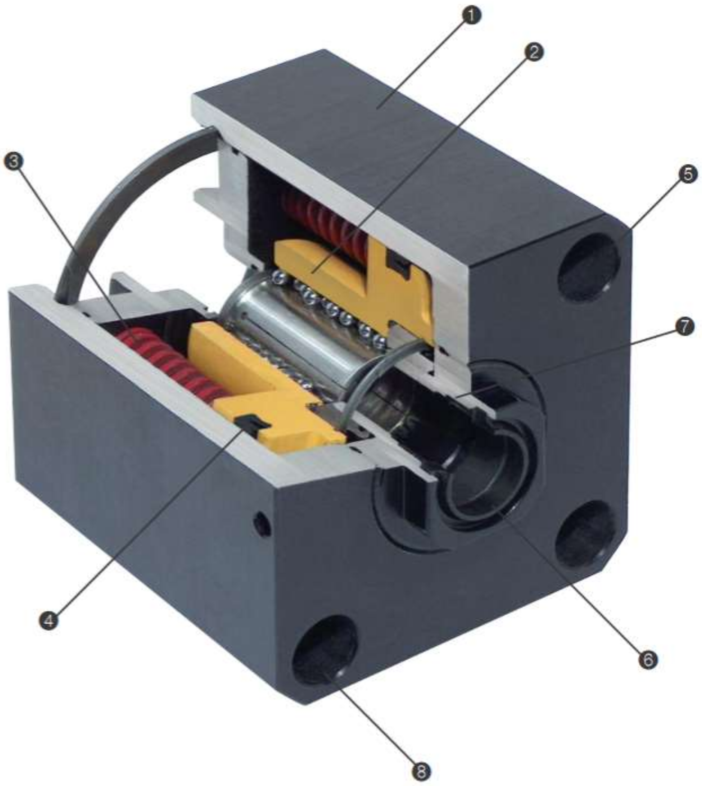

Figure 5-44. Amlok rail brake cutaway [8]

Should the combination of the body cap pallet and vertical rail brake leave any room for the drivetrain to lean the shock during high torque inputs, the upper fixturing of the v-block and toggle clamp should provide any remaining stiffness needed. For an estimated 30 lbf horizontal load during shock loading or drivetrain / structural flex, treating the vertical 8020 post holding the clamp as a cantilever beam resulted in a mere 0.011" deflection. Calculations and associated assumptions can be seen in Appendix O. Should loads during testing result in more deflection than expected, a gusset can be added, but until it is deemed necessary the upper fixture will be kept as simple as possible.

To provide the downward force necessary, a low-profile air cylinder was chosen from McMaster which is capable of 314 lbf at 100 psi, just shy of the factory line pressure of 105-120 psi. This oversized cylinder will only need to provide 60 lbf for the first shock family this project is directly concerned with, but the extra capacity guarantees scalability and the ability to adjust for different assembly grease or O-ring resistance. To keep the cylinder itself from wearing, a simple ram assembly was designed to thread into the cylinder and push on the bottom of the fixturing base plate. This cylinder and ram assembly are shown below in Figure 5-45. The ram is comprised of a 3/8"-24 bolt with the head parted off in order to be fastened to a wear plate with a countersunk screw.

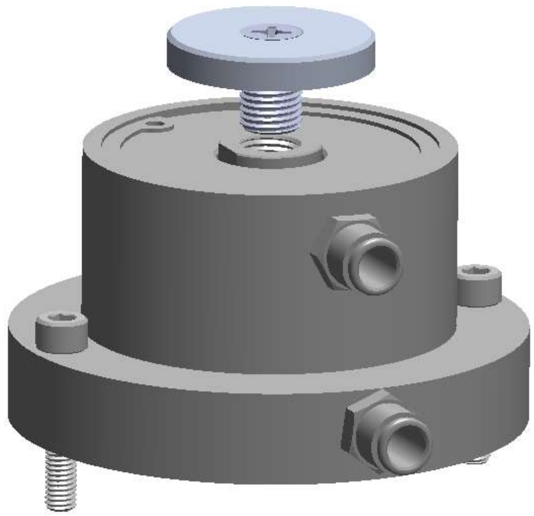

Figure 5-45. Pancake cylinder and ram

This cylinder and ram combination is shown in Figure 5-46 underneath the body cap pallet baseplate, where it will push in line with the shock axis to avoid any bending moments in the shock shaft.

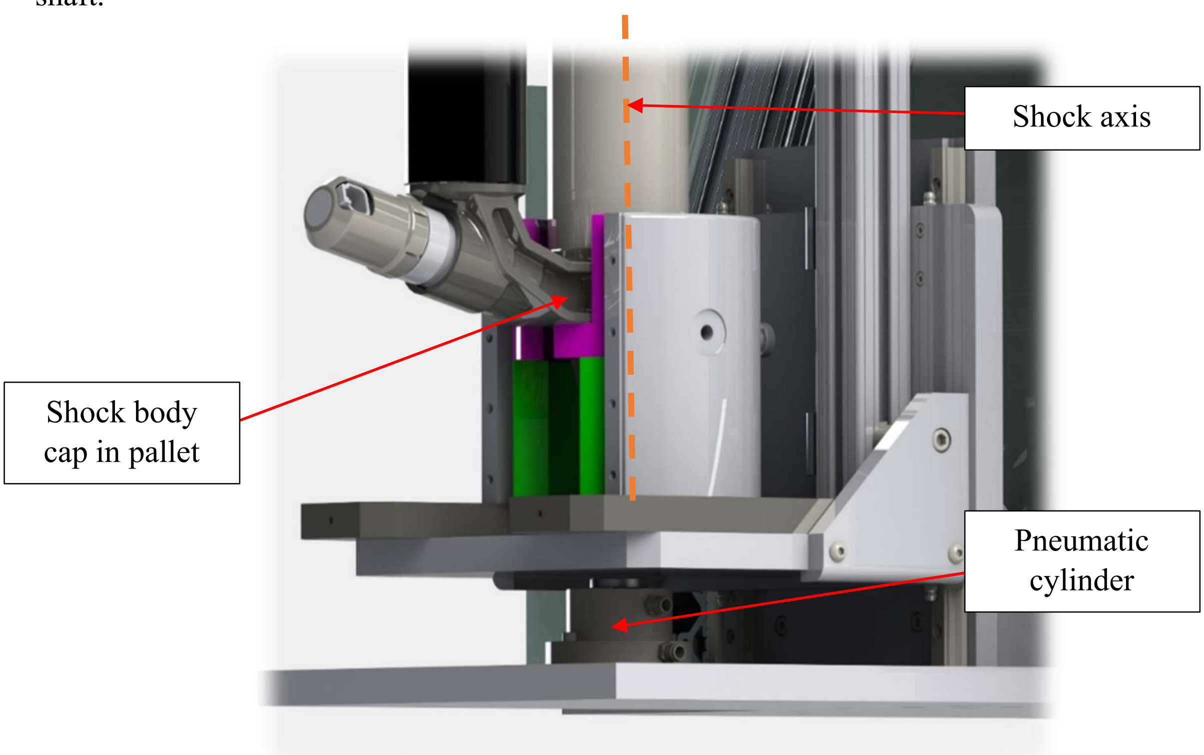

Figure 5-46. Lower fixturing assembly, cylinder in line with shock axis

When fixturing the shock, two components need to be out of the way to allow the drivetrain to have access to the bearing. These are the boot and body tube endcap. The boot will be raised by the previous station, so it will be out of the way. The body tube endcap typically covers the bearing, and rides on the shock shaft. To keep this component out of the way, a magnet will be used. The line associate will raise the endcap up the shaft and place a magnet to the shaft, under the endcap. This magnet will clip to both the shaft and endcap, keeping it safely out of the way during the torqueing operation. Once the shock is ready to be removed and the drivetrain is out of the way, the magnet can easily be removed, and the endcap placed over the bearing. This magnet assembly, shown in Figure 5-47, is made up of a standard McMaster handle and a Neodymium magnet rated for a 20lbf pull. This should be sufficient to hold the boot and body tube end-cap out of the way without becoming an ergonomic issue on the operator repeatedly loading the magnet.

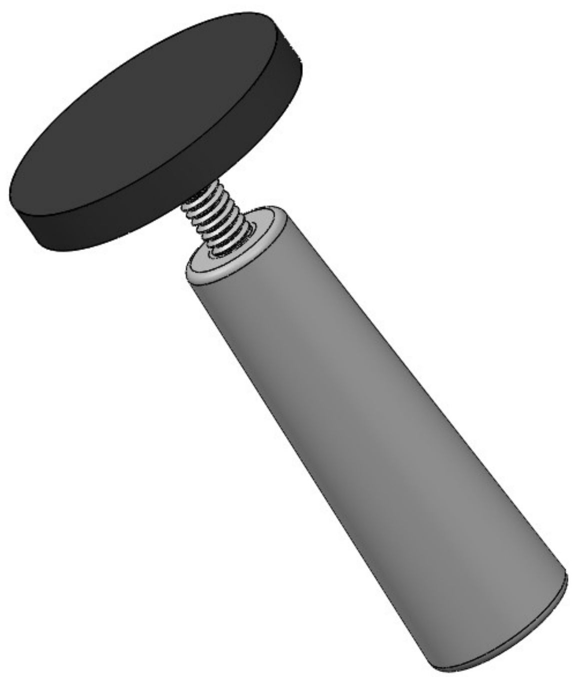

Figure 5-47. Magnet and handle end-cap holding assembly

5.6.1 Fixturing Redesign

During the mechanical redesign period, some changes were made to the fixturing carriage in the interest of decreasing outsourcing cost. First, the original gussets on the front side of the fixture (facing the operator, seen) had a machine step to cradle the underside of the carriage base plate and an external radius designed to be rolled with a belt sander by hand. Furthermore, one side gusset was a mirrored version of the other, which would complicate the manual machine setup between parts. To remove these complications, these original gussets were replaced with duplicates of the gussets on the backside of the machine, which have a simpler 2.5 axis profile and tapped holes on the two longest side surfaces. Having more duplicates of the same, simpler part likely provided a much lower quoted cost. These gussets are compared below in Figure 5-48.

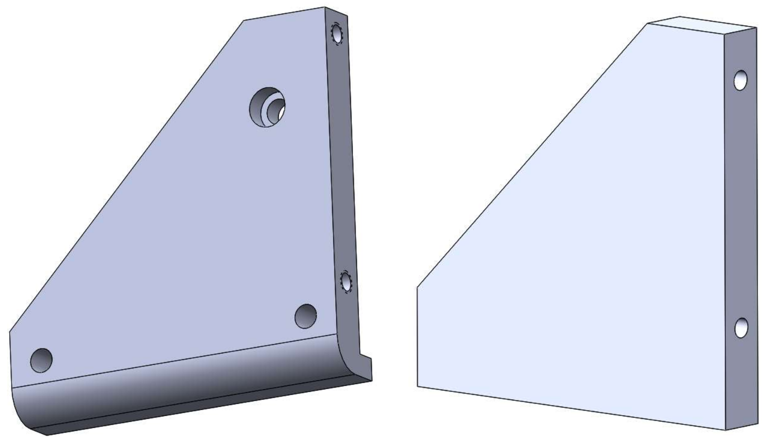

Figure 5-48. Comparison of old front gusset (left) with simpler duplicate of rear gusset (right)

The other major change was removing the faced-down cylindrical spacer between one of the front gussets and the vertical 8020 post. This change removed the need to machine a McMaster spacer and removed the counterbored hole in one of the gussets, reducing the total number of machine setups by 1. Instead, one additional tapped hole was added to the back plate to accommodate a third 8020 bracket. Beyond reducing manufacturing cost, this change clearly increases stiffness for the clamping mechanism by further limiting 8020 post deflection. This redesigned feature is shown below in Figure 5-49.

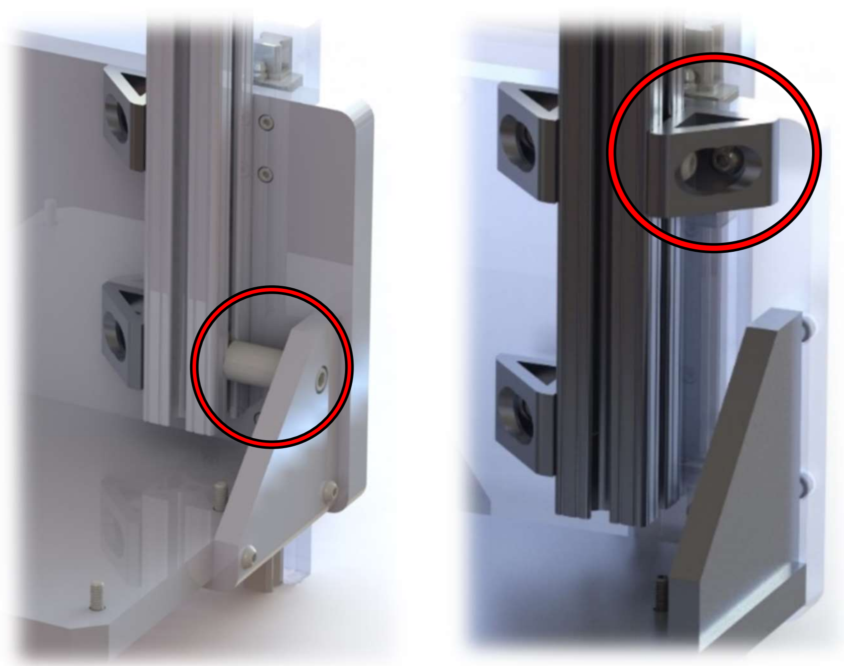

Figure 5-49. Comparison of original spacer design with redesigned 8020 attachment

The combination of these two primary changes resulted in a final fixturing assembly shown below in Figure 5-50, shown with transparent vertical plates to highlight the duplication of the back gusset plates.

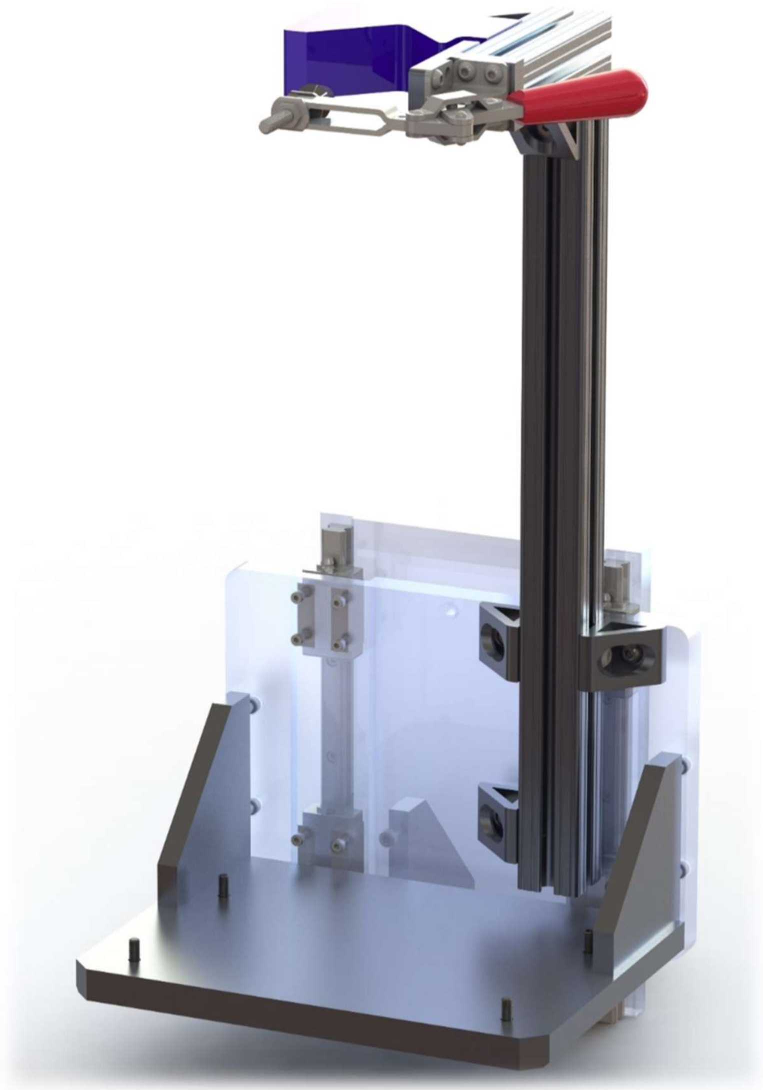

Figure 5-50. Final fixturing subassembly (post-redesign)

5.6.2 Stretch Goal Shock Accommodation

While we didn't have the time to fully accommodate the stretch goal shock (shown in Figure 2-3 and described in section 2.2), the fixture design does provide the ability for the machine to accommodate it in the future with some modification to the programming. The main base plate for the machine has some counterbored holes from the bottom side to mount the manual fixture (with u-shaped support for the larger diameter spanner tool). This was spaced from the shock axis at the same distance as the manual process for the stretch goal shock. The base plate was designed in two main sections with a plate to join them such that a 2nd front base plate could be swapped out to get the 8020 and toggle clamp / v-block fixture out of the way if needed. This 2nd front base plate would not need the pneumatic cylinder and would only have to locate the body cap pallet. Beyond designing a 2nd base plate, a modified hex adapter assembly would need to be designed to fit the smaller bearing. In the event this machine is used for the stretch goal shock, the pneumatic cylinder is no longer needed since the downward force to engage the first thread is minimal in this case. As a result, the control system programming would need to be modified to remove this output. The machine flow would otherwise function almost exactly as normal after spinning the outer spanner by hand and flipping down the u-shaped support to constrain it. This initial step could also be automated with a PF program written for a left-hand thread outer spanner, but this process is likely more efficient left as manual process due to the small number of revolutions & low torque needed.

5.7 Pneumatic System

Pneumatic controls are used to actuate the low-profile air cylinder underneath the body cap pallet as well as the rail brakes on the horizontal portion of structures. A layout of the panel is shown in Figure 5-51.

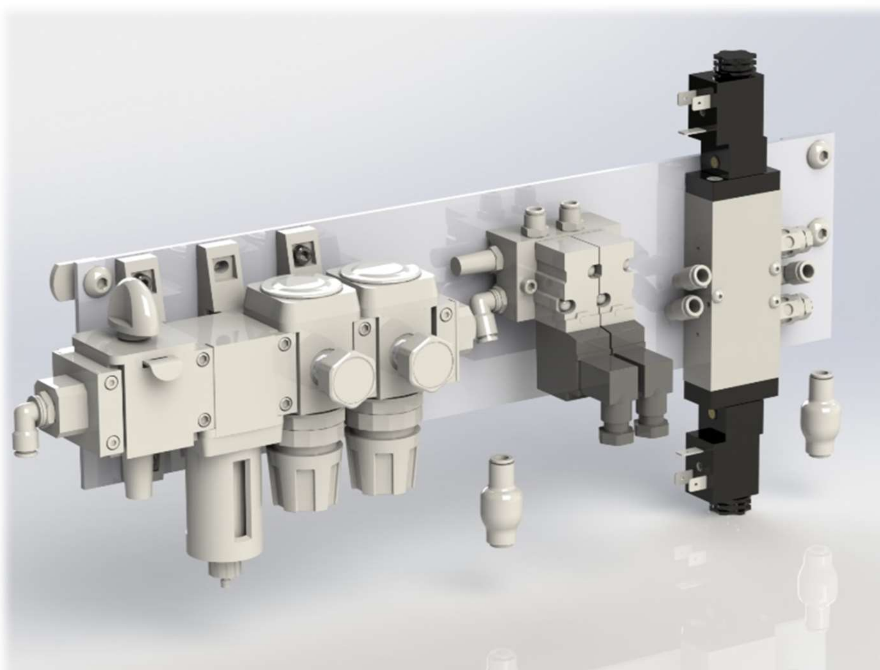

Figure 5-51. Pneumatic component panel

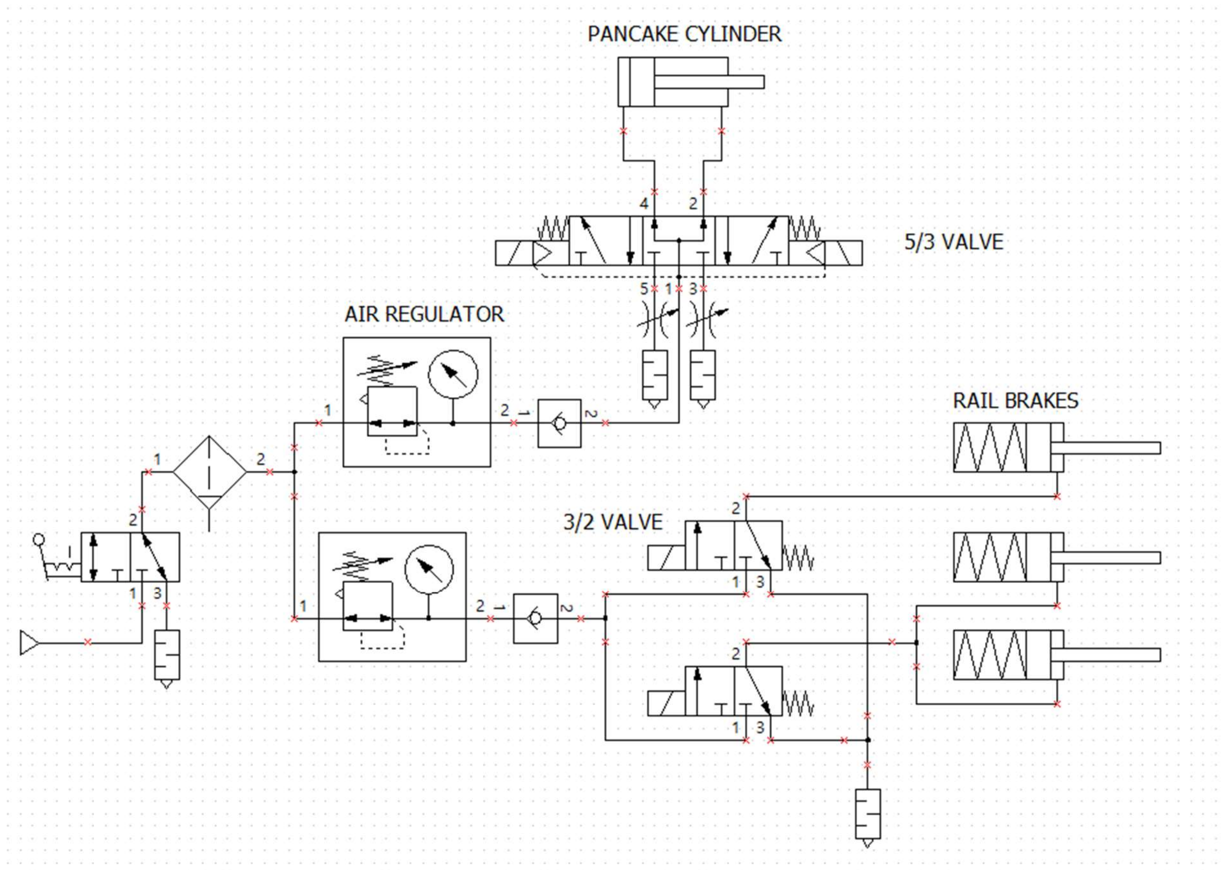

Figure 5-52. Pneumatic controls diagram

The pneumatic controls diagram is shown above in Figure 5-52. Air at 120 psi is brought into the system from the factory air supply. It is run though a manually actuated 3/2 valve into a filter. The 3/2 valve is left open during machine operation and only closed if the system needs to be depressurized for maintenance. After the filter, air is fed into two pressure regulators. One regulator, set at 20 psi, supplies a 5/3 solenoid valve. This valve controls the low-profile air cylinder. A flow regulator is used on the exhaust of the valve to allow the user to control the speed at which the air cylinder actuates.

The second regulator, set at 85 psi, supplies air to two 3/2 valves. One valve actuates the rail brake on the vertical shaft, and the other valve actuates the rail brakes on the two horizontal shafts. Independent actuation of the horizontal and vertical rail brakes is not strictly necessary but allows for future versatility if needed.

5.8 Functionality of Design:

The three main functions of the design are 1) to push the shock shaft bearing past the first o-ring seal, 2) spin the bearing into the shock body until it seats, and 3) torque the bearing to specification.

The machine functions as follows:

1. The operator begins by placing the shock into the body cap pallet, with the shaft assembly loosely placed in the body assembly. The shock is then secured by closing the toggle clamp, as shown in Figure 5-43.
2. The hex adapter is placed on the bearing housing.
3. The operator brings the drivetrain assembly into position and lowers it onto the hex adapter. A tool balancer is used to support the weight of the drivetrain and all supporting structures to reduce operator effort in moving the system to a minimum.
4. Using the handle mounted buttons, the operator actuates the torque driver to spin at a low RPM until full contact is made with the hex adapter and the c-shaped gear. Full contact is made when the c-shaped gear is seated onto the flange of the hex adapter.
5. Once full contact is made, the buttons are released, and then the operator fully seats the split gear on the hex adapter.
6. The buttons are again pressed, engaging the rail brakes & locking any motion of the drivetrain housing. The pancake air cylinder underneath the body cap pallet is energized to push the top of the shock body past the first O-ring seal on the shock shaft bearing, as seen in Figure 0-1.
7. With the force required to engage the first thread, the torque driver begins the rundown & torque procedure, seating the bearing threads into the shock body until the specified torque resistance is experienced by the servo.
8. Upon completion of the torqueing operation, the rail brakes unlock, the pneumatic cylinder lowers back down, and the operator can disengage the gear from the hex adapter.
9. With the gear clear of engagement, the buttons are re-pressed, and the torque driver returns the servo to the initial angular position. This allows the shock shaft to fit back through the opening in the c-shaped gear & gear housing.
10. The operator can move the drivetrain back behind the shock before releasing the buttons, reengaging the rail brakes. The hex adapter is removed from the bearing, and the new shock assembly is removed from the body cap pallet.

These functions, along with various conditions for errors throughout the cycle, are shown in a machine state diagram in Figure 5-53. An operator's manual was also created following these function steps, along with a variety of error conditions, attached in Appendix S.

5.9 Electrical System

There are 3 main electrical components in our system: a PF6000, an Allen-Bradley MicroLogix 1400 PLC, and a human machine interface (HMI). The PLC takes 120 volts and is connected to all other major components, communicating with them through signal wires. The PLC will be connected to two buttons. The two buttons are simple three wire buttons consisting of equipment ground and power. These buttons will go through a logical safety relay that will only allow a signal to pass if both buttons have been pressed with 0.5 seconds of each other. The solenoids control the pneumatics and requires 24 v of power provided by an output terminal of the PLC.

The PF6000 takes 90-120v wall power and will be connected to both the PLC and the torque driver. The PF6000 will be connected to the torque driver via an Atlas Copco cord that connects to the end of the torque driver and into the PF6000. The PF6000 will be connected to the PLC by an ethernet cord. Communication with the buttons and solenoid will be relatively simple as they only have two states each. The buttons are either pressed or released and the solenoid is either triggered or released. The communication between the PLC and PF6000 will be more complicated. The PLC will need to know when the PF6000 has reached a specified torque value and the PF6000 will need to know when the PLC wants it to start and operation. Furthermore, the PLC will need to be able to stop the torque driver while it is in the middle of an operation.

The HMI is the last major component and is the easiest to deal with electrically. Communications will be done through an ethernet cable, and will talk to the PLC in a similar manner that the PF6000 communicated with the PLC. They will be all wired together using an ethernet switch, but the signals sent should only be able to be read or received from one device. The power will be received from its own independent power supply located inside the PLC box. It is important that the power supply be independent of the one feeding power to the solenoids and other components because inductive loads on the same power supply can cause the HMI to behave in unexpected ways without a power factor correction, i.e. capacitive loads that balance out the inductive loads.

The basic electrical wiring diagram is attached in Appendix P. This is to be used in conjunction with the existing wiring diagram of the PLC provided in Appendix Q. The symbols used in the basic electrical wiring diagram will not make entire sense without the existing wiring diagram. For components necessary to complete the electrical system see the controls section of the iBOM in Appendix L.

5.10 Software

The control system for this machine is comprised of three programmed elements, each requiring a different software:

- Atlas Copco's PF6000 torque driver controller, which uses AC's *Tools Talk* software and a condensed version which is accessed on the controller's touch screen
- A touchscreen human-machine interface (HMI) panel, designed with *C-more programming software*
- An Allen-Bradley MicroLogix 1400 programmable logic controller (PLC), programmed with Rockwell Automation's RS Logix 500

The combination of these control elements takes several external inputs (along with some closed-loop feedback from the torque driver) and moves through a cycle of operation steps to rundown & torque the shaft bearing into the shock body tube. The main I/O with brief function descriptions are shown in Table 5-4.

Table 5-4. PLC I/O

Inputs:	Outputs:
• Two buttons & a safety relay for normal operator input • Torque & position feedback from the Atlas Copco torque driver • Several HMI reset options in the event of an operator error • An emergency stop to cut power to the driver and activate an emergency & maintenance mode	• Several programmed tasks for an Atlas Copco Tensor ST torque driver • Three pneumatically actuated Amlok linear rail brakes, preventing drivetrain motion • A pneumatic cylinder to supply o-ring compression force while engaging the bearing threads • Information for the operator, to be displayed on the HMI

Figure 5-53 shows the state machine diagram that will dictate how the final code is written for each of the described control elements. States 0 → 7 show the normal operation loop for the machine, as described in the attached operator’s manual in Appendix S. The remaining states 8-13 account for potential error situations & maintenance.

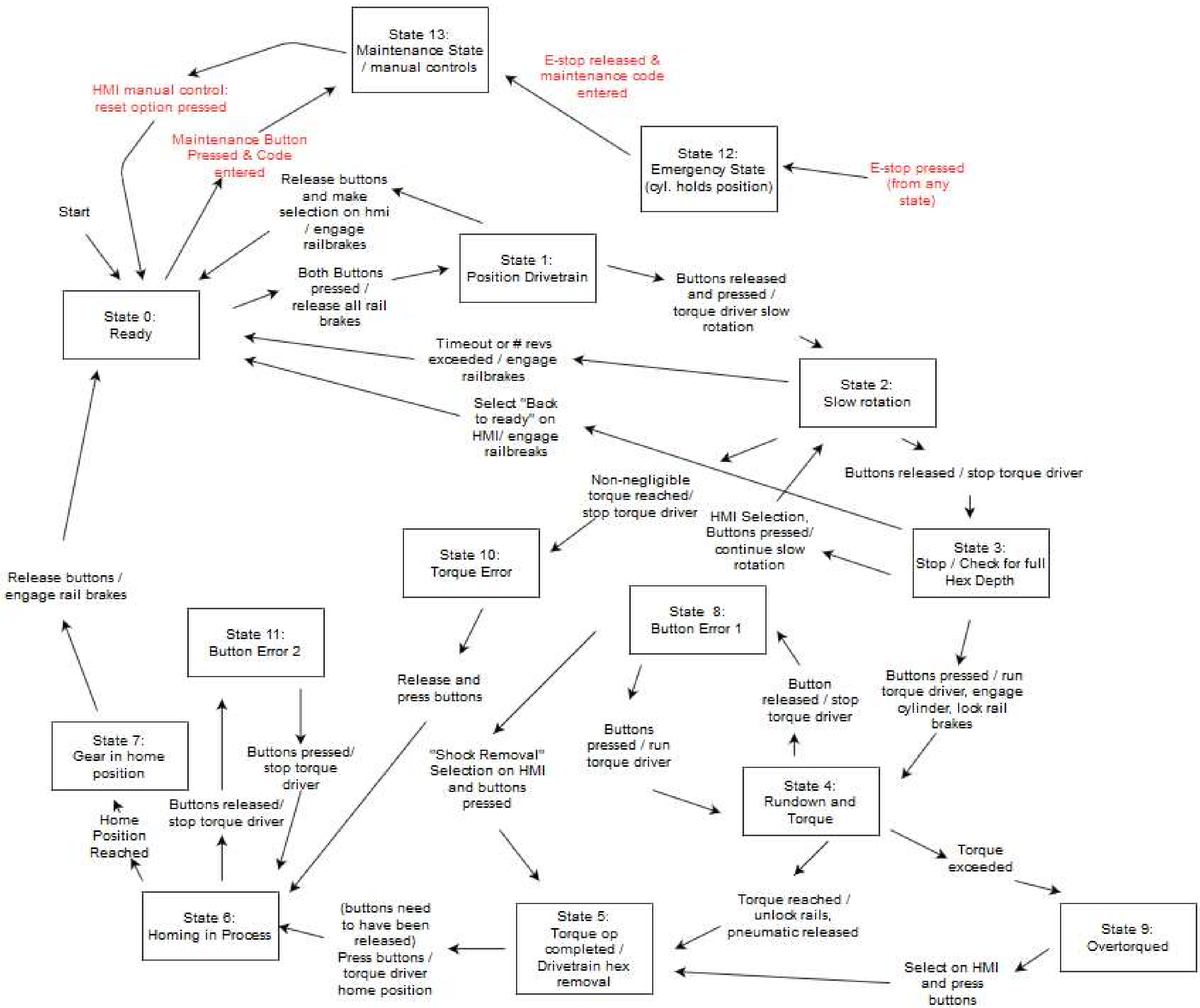

Figure 5-53. State machine diagram

To keep the state diagram from being too cluttered, not all outputs were shown with each state. Instead a table of outputs for each state was created, shown below in Table 5-5.

Table 5-5. State output table

STATE #	DRIVER	BRAKES	CYLINDER
0	OFF	ENGAGED	OFF
1	OFF	DISENGAGED	OFF
2	ON (P1)	DISENGAGED	OFF
3	OFF	DISENGAGED	OFF
4	ON (P2)	ENGAGED	ON (UP)
5	OFF	DISENGAGED	ON (DOWN)
6	ON (P3)	ENGAGED	OFF
7	OFF	DISENGAGED	OFF
8	OFF	ENGAGED	ON (UP)
9	OFF	ENGAGED	OFF
10	OFF	ENGAGED	OFF
11	OFF	ENGAGED	OFF
12	OFF	ENGAGED	OFF
13	OFF	*HORIZONTAL & VERTICAL ON/OFF*	*UP/DOWN/OFF*

**Manually controlled from HMI*

Our state machine diagram has 13 states and transitions from one to another when a specific event has occurred. A safety note of interest is that the machine is programmed to cease output from the torque driver if the buttons are released, as can be seen for the three states (2,4,6) which output a task to the torque driver.

The following sub-sections provide detailed descriptions of how each control element was programmed.

5.10.1 PLC Fiddle Simulation

To simulate the system and work out the programming logic required to correctly move the machine through the sequence listed out by the state diagram, PLC Fiddle was used. PLC Fiddle is a free online simulator which includes a basic introductory course for learning to program ladder diagrams. While there are more powerful ladder diagram PLC simulators available, PLC Fiddle was chosen due to familiarity from using it in Cal Poly's manufacturing automation (IME 356) lab. This simulation step was crucial to sorting out the biggest logic issue during the early programming stage, which was the need to check that the buttons had been cycled in order to move the machine along into the next state. The safety relay only checks to ensure the buttons were pressed within a short time of one another, but didn't seem to have the capability to output any sort of different signal based on whether or not the buttons had been released and then re-pressed. To sort this out, a counter was used to keep track of how many times the button relay had started sending a signal to the PLC. Certain states or transitions between states that required the buttons be cycled for safety reasons would check for the count to be equal to the preset value of 2, and a count reset was performed where appropriate. While this solution in hindsight seems very simple, this came after attempting several different methods, including spending a significant amount of time attempting to use a second state variable for the button to check if it was in a cycled state. The other logic issue that was worked out during the simulation phase was introducing a timer during the third state. This state had two different HMI reset options which could either return to the initial idle state or go only one state back to the slow rotation program. The timer gave the operator a chance to transition back to the buttons before resuming the torque driver rotation, since a clear safety goal with the project was to only allow power to be supplied to the driver when both of the operator's hands were occupied with the handles/buttons. A sample section of the PLC Fiddle ladder diagram is shown below in Figure 5-54 for states four & five, where state four instructs the torque driver controller to run the torque & rundown program.

Figure 5-54. PLC Fiddle ladder diagram sample rungs

State 4 was chosen for the PLC Fiddle sample to compare to the added complication for the ladder diagram after it was moved into Rockwell Automation's PLC programming software, RS Logix. The final PLC Fiddle program did not include all the various error states due to the tedious nature of expanding lengthy PLC Fiddle diagrams. However, the completion of the normal cycle provided sufficient confidence in the programming logic to move forward into RS Logix programming. The final PLC Fiddle ladder diagram can be viewed with the following link:

https://www.plcfiddle.com/fiddles/97e8ddf4-1790-4d81-9867-3a39d3c5e86d

5.10.2 RS Logix PLC Programming & Communications

The PLC programming needed to be moved into RS Logix to transfer the ladder diagram & signal addresses to the Allen Bradley PLC. The team was unable to acquire access to the full version of RS Logix 500 (which is used by Fox at the factory for other automation projects), but a free version (RS Logix Micro Starter Lite) was found through the Rockwell Automation website. This free version of the software did not have the full capabilities of RS Logix 500 but created the same file type so programs could be sent back and forth. The biggest limitation of the free version that affected us was the limited list of processers included with the software. The MicroLogix 1400 was not included, so Fox will need to update ethernet communication information and possibly other I/O addresses after switching processors. After learning the basics from Tom and receiving an example program he sent over, the ladder diagram was transferred over from PLC Fiddle and signal locations were defined for the various inputs and outputs (I/O).

This new rendition of the ladder diagram required significantly more complication to add in all the different error states and take into account all of the different signals required. The ladder was lengthened significantly due to limitations with the free version of the software; branches in the ladder could not contain both inputs and outputs on a single branch so multiple rungs needed to be added for more complicated states. Error states were added for conditions outside the normal operation cycle, such as experiencing torque feedback from the driver when it was not expected (due to something pinched in the rotating gear) or the operator letting go of the buttons prematurely. The outputs were also split up into different programs for the torque driver, added options for the HMI to control the system, and split up the solenoids to actuate the horizontal and vertical rail brakes. For example, the PLC Fiddle's "DRIVER ON" output coil was now split into different PF6000 task, as shown in the following RS Logix diagram sample in Figure 5-55.

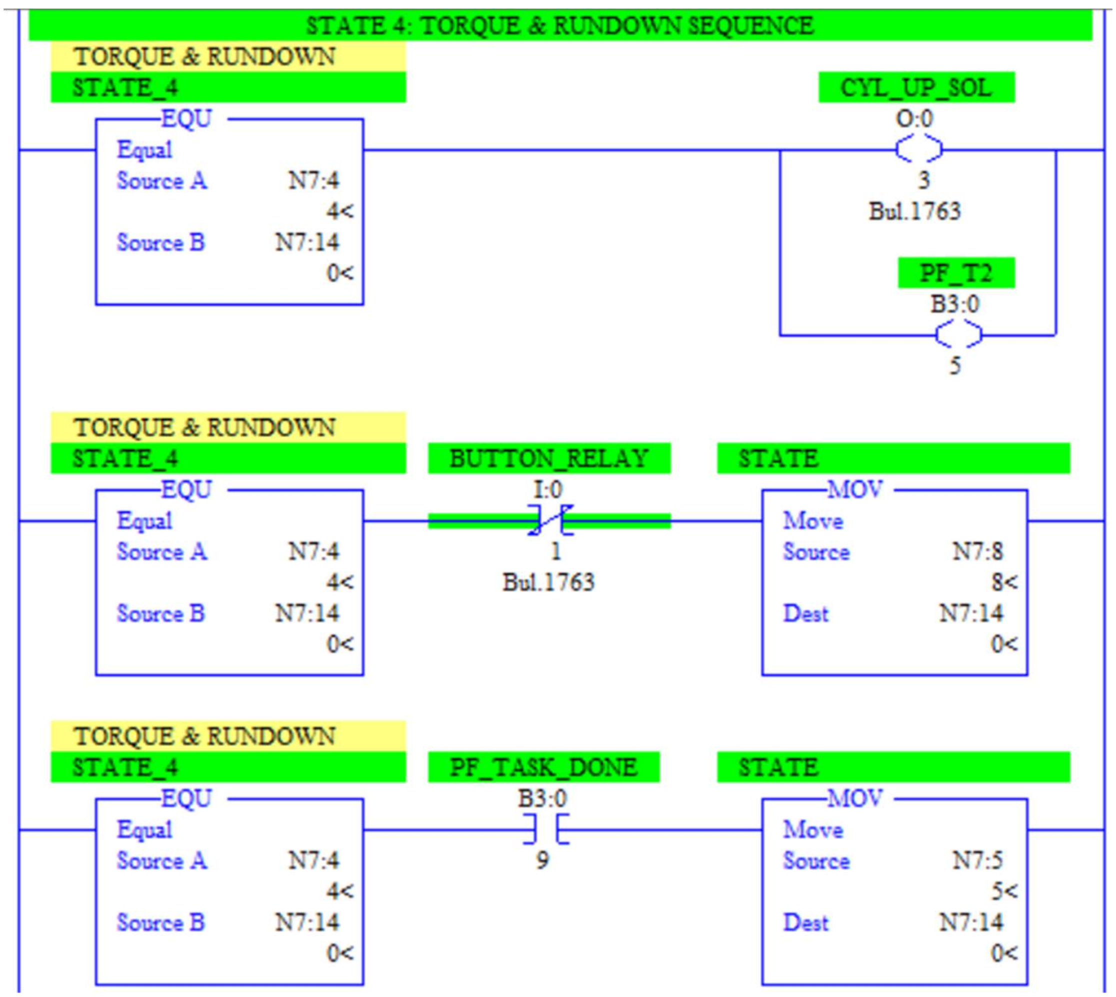

Figure 5-55. RS Logix ladder diagram sample, torque & rundown state

Rather than the equal checking block listing state names in this diagram, it checks (in this case) between state 4, at signal bit address N7:4, with the state variable, stored in N7:14. N7 defines the integer data type, which happens to be the 7th possible data file for the selected processer. Other data types shown in this example include B3, or the binary signal type, and I & O, which correspond to the hardwire input & output terminals, respectively. Signal types not shown in this state example but used elsewhere in the program were T4, for timers, and C5, for counters, but these signals were only needed for internal PLC logic. It was learned that signals sent via ethernet did not require physical I/O signal address and were instead given a binary bit address to be interpreted by the HMI or PF6000. As will be mentioned during the discussion of PF6000 programming, ethernet communication for the PF was less clear to understand. If Fox does end up hard wiring the PF, the ladder logic will remain the same structurally and would only affect the outputs remaining as binary or changing to physical I/O.

For the other control elements to correctly identify the different signals present in the PLC operation, a CSV file was output from RS Logix with a complete list of signal addresses & names. This spreadsheet needed to be reformatted for use with the HMI, which will be further explained in the HMI programming section.

Finally, it's worth mentioning the emergency & maintenance states added. As mentioned previously, an e-stop was added to the system to prevent power from being sent to the torque driver. No outputs were added for the emergency state to ensure that there would be no driver output & the rail brakes would lock the drivetrain travel. The emergency state was kept separate from the maintenance state in order to get the sponsor's tech team involved whenever the e-stop was pressed. Releasing the e-stop would transition the machine to the maintenance state, after which a maintenance password was entered and five generic HMI inputs could be accessed (on the PLC side), as shown in Figure 5-56.

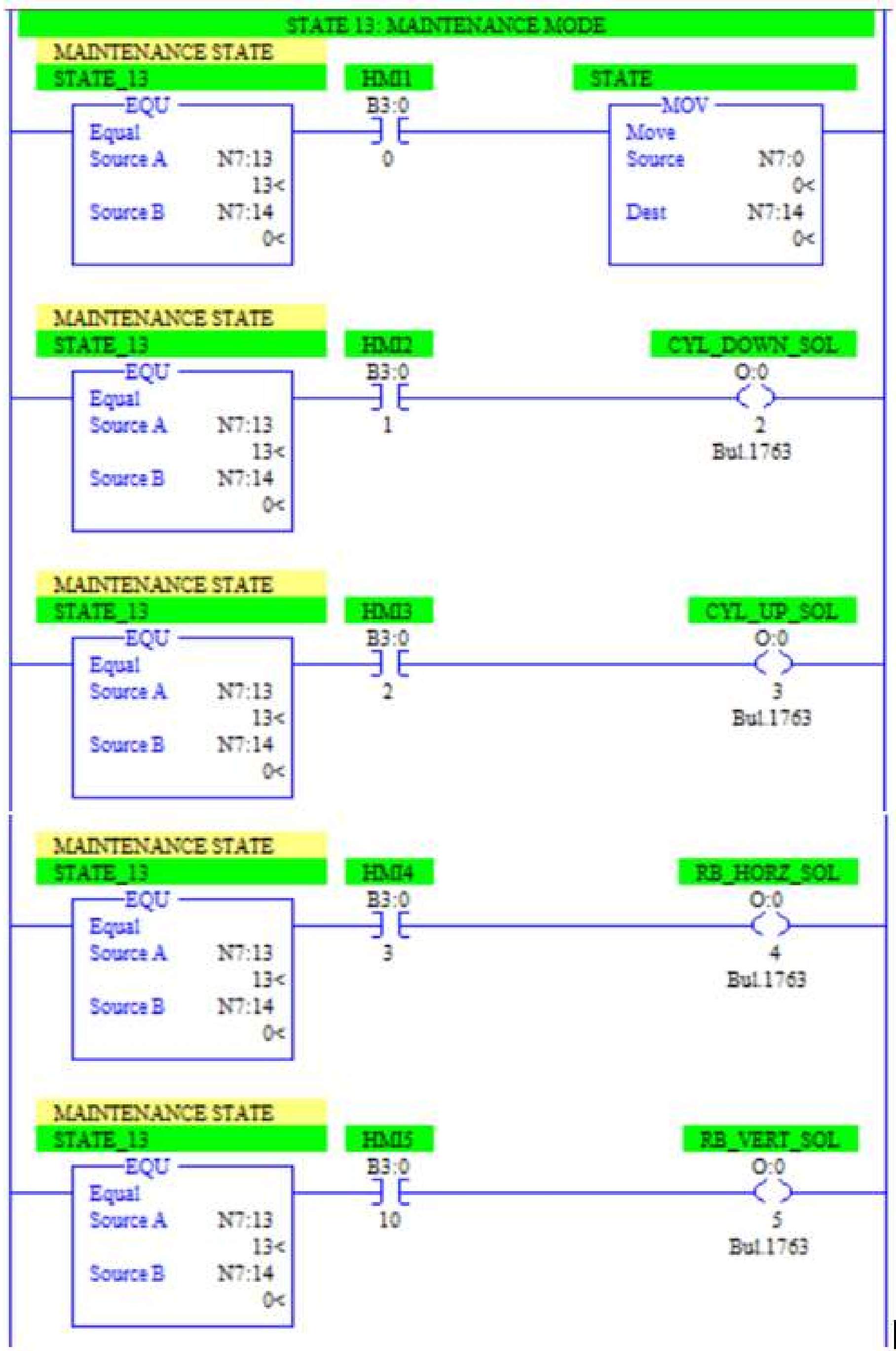

Figure 5-56. Maintenance mode section of ladder diagram

These five HMI binary inputs were connected to four hardwired output terminals for the system's pneumatic solenoids with the fifth option returning to the idle state. This program logic of using generic inputs from the HMI depended on the HMI program being able to recognize which machine state the PLC was in and display different texts on the touchscreen buttons. From an HMI programming standpoint this was not ideal but would keep the ladder diagram as simple as possible and would prevent the HMI display from becoming cluttered with unnecessary buttons.

5.10.3 HMI Programming

The next piece of hardware requiring programming is the HMI display (Human Machine Interface) that connects to the PLC. The HMI provides the operator visual data about the machine's operations and allows the operator to make changes. The HMI displays two important pieces of information. The first is the current state or operation of the machine. The second is the status of the actuating devices on the machine. Figure 5-57 shows the simulated HMI screen during state 3 of the overall process.

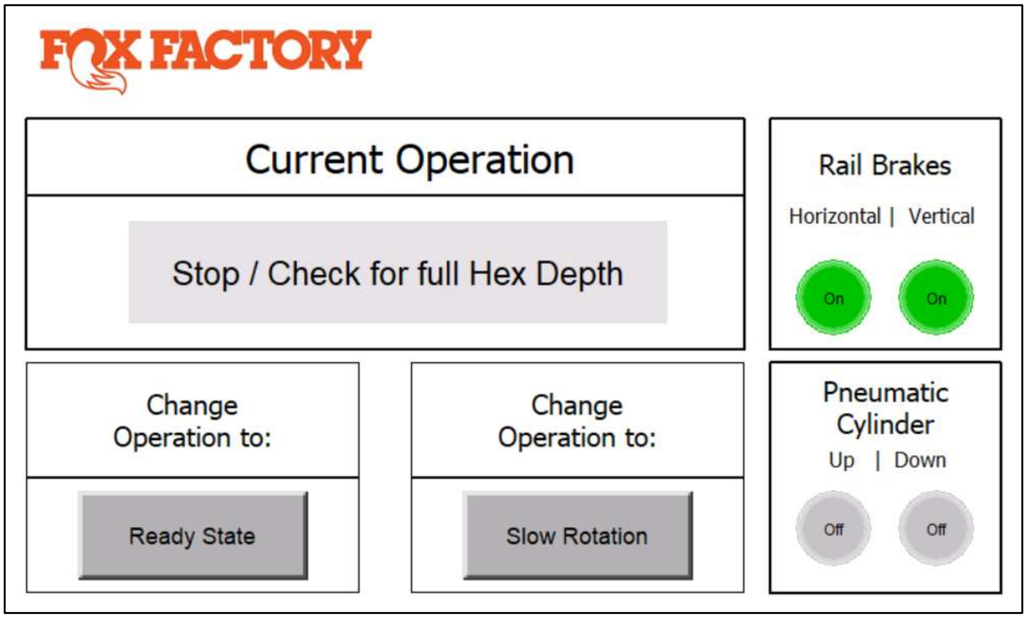

Figure 5-57. HMI Main Screen

Front and center is the box containing the current operation. The text in the light gray box changes depending on the current state of the machine. This was initially tricky to program because the HMI looks for a variable to pull the text from and display on the screen, and there was difficulty programming this on the PLC. It was found that the C-more software supports basic logic and if/then statements, which was used to solve this problem. Now the PLC only needs to pass one variable that contains the integer value corresponding to the current state. The HMI sets the current operation text according to that integer value.

The HMI also tells the operator of the status of the rail breaks and pneumatic cylinder. The PLC simply passes variables corresponding to each device and the HMI updates the display lights accordingly. While technically not necessary for the machine to operate, having these display lights aids with troubleshooting and keeps the operator aware about the status of the machine. The HMI is also used when the operator needs to change to a state that does not follow the typical flow of the overall operation. For example, as in Figure 5-57, the operator has the opportunity to change the operation to the ready state, or to slow rotation. If neither of these options are picked, the program will continue into the next nominal state. Additionally, some states do not have the option to change to an out-of-order state. In this case, the buttons are covered by a light gray box, clearly indicating that the button is not accessible.

The HMI also has a maintenance mode, in which the operator can manually actuate the various powered components on the machine. This screen is shown in Figure 5-58.

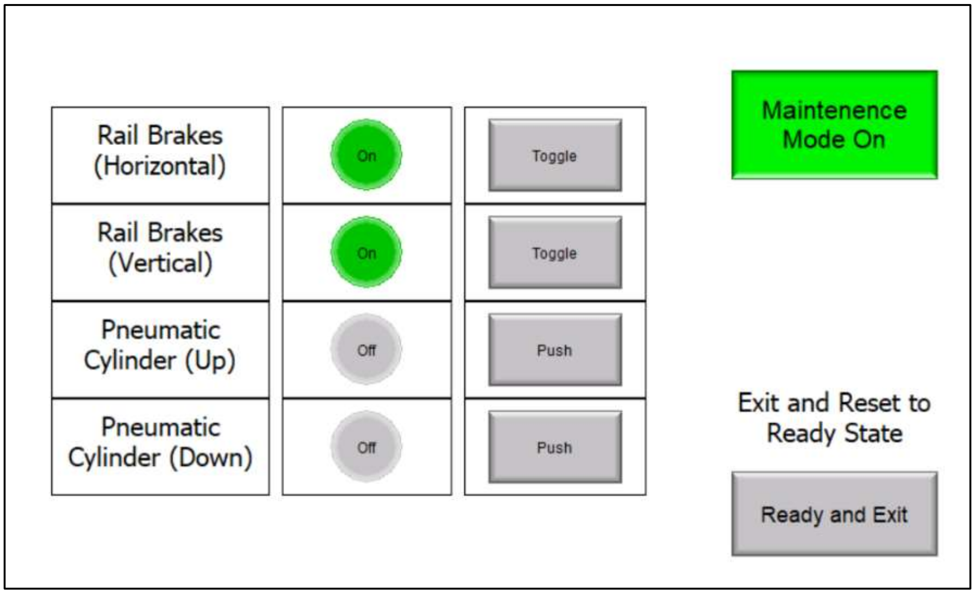

Figure 5-58. HMI Maintenance Mode Screen

This screen can be accessed by clicking a hidden button and entering in a password. Once in the maintenance screen, you can see the status of the rail brakes and pneumatic cylinders, just as in the main screen. If maintenance mode is turned on, the operator will be able to toggle the rail brakes and pneumatics and will also be able to manually set the machine back to the ready state. This screen is designed to be helpful if there is ever a malfunction and the machine crashes in the middle of operation. With this screen the operator can gain full control of the machine and then re-set it once the problem is solved.

As mentioned in the previous section, the HMI is primarily communicating to the PLC through the use and updating of the variables HMI 1-5. On the HMI side of the program, each variable need to be specifically defined, especially the variables that will be stored on the PLC. To fully specify a variable, three major things need to be defined: the variable address, the type of address, and data type of the variable. This information must initially be manually passed from the PLC to the HMI in the form of a .csv file, which must then be properly formatted to be recognized by the HMI. The other variable type are internal variables. These variables are stored on the HMI and are not referenced by the PLC. These variables can change depending on variables changed by the PLC but are not directly updated by the PLC. Internal variables include variables allowing the screen to change of for buttons to be hidden and shown.

5.10.4 PF6000 Programming

It should be noted that the communication to the PF6000 is not entirely finalized. The PF6000 utilizes its own communication system called Open Protocol which utilizes an integer string. Currently it is believed this integer string can be stored within the PF and then “activated” with binary inputs and outputs, however that has yet to be fully sorted. Open protocol would allow the device to communicate to the torque driver via ethernet cable. Another method of communication would be to utilize the PF6000's inputs and outputs to send and receive binary signals that can tell the torque driver to run, or the PF6000 telling the PLC that the operation has been completed.

The PF6000 also uses a software called ToolsTalk2 to program its tools. Currently the team does not have access to this software as FOX is also having trouble getting access to ToolsTalk2. There is basic software that is locally stored on the PF6000 that can be accessed either manually through the touchscreen or by connecting a computer. While this software can program basic tool operations without much difficulty, the team has not been able to locate a homing feature in this software. This feature allows the torque driver to set a home spindle position and then return to that position once the function is called. This function is critical as the shock would be impossible to remove if the output gear is not homed so that the drivetrain slot and the gear slot line up. While this function doesn't appear to be on the native PF6000 software, it was included in the ToolsTalk version for the PF4000 so it is hoped that the function is somewhere in the updated ToolsTalk2 software. This will be up to Fox to finalize once they have been able to source a copy of the new version of ToolsTalk.

Helpful resources on Open protocol, PF6000 communication & programming, and ToolsTalk can be found directly through the Atlas Copco website [19] [20] [21] [22].

5.10.5 Software Recommendations for Future / Similar Projects

If we were to repeat the PLC programming portion of this project, we would avoid PLC fiddle simulation entirely. PLC Fiddle is a great tool for PLC beginners creating very short programs but is buggy and tedious to use for longer programs. PLC Fiddle accommodates atypical ladder structuring which can be misleading as a learning tool, does not accommodate reordering of input buttons for easy access, and does not allow copying & pasting for similar rungs which only need slight changes between states. If we were to attempt program simulation using software again, the combination of RS Linx (which allows other software to be integrated into RS Logix) and an RS Logix emulator would be used instead. Tom at Fox also recommended looking into a PLC simulator offered through the AutomationDirect website, but we ran out of time to explore either of these options. Ideally, the best way to test the ladder diagram's functionality would be to physically connect all of the components together and test outputs in a safe & controlled manner, such as using LEDs instead of components which could be hazardous with incorrect PLC outputs. Unfortunately, this was not an option for us due various delays & home-wiring safety restrictions resulting from COVID-19.

5.11 Safety Considerations:

The main safety hazards identified with the machine, as shown in the design hazard checklist in Appendix I, are the clear pinch hazards, high pressure pneumatic lines, a large suspended weight of the drivetrain assembly, and potential for either the shock or entire machine to tip. Steps have been taken throughout the design process to mitigate these hazards as much as possible, along with other risks to the machine and shock assembly, which are listed out in the failure modes effects and analysis (FMEA) shown in Appendix J. A risk assessment was also performed with *DesignSafe* software, which can be found in Appendix U.

The largest concern with the potential to cause serious injury to the operator are the pinch hazards, shown in red in Figure 5-59. The worst pinch hazard is the drivetrain open gear. As this hazard is not possible to fully eliminate without preventing machine functionality, a variety of methods will be utilized to protect the operator(s). First, on the programming side, it will be necessary to hold the buttons on both drivetrain handles, away from the opening in the housing, to supply power to the torque driver. While this is seen as sufficient to protect the direct operator's hands and fingers, there is still possibility for tools or other objects placed on top of the drivetrain housing to be caught or any nearby line associates to be in harm's way. To limit access to the front of the machine only, a polycarbonate safety guard will be placed around the sides and back of the machine assembly. With the redesign to the machine during the delays caused by COVID-19, the senior project team did not finalize a revised Polycarbonate guard. It will be up to Fox to implement a guard once the machine is assembled. Finally, safety decals highlighting the pinch hazard will be placed on the drivetrain housing to immediately and visually indicate the danger to a new operator, which again will be applied by Fox upon completion of the assembly.

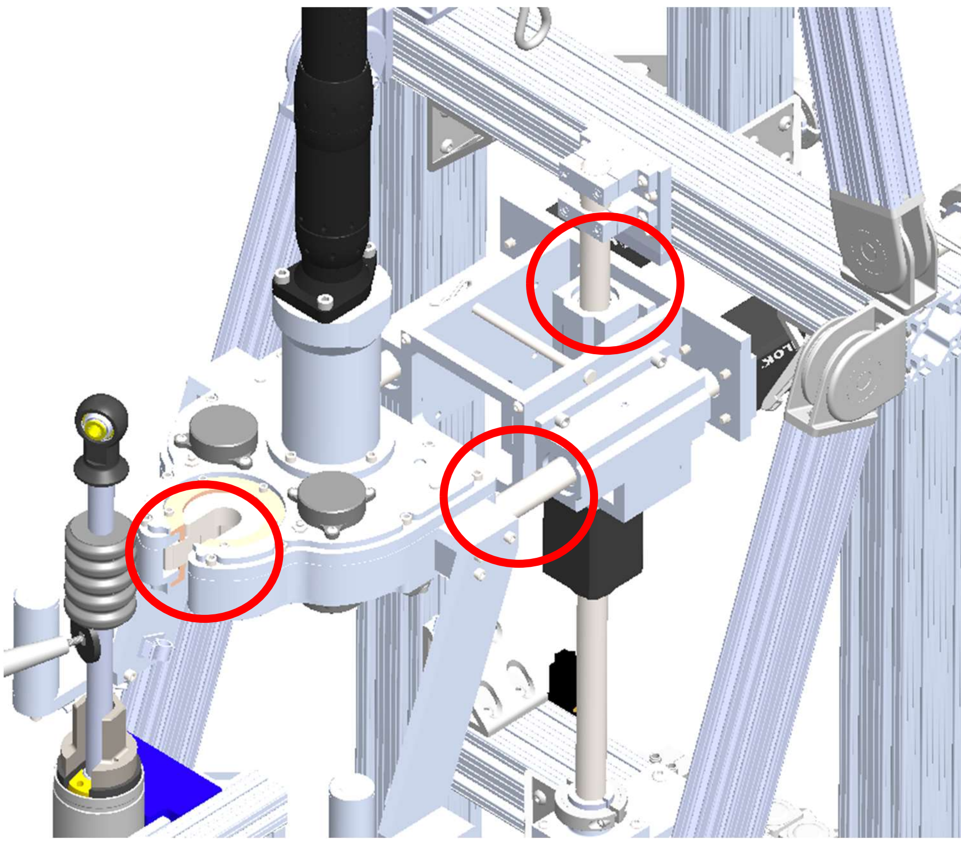

Figure 5-59: Pinch Hazards

In terms of stored energy in the system, the first line of defense from the high-pressure pneumatic lines potentially coming loose and projecting oil and grease towards the operator is the safety glasses policy already in place on the factory floor. The only other safety precaution currently taken in terms of pneumatics is a manually operated safety valve at the inlet to the regulator panel. This would allow depressurization of the lines during maintenance or machine down time.

To reduce any limitations included in the design, the drivetrain has a wide range of motion in the lateral and vertical directions. This allows the machine to be scaled to another shock family without much trouble. With respect to the hanging mass, care has been taken with limitations placed on drivetrain movement to ensure that the CG of the machine cannot shift off the base plate for the machine, and the base plate will be clamped to the table just in case. Shown below in Figure 5-60 is the center of gravity displacement from center at full extension of the sliding drivetrain. No case was found where the CG of the drivetrain and structures alone migrated outside the base of the 8020 structure, which indicates a large tipping factor of safety for the machine in its entirety.

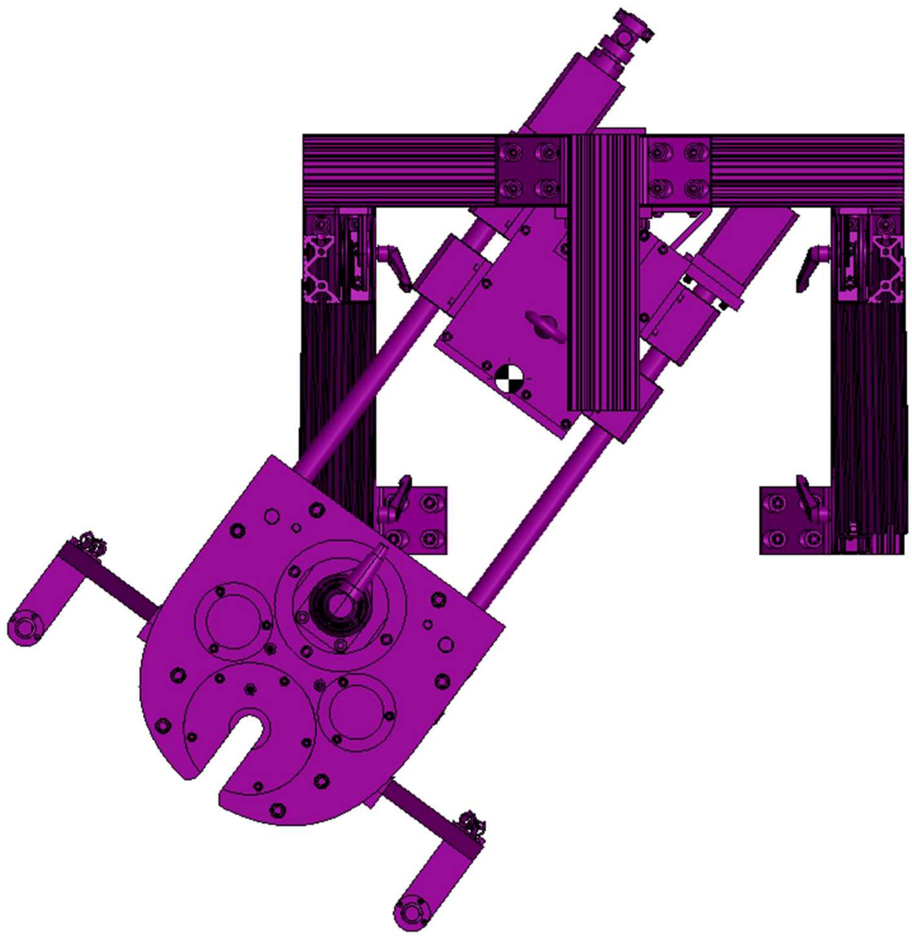

Figure 5-60. CG location at maximum drivetrain extension, overhead view

For the tool balancer, which supports the sliding structures and drivetrain weight, a secondary restraint will be added similar to the one shown below in Figure 5-61, which will prevent the assembly from dropping in the event that the pivoting top clip of the counterbalance fails. Cable failure is still a risk, but once experimental data is found for life cycle of the Atlas Copco cable, the cable maintenance interval will be refined, and this risk can be avoided. Most times, however, the cable failure will not be an issue as the weight of the sliding assembly will be supported by the normally closed vertical rail brake.

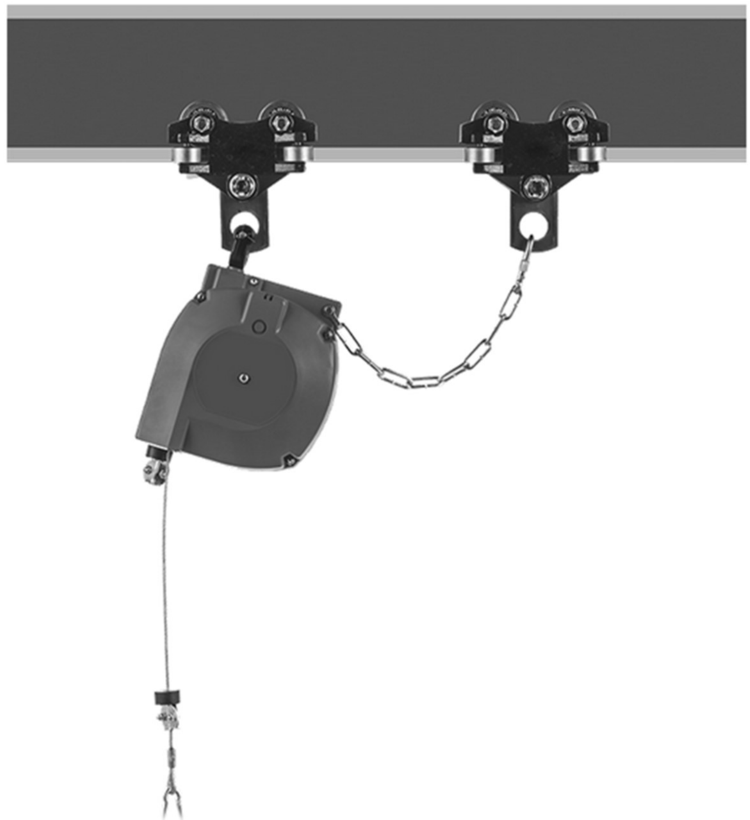

Figure 5-61. McMaster tool balancer secondary restraint chain [14]

To prevent the shock from tipping over, a V-block and toggle clamp were added to the fixturing assembly. This allows the shock to be constrained at the bottom with the body cap pallet and at the top using the clamp. The clamping mechanism can be seen in Figure 5-43.

As a final safety note, it is worth repeating the ergonomic constraints that drove the need for this project in the first place. As mentioned in section 5.4, the drivetrain handles have been designed to be as comfortable to use as possible for a typical operator on the PS03 line at Fox, with elbows typically at roughly 90 degrees during operation. Furthermore, forces and torques on the operator have been drastically reduced from the manual process by supplying both the drive torque and counteracting reaction in the structures, as well as the downward force needed to engage the first thread during rundown.

All of these safety hazards and the proper operating procedure have been outlined in the operator's manual, which is attached in Appendix S. While less clearly a safety issue, the team also performed analysis for universal design performance measures to determine how safe & equitable the machine use is to people with varying abilities. This universal design measure analysis can be found in Appendix T.

5.12 Maintenance and Repair Considerations:

To ensure smooth machine operation and prevention of machine down-time or a production bottleneck, some components should be checked for wear on a regular basis. While the manual process can still be used in an emergency should any catastrophic machine failures occur, this should be avoided as much as possible. Avoiding returning to the manual process will limit the ergonomic stresses that drove the need for the project in the first place.

As the drivetrain will experience the most severe loading and contains the most components with metal-on-metal contact, it will contain most of the items to be either checked or replaced. Within the drivetrain, the slotted bushings will likely be the first component in need of replacement, followed by the ½”-13 drive bolt. The gears and tapered roller bearings should also be checked during a major maintenance period, which currently is estimated to be approximately every 30,000 cycles, or roughly 100 runs of the machine (where each run is approx. 300 shocks in a shift). Outside of the drivetrain, the tool balancer cable will likely need to be replaced on a similar interval to the major drivetrain maintenance as this is a large safety concern. While no data was readily available in Atlas Copco’s catalog about estimated lifespan of the cable, it is known that the Ingersoll-Rand counter balancers already in use at the factory have a relatively short cable life. For less critical maintenance items, the bearing carriages in the fixturing subsystem will need to be re-greased and the hex adapter should be frequently checked for any cracking, edge rounding, or dowel pin wobble. Finally, the most frequent maintenance item will likely be re-greasing all drivetrain zerk fittings (especially those at the slotted bushings) before each use of the machine. For replacement components, shown below in Table 5-6, and other maintenance items, shown in Table 5-7, these estimated maintenance intervals are subject to refinement as the machine is tested and implemented on the line at Fox.

Table 5-6. Replacement component timeline

Component:	Replacement Interval (initial estimate)
Slotted Bushings	200,000 shocks (approx. 600 runs)
Tool balancer cable	30,000 shocks (approx. 100 runs)
Drive bolt	30,000 shocks (approx. 100 runs)

Table 5-7. Non-replacement, maintenance component timeline

Component:	Maintenance Interval (initial estimate)
Re-grease drivetrain zerk fittings	300 shocks (approx. once per run)
Re-grease bearing carriages	3,000 shocks (approx. 10 runs)
Check tapered roller bearings, re-pack grease	30,000 shocks (approx. 100 runs)
Check gears for excessive wear	30,000 shocks (approx. 100 runs)
Check hex adapter for edge rounding, cracking, and dowel pin wear	1500 shocks (once every 5 runs)

5.13 Summary Cost Analysis

The cost of this project has built up as more features are needed for the assembly tool to fully function. Because this is a one-off machine the cost is driven up by machining costs for the setup and CAM for single parts and by the cost of 8020. But the fasteners associated with the design and assembly of 8020 structures offer a relatively easy solution from a design standpoint. To re-iterate, 8020 cuts engineering costs at the trade-off of inflated pricing for the fasteners associated with the material.

To keep costs low, the team planned to machine a majority of the parts in-house at the Cal Poly shops, only sending out the more complex components. The drawback is that machining so many parts in-house will take a large amount of the team's time. COVID-19 caused those plans to change. Post Covid-19, parts will be machined through Fox and their manufacturing sources. Fox standardized manufacturing drawings were prepared so each part could be quoted. Going through the appropriate Fox channels, quotes were requested and received for both manual and CNC parts and the prices added to the indented bill of materials.

An indented bill of materials (iBOM) was made so that each assembly could easily be identified by its dependents, which can be seen in Appendix L. The iBOM also identifies the cost of each individual component and the quantity to purchase. Shipping and tax were not included, because a great number of parts were quoted with shipping and tax already included. Furthermore, some components are already owned and been laying around the factory for a while, and a great number of components will not be purchased at the same time, making shipping and tax difficult to estimate. Currently, small cost items such as pneumatic tubing and wires are left out of the shopping list or have a small cost to blanket the price because a lot of those components are on hand at the factory.

The entire cost to build this system is approximately $61,050. This includes all parts that have been purchased by or are already owned by Fox. The cost of the controls system and the torque driver cost approximately $36,000 out of that $61,050. The cost of a second system could potentially cost less because elements such as the PF6000 & PLC can run multiple systems at a time.

6 Manufacturing Plan

Due to the COVID-19, the team made significant changes to the manufacturing timeline and method. All parts that were originally scheduled to be made in the Cal Poly machine shops will now be made by outside vendors chosen by Fox. In addition, the initial manufacturing scope was reduced to include only the drivetrain and a test stand designed by Tom Mulrooney. This will allow Fox to ensure the drivetrain and the control system are functional before building the structures and implementing the machine on the factory line.

Individual piece part drawings are not attached due to some items being defined based on fox product geometry, which is confidential data.

6.1 Outsourced Parts

As mentioned above, all parts will be outsourced to Fox. The team delivered all drawings and IGES files. Fox will handle getting the drawings to vendors to be machined. This will take anywhere from two to four weeks. In addition, the drivetrain shafts and gears will be heat treated after they are machined. Fox will also handle this process, which will take an additional one to two weeks.

6.2 In House Parts

The team had originally planned to manufacture most of the components in the Cal Poly Machine Shops. This was no longer a possibility after the campus was closed due to COVID-19. The team spent time redesigning all parts originally meant to be waterjet so that they could be made on a knee mill. This was the only impact on the design due to outsourcing all parts.

6.3 Manufacturing Timeline

Date	Tasks to be completed
3/11	• All work orders for drivetrain and test stand components sent out
3/16	• All prints completed
3/22	• All controls completed
3/27	• Drivetrain and test stand completed

6.4 Assembly Procedure

The overall assembly order is 1) static portion of structures, 2) fixturing, 3) moving portion of structures, 4) drivetrain, 5) handles, and 6) pneumatics. The PF6000 mount is not attached to the main assembly and can be assembled at any step. All part numbers are referenced from the bill of materials from the corresponding assembly drawing unless otherwise noted.

All assembly drawings were laid out in a manner such that further assembly instruction would not be needed. However, in order to be a thorough as possible further assembly instructions were added to ensure that there would be no confusion in the assembly of this product. This was done because the senior project team will not necessarily be available to assist in the assembly of this project.

6.4.1 Static portion of structures

(See Figure 6-2)

1. Assemble 8020 structure (9 and 10) from bottom up with t-nuts (13) and 5/16-18 screws and fasten it to the machine baseplate.
2. Attach eyebolts (20) to uppermost 8020 member with nylock nuts (17).
3. Secure the machine baseplate (2 in Figure 6-1) to the table with large c-clamps.

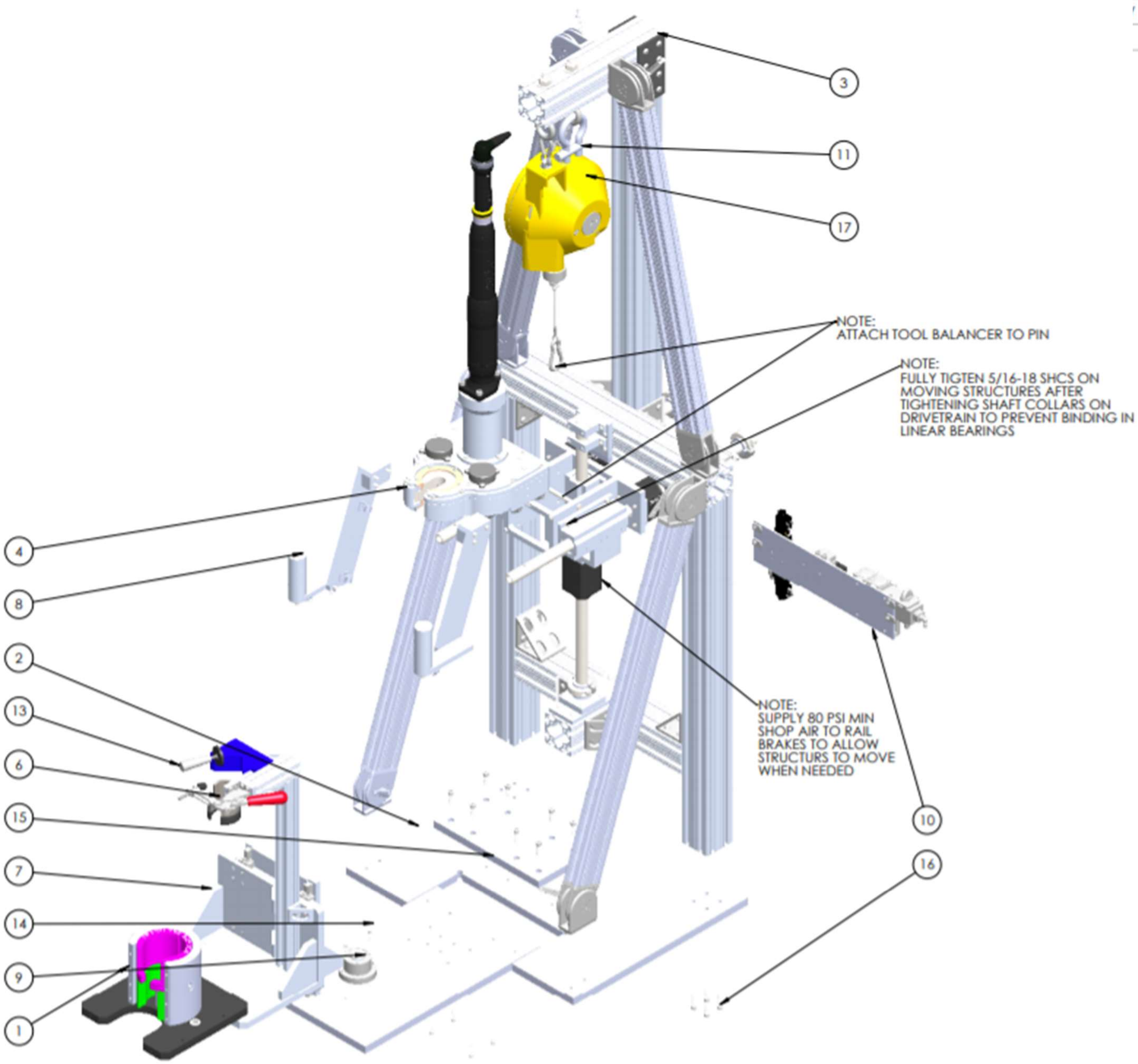

Figure 6-1. Full Assembly

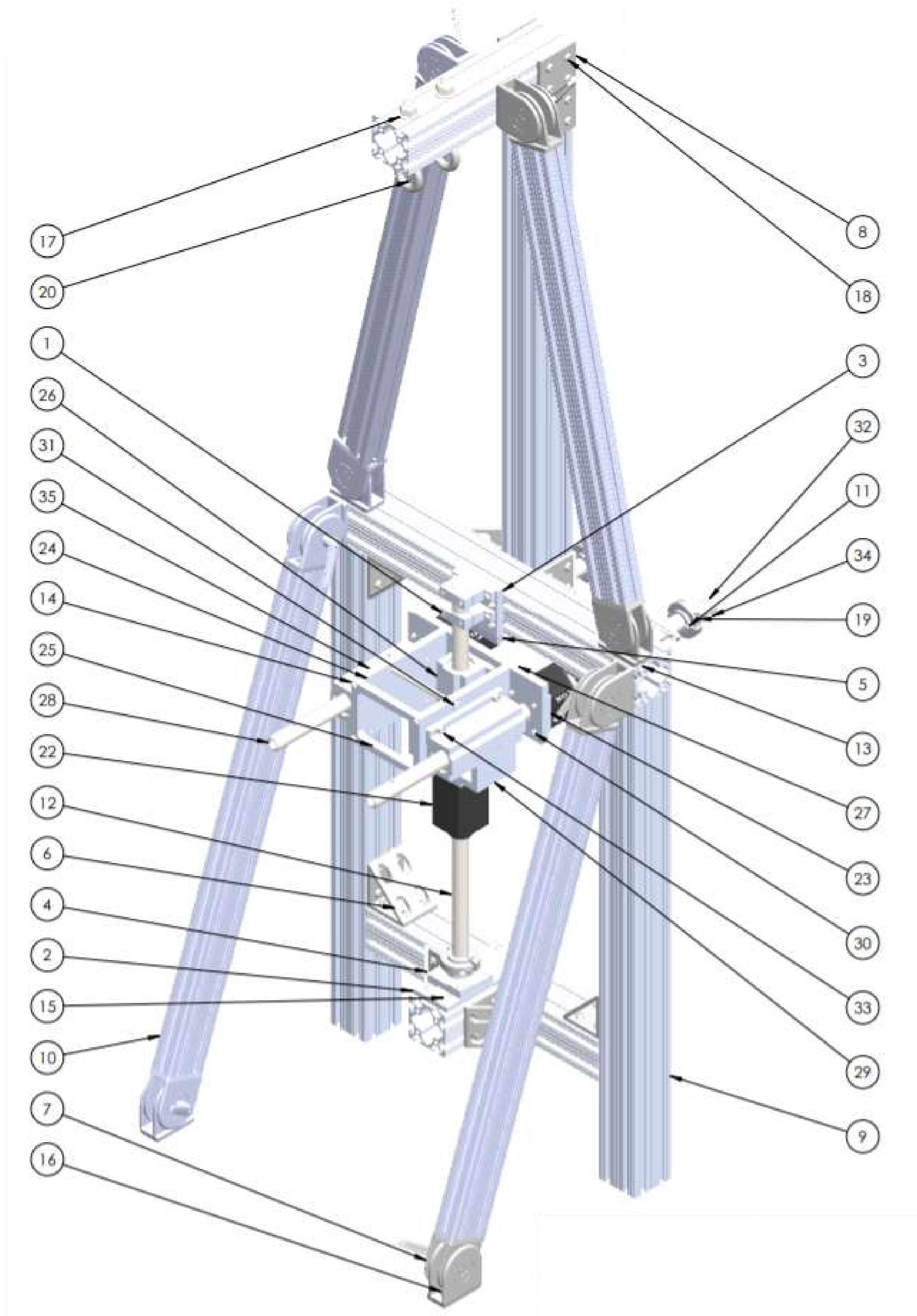

Figure 6-2. Structures Assembly

6.4.2 Fixturing

(See Figure 6-3 and Figure 6-4)

1. Attach pallet base plate (14 in Bearing Run Down And Torque Machine) and pallet connector plate (15 in Bearing Run Down And Torque Machine) to the machine baseplate (2 in Bearing Run Down And Torque Machine).
2. Push linear rails (1) against the steps in the rail backing plate (5).
3. Inset and tighten screws (19) into the linear rails (1).
4. Mount gusset plates (6), carriage plate (3), and 8020 vertical (7) and horizontal (8).
5. Mount toggle clamp (10) and Delrin v-block (13).

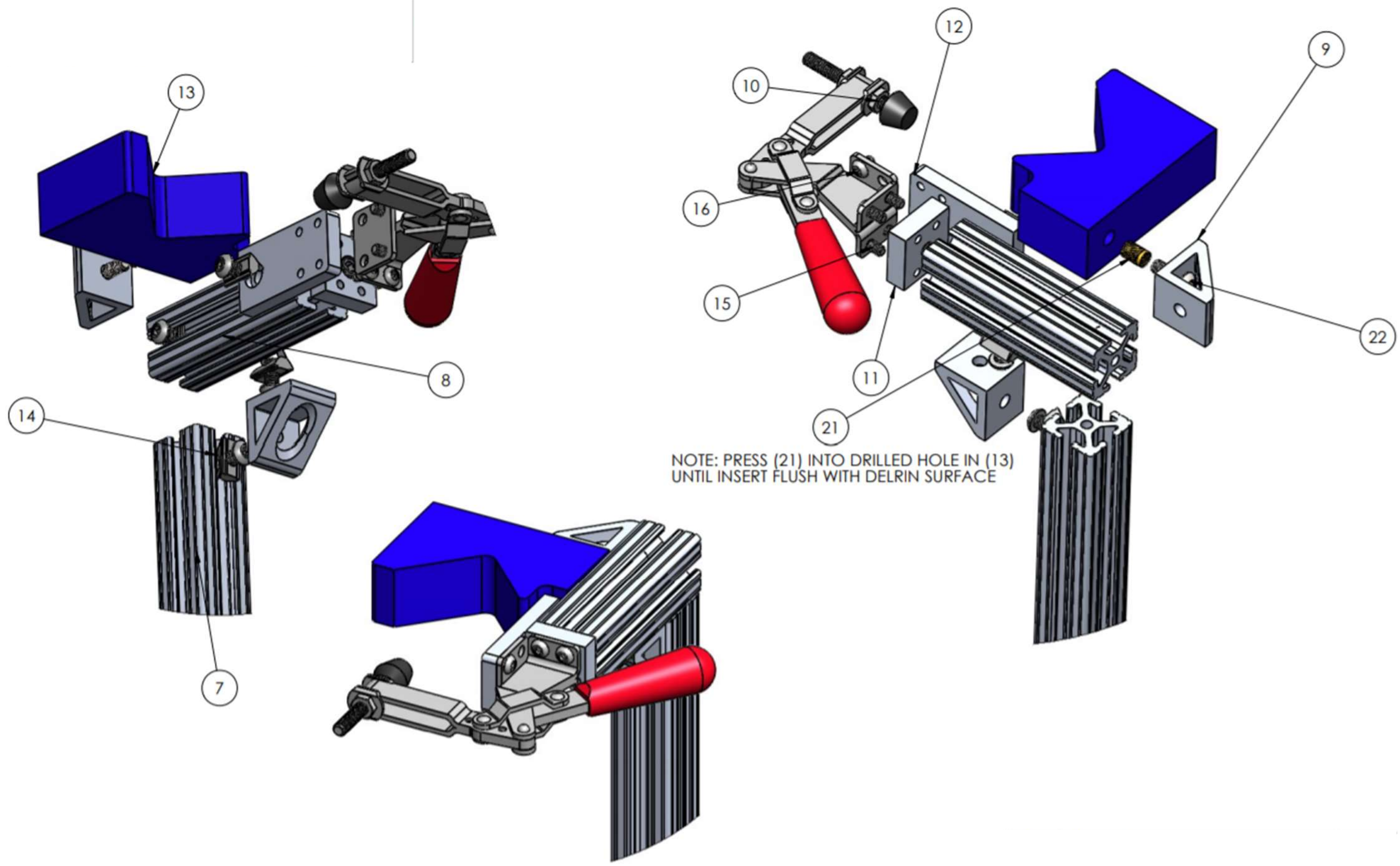

Figure 6-3. Upper Fixturing Assembly

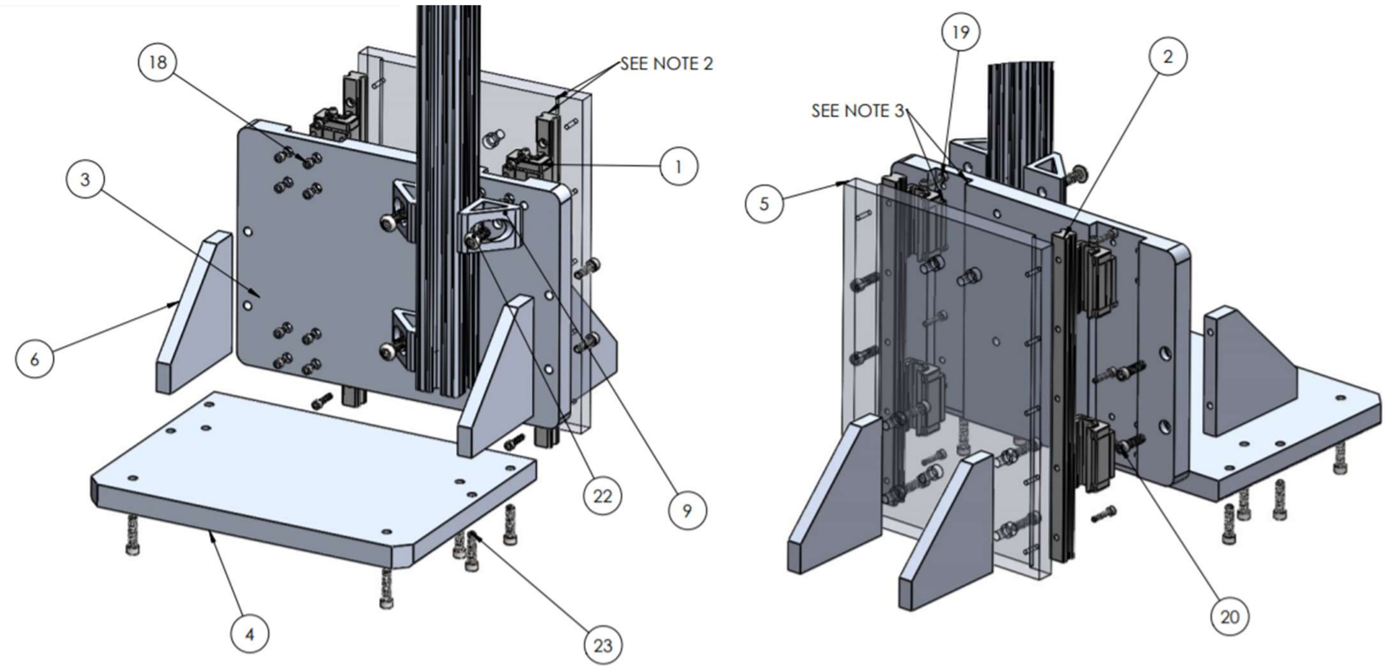

Figure 6-4. Lower Fixturing Assembly

6.4.3 Moving portion of structures

(see Figure 6-2 and Figure 6-5)

1. Fasten side (24) and back plate (27) together.
2. Fasten linear bearings (26) onto back (27) and side plates (24).
3. Slide linear bearings (26) onto shafts (12 and 28).
4. Attach front (25) and bottom plates (29).
5. Fasten rodlock mount (23) to bottom (29) and back plates (27).
6. Apply 80 psi minimum to rail brakes (22) to disengage clamping.
7. Mount rail brakes (22) to rodlock mounts (23).
8. Attach base mount shaft supports (1) and head plate (3) to top of the vertical shaft (12).
9. Attach flange mount shaft support (4) and foot plate (2) to bottom of vertical shaft (12).
10. Mount the assembly onto the 8020 section of the structures assembly (9).
11. Attach the retaining clevis pins (31 and 32), cotter pins (34 and 35), and Delrin wear pads (5 and 11).
12. Support the structures carriage so it is as high up as possible.
13. Mount and secure the Atlas Copco tool balancer (17 in Bearing Run Down And Torque Machine) to the structures assembly.
14. Attach the tool balancer cable onto the clevis on the moving portion of structures.

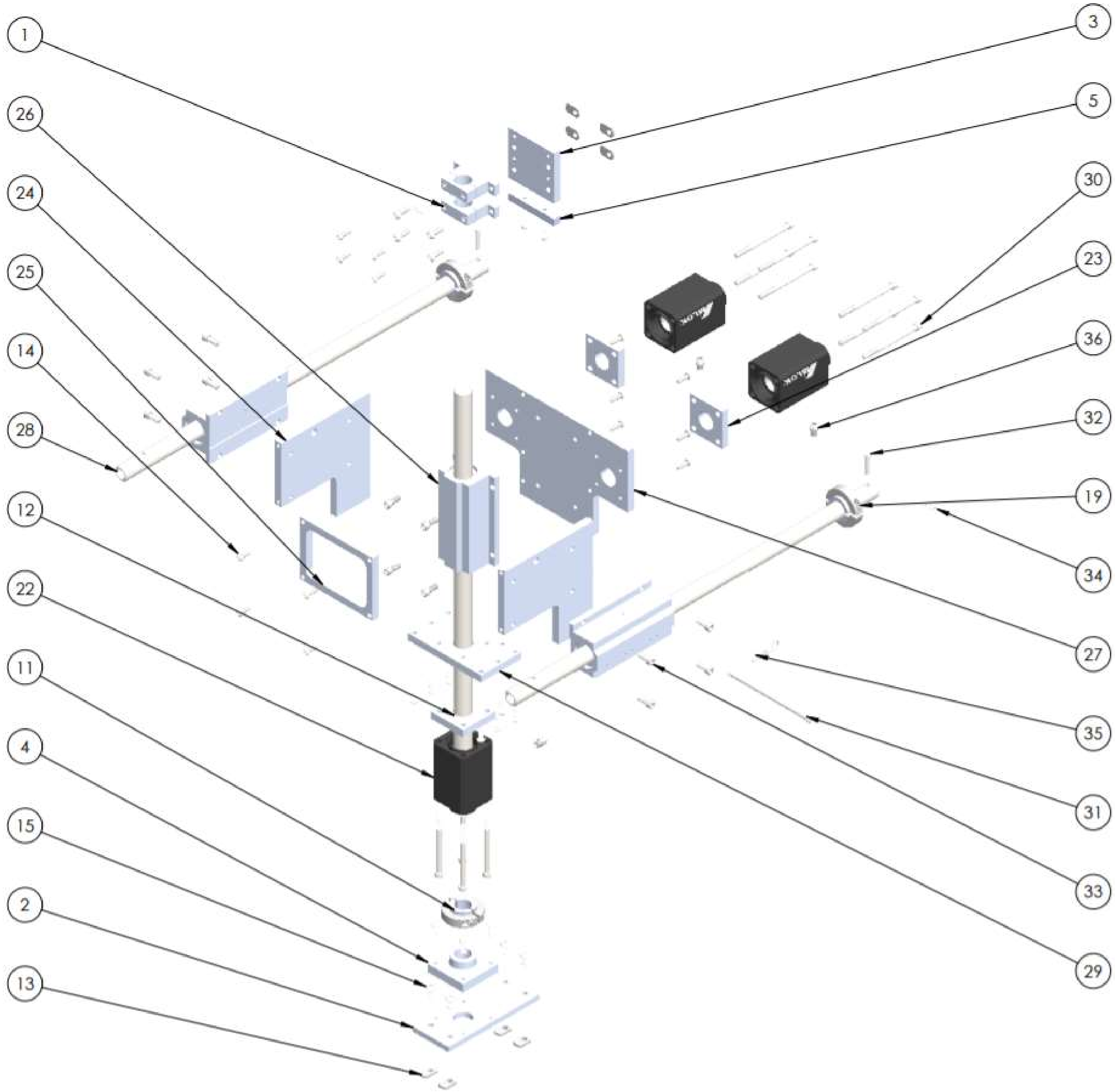

Figure 6-5. Moving Structure Exploded View

6.4.4 Drivetrain

(see Figure 6-6 Figure 6-7 Figure 6-8)

1. Insert key (6 in Figure 6-7 and 4 in Figure 6-8) into both idler shafts (1 in Figure 6-7) and the driven shaft (1 in Figure 6-8).
2. Slide idler gears (5 in Figure 6-7) onto idler shafts (1 in Figure 6-7) and the driven gear (5 in Figure 6-8) onto the driven shaft.
3. Install snap rings (2 in Figure 6-7 and Figure 6-8) on both sides of idler (5 in Figure 6-7) and driven gears (5 in Figure 6-8).
4. Secure the grade 9 bolt (15) into the driven shaft (1 in Figure 6-8) with 100 ft*lbf of torque and red Loctite.
5. Fasten the c-shaped bearings (5 in Figure 6-6) into their respective case halves (4 and 5 in Figure 6-6).
6. Place each gear-shaft assembly, threaded end down, into their respective hole in the bottom-case half (4 in Figure 6-6).
7. Slip the tapered roller bearing (3 in Figure 6-7 and 6 in Figure 6-8) inner race onto the threaded end of each shaft.
8. Place the c-shaped gear (1 in Figure 6-6) into the c-shaped bearing (5 in Figure 6-6) in the bottom-case half (4 in Figure 6-6).
9. Place and fasten the top-case half (6 in Figure 6-6) to the bottom-case half (4 in Figure 6-6).
10. Install bearing locknuts (4 in Figure 6-7 and 7 in Figure 6-8) on all three shafts and tighten.
11. Install the snap ring (2 in Figure 6-7 and Figure 6-8) onto the top of each shaft.
12. Install Delrin shaft caps (7 in Figure 6-6) into the top and bottom-case halves.
13. Install the torque driver mount (8) onto top-case half (6 in Figure 6-6).
14. Place the drivetrain assembly onto the horizontal shaft in the moving portion of structures.
15. Secure the drivetrain with shaft collars (17), clevis (13), and cotter pins (19).
16. Attach the ¾ drive ¾ inch socket (16) onto the Atlas Copco torque driver.
17. Install the torque driver into the torque driver mount (8) with the socket fully engaged on the grade 9 bolt (15).

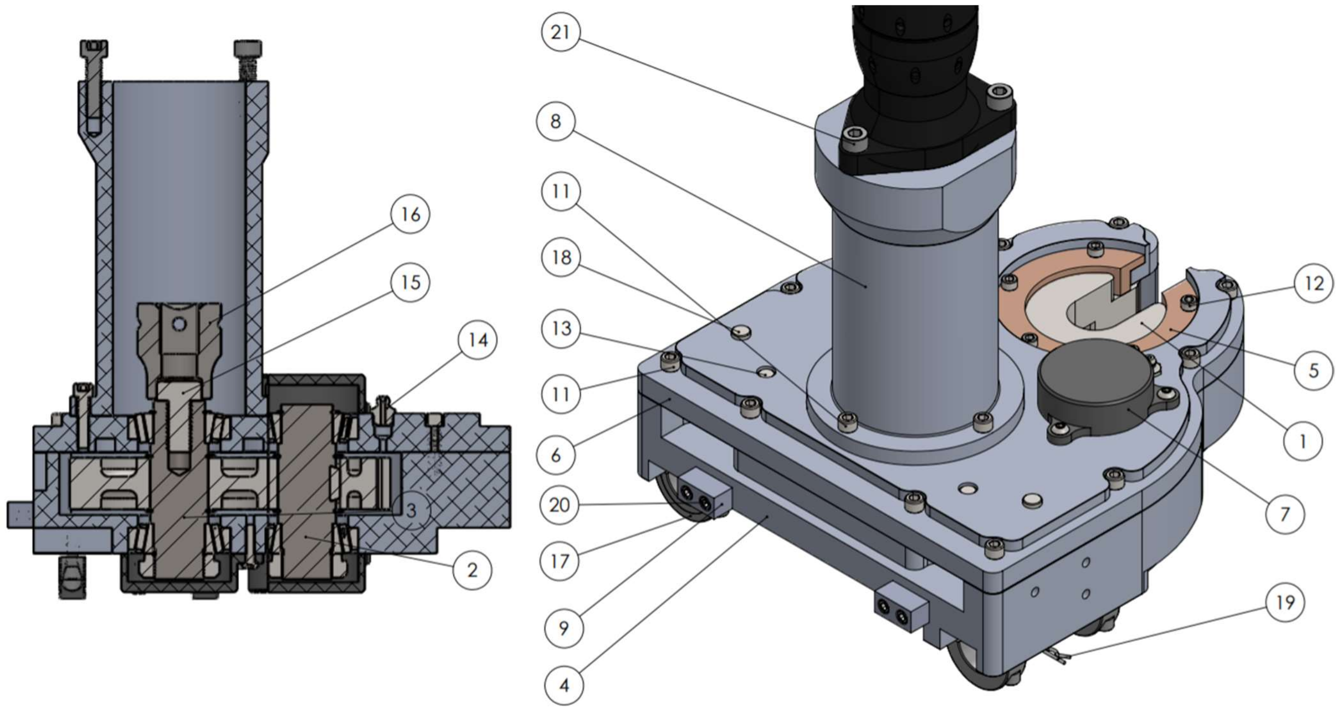

Figure 6-6. Drivetrain Overall Assembly

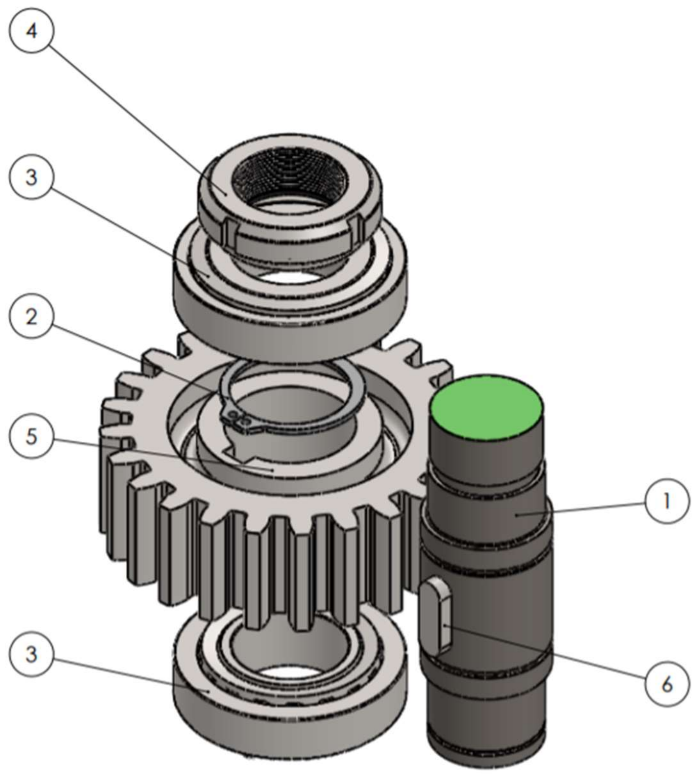

Figure 6-7. Idler Shaft

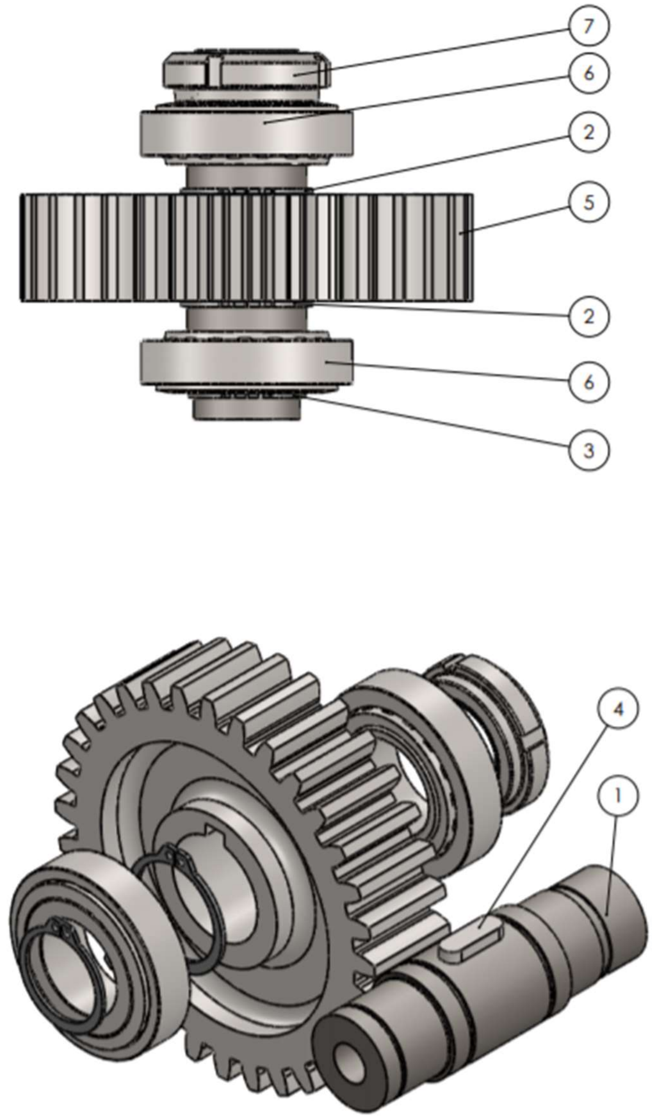

Figure 6-8. Driven Shaft

Each subassembly is shown below. The completed idler shaft and driven shaft assemblies are shown in Figure 6-11 and Figure 6-12 respectively. The top and bottom case halves are shown in Figure 6-9 and Figure 6-10 respectively. An exploded view of the assemblies with the assembly order is shown in Figure 6-13.

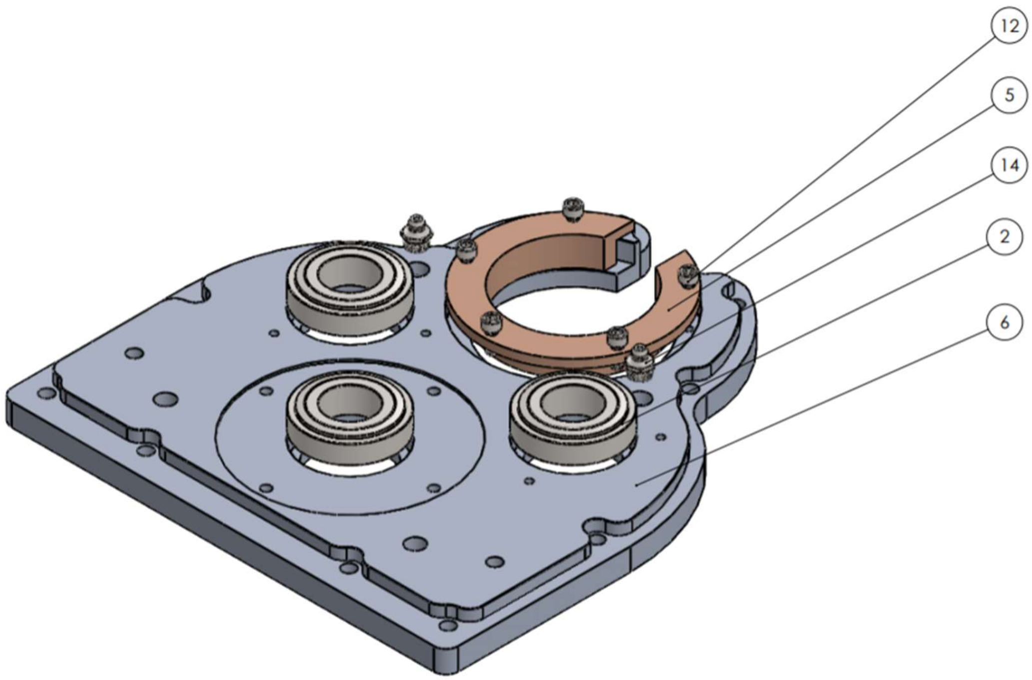

Figure 6-9. Top Case Half Assembly

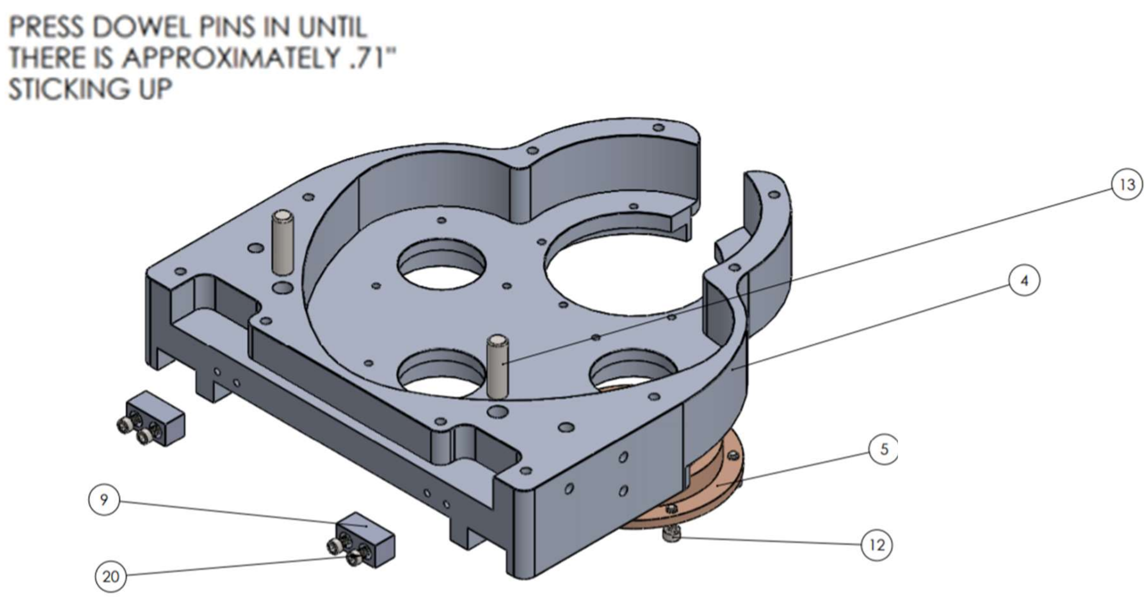

Figure 6-10. Bottom Case Half Assembly

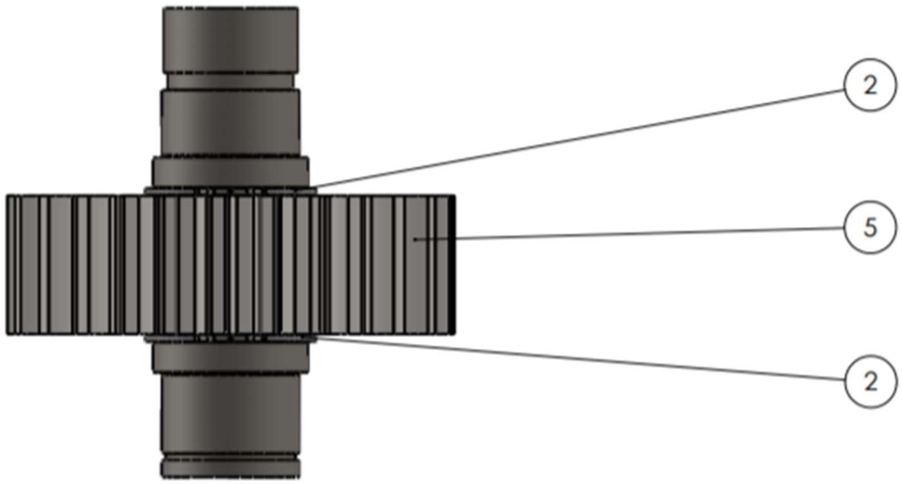

Figure 6-11. Idler Shaft Assembly

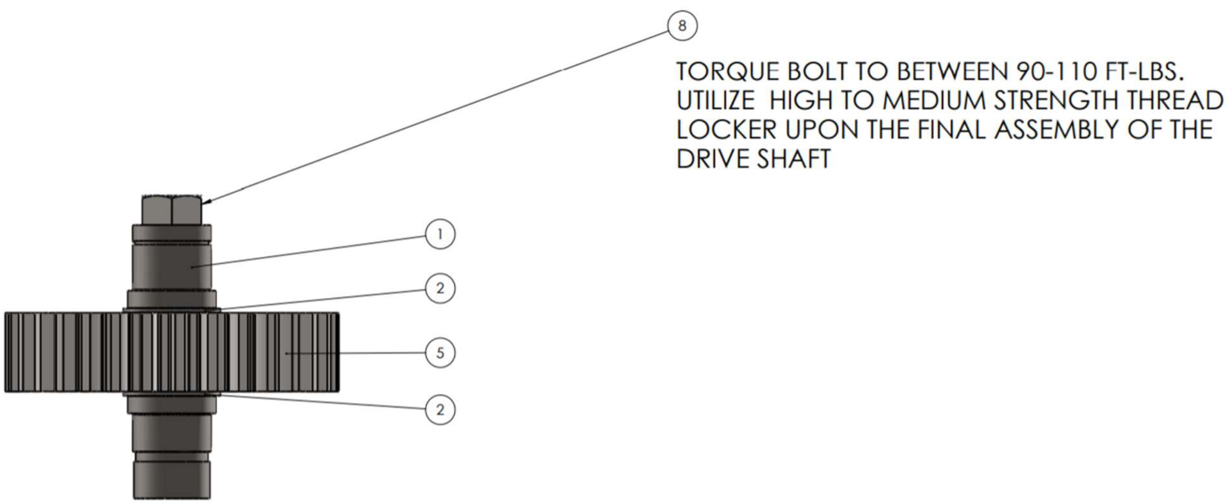

Figure 6-12. Driven Shaft Assembly

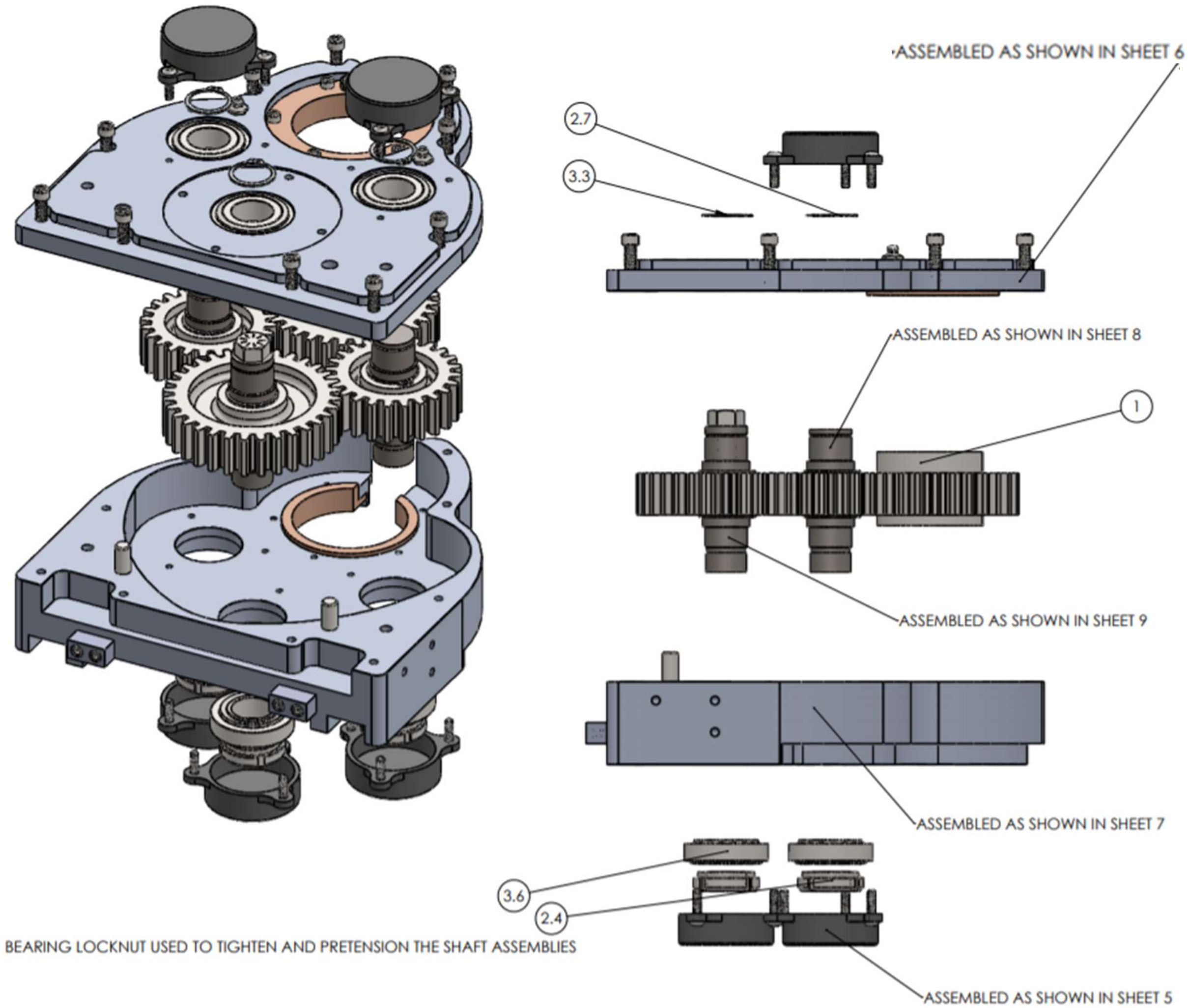

Figure 6-13. Full Drivetrain Assembly Order

6.4.5 Handles

(see Figure 6-14)

1. Fasten handle connector plates (7) to the main beams (2).
2. Fasten the handle mounts (3), handles (4), and buttons (5 and 6) into the main beams.
3. Fasten each handle into the drivetrain.

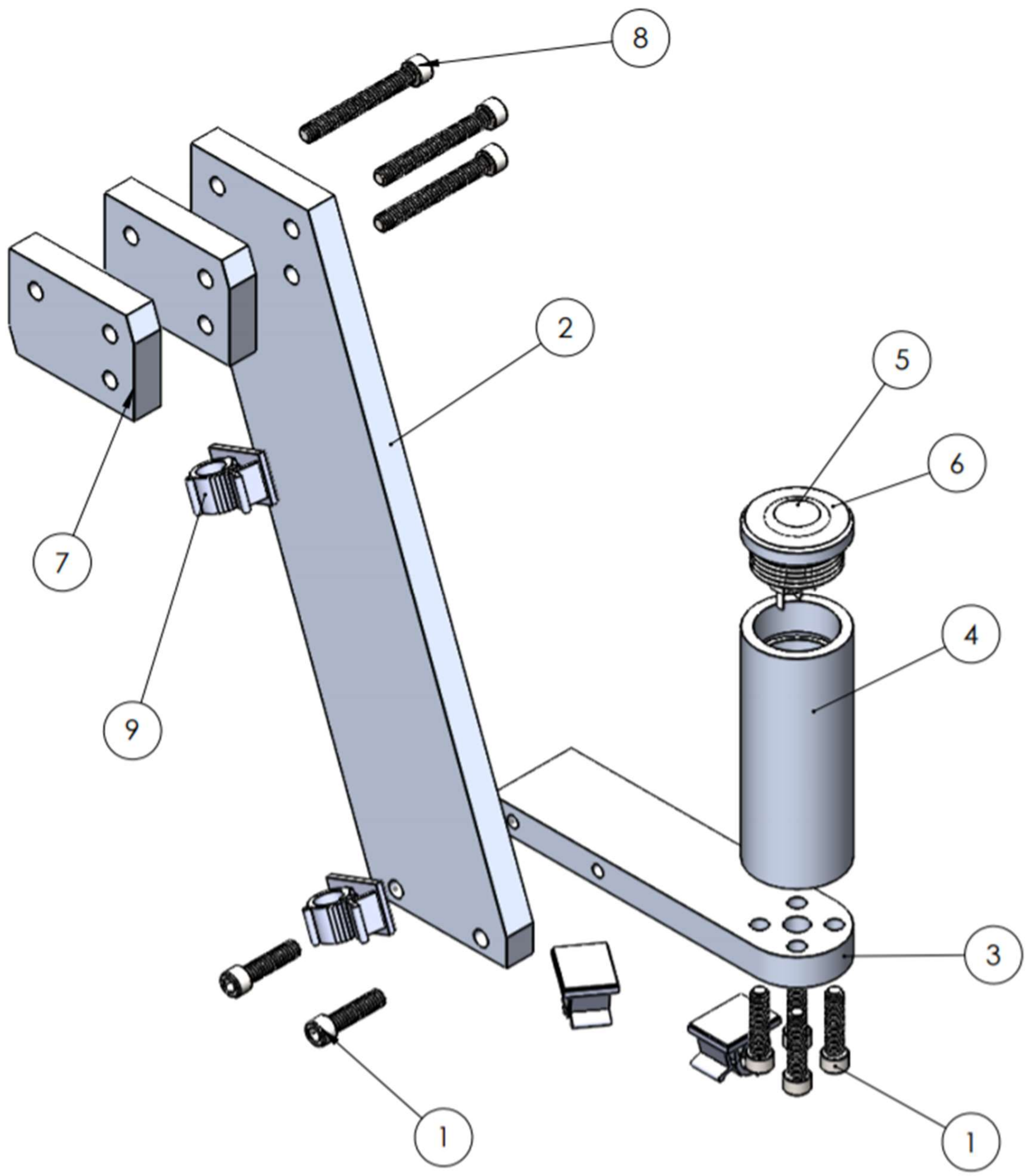

Figure 6-14. Handle Assembly Exploded View

6.4.6 Pneumatics

(see Figure 6-15)

1. Refer to Figure 5-52 for system layout.
2. Attach push to connect fittings (13) to the back of the pressure regulators (7).
3. Thread the pressure gauges (11) into the front ports on the pressure regulators (7) using the adapter (12).
4. Assemble lockout valve (10), air filter (9) and regulators (7) together with joining clamps (8) and end blocks (6).
5. Assemble manifold using manifold block (1), silencer (5), push fitting (16), plugs (4), and 3/2 valves (2) with mounting hardware (18).
6. Add push fittings (16) and flow regulating silencers (22) to 5/3 valve (21).
7. Fasten air treatment assembly, manifold, and 5/3 valve to backing plate (15).
8. Install check valves between output of regulators and inputs to the manifold and 5/3 valve using ¼ tubing.
9. Attach completed assembly to rear of structures.

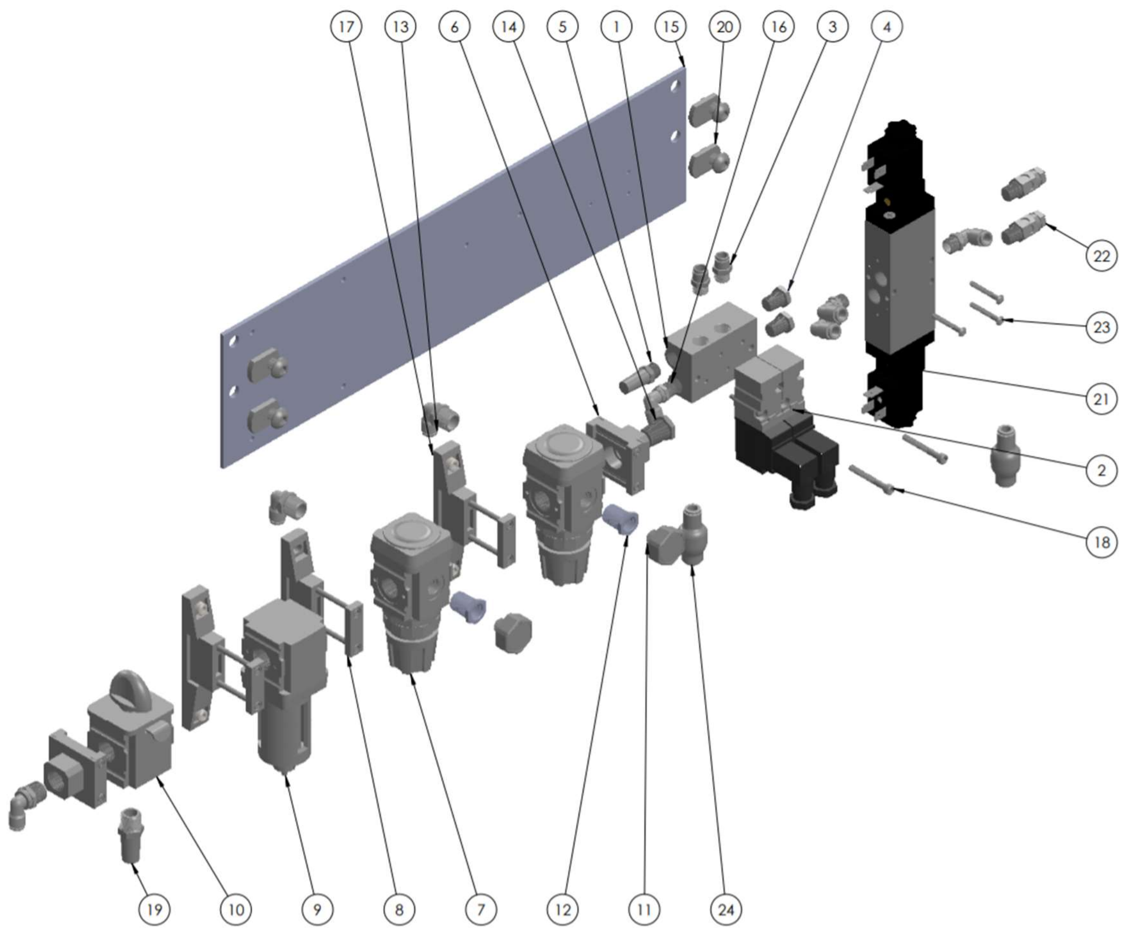

Figure 6-15. Pneumatics Assembly Exploded View

7 Design Verification Plan

In order to develop a trustworthy design that met all the specifications detailed out in Table 3-2, a testing and verification plan was created. The design verification plan (DVP) lays out the planned tests that will be done to ensure the integrity of the design.

Due to the timeline of the project all tests were planned to be carried out in the assembly and final prototype stages of the build. Testing prior to these stages was done conceptually and through Finite Element Analysis. This leaves little time for change and redesign of the assembly tool and creates a time risk in the case that a part needs redesign and potential remanufacture. To minimize this risk, analysis and FEA were done, and large factors of safety were placed on components of concern.

The tests that will be implemented will be done to make sure that the engineering specifications will be met and to determine necessary maintenance intervals and procedures for the automated assembly tool. The design verification plan can be found in Appendix K. There is at least one test per specification detailed out. The more critical specifications require multiple tests to ensure that the specification is met. The following will detail out the specifications and the tests associated.

Due to COVID-19 these tests will no longer be carried out by the senior project team. Fox will be responsible for testing and final development of the project. The following tests are still highly recommended in order to get the machined perfectly tuned to be the most effective and ensure safety.

Fox is currently in the manufacturing process of the drivetrain and support components to test the concept. Fox has their own testing methods and will be developing their own test stand for the drivetrain. This test stand will be able to test a number of these specifications. Without fully developing the system the hardest specifications to full test would be: Failure modes, ease of maintenance, and line associate fatigue. Figure 7-1 below shows a preliminary concept put together by Fox for a drivetrain test stand.

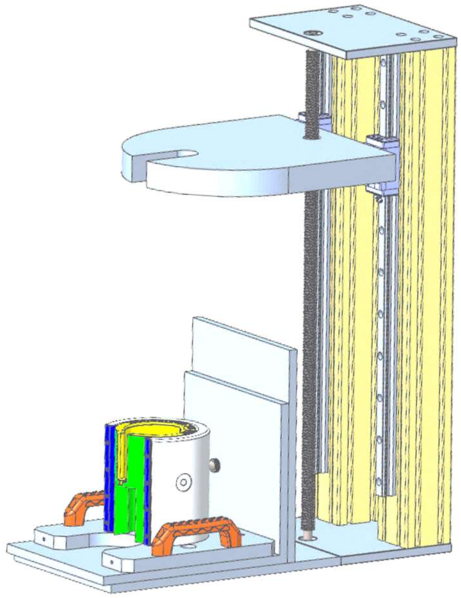

Figure 7-1. Preliminary Drivetrain test stand design

7.1 Specification 1: Torque Repeatability

The first specification is the torque repeatability of the system. It is important that the system will consistently report the same torque every time in order to maintain quality and consistency is shock assembly. Two tests will be implemented to ensure torque repeatability and accuracy

Pass Criteria: The torque is repeatable and accurate to within ±2%.

Test 1: Measure the repeatability of the Drivetrain system. This will require the full systems functionality to torque the bearing down. Compare this torque to that of the original manual operation to ensure that the torque was hit. After torque has been hit, measure the torque required to remove the bearing. Repeat this process a minimum of 20 times to ensure that the torque is repeatable.

There will be no special equipment required for this experiment. It will require the full system assembled and operational and have the manual operation accessible to be compared to.

7.2 Specification 3: Safety

Safety is paramount in a factory setting. A line associate will use this automated assembly process for potentially 8 hours at a time, and the machine itself can potentially be in use 24 hours at a time. Potential for injury not only puts the assembly time at risk, but more importantly puts valued Fox associated at risk. For this reason, potential risks and hazards must be minimized.

Test 2: Test the fixturing system to make sure the shock cannot be easily ejected from the fixture. Apply a 100lbf load to the shock shaft in various directions, with the most important direction being towards the operator.

7.3 Specification 4: Cycle Time

While ergonomics is much more important in the design of this system it is also important that this automated assembly step does not become a bottle neck.

Test 3: Measure the time it takes to complete the original process at a rate that an associate can maintain for 1 hour. Measure the time it takes to complete the automated process at a rate than an associate can maintain for 1 hour. Compare the two times. The automated process should take no longer than 1.5X the original process.

Pass Criteria: No longer than 1.5X the original process.

There is no special equipment needed for this process; only access to the complete automated assembly and the original manual assembly process is necessary.

7.4 Specification 5: Setup Time

Like the cycle time, it is important to keep setup time similar to the original to prevent from bottlenecking the assembly of the shock.

Test 4: Measure the time it takes to complete the setup of the original process 10 times and average those times. Measure the time it takes to complete the automated process 10 times and average those times. Compare the two times. The automated process should take no longer to setup than 1.5X the original process.

Pass Criteria: No longer than 1.5X the original setup time.

Again, there is no special equipment required for testing. It is only required that one has access to the full assembly of the automated process as well as that of the manual process.

7.5 Specification 10: Time before maintenance/failure

It is important to maximize the time before required maintenance or potential failure of the machine. Machine maintenance is downtime where the machine cannot be making money and for that reason the maintenance intervals should be as spread out as possible without causing harm to the machine.

Test 5: Test the drivetrain sub assembly in order to get an idea of how often it will need to be cleaned and or greased. Assemble the drivetrain sub assembly with grease in the correct places. Run the subassembly and take note of the grease being pushed out of the assembly. Take note of the torque measured from the Atlas Copco torque driver analyze as torque to drive the subassembly goes up. Schedule greasing intervals as a result of this test.

Pass Criteria: Time before major maintenance should be no shorter than 3 months

7.6 Specification 11: Failure Modes

It is important to minimize the common failure modes of a system in order to make maintenance and diagnosis of a system quick and easy. In order to do this the team used finite element analysis to build certain components with more common wear and failure points than other components.

This was also done to only have to replace the cheaper or two components that would wear against each other.

Test 6: Utilize design and analysis tools to make sure components that are working together only wear down one part specifically. Analyze the C-shaped bearing to ensure wear is as calculated to minimize issues in production. Design for two main failure modes.

Pass Criteria: There should be no more than two major failure modes in the final assembly.

It should be noted that over long amounts of time all components are susceptible to failure. In which case those components will need replacement. The designed failure modes are the ones that the team wants to fail more often than others.

7.7 Specification 12: Ease of maintenance

Like the failure modes specification ease of maintenance is important because the more time that the machine is down for maintenance, the more likely the machine is bottlenecking the production line. In order to prevent this machine from holding up maintenance the team wanted to ensure it would be quick easy to maintain.

Test 7: After determining the main failure modes and common wear components from Specification 11. Measure the time it takes to replace the major component in the system

Pass Criteria: Replacement of any major component should take no longer than 2 hours.

Test 8: Assemble and disassemble each major subassembly. Measure the time it takes to fully assembly and disassemble each major subassembly.

Pass Criteria: Assembly for each major subassembly should take an average of no longer than 2 hours. Disassembly of each major subassembly should take an average of no longer than 2 hours

7.8 Specification 13: Line associate fatigue

The final specification is line associate intervention. In order to meet the ergonomic requirement of the design it is desired that the design not only be comfortable to the user, but also ask for as little operator effort as possible in order to prevent operator fatigue which was very common with the manual process.

Test 9: Test. Utilize an array of different operators. Allow each person to operate the machine for between 20 to 30 minutes taking note of any places of fatigue or strain. Utilize this knowledge to increase comfort and use of the machine.

This test requires the full assembly and at minimum 4 different operators.

8 Project Management

Should no major project concerns remain from Will and Tom, the team will hand off full responsibility of the project and completion of the machine. All provided physical materials will be returned to the factory at a convenient time after completion of the senior design project, and all digital files will be turned over to Fox for future reference or update. A final design & project hand-off meeting occurred at the end of the final week of regular instruction in Cal Poly's spring quarter of 2020. This meeting provided an opportunity to work out the details of handing off materials and responsibilities, as well as providing a final update on the state of the control system programming. A schedule of milestones for the remainder of the project is shown below in Table 8-1, which includes the final design review & project hand-off date (via Webex) on Friday, June 5th. This table also tracks the unforeseen deliverable dates resulting from the project scope & timeline change due to COVID-19. A more detailed Gantt chart schedule showing the project progress since the previous design report can be found in Appendix C.

Table 8-1. Project Milestones and Key Deliverables

Date	Deliverable / Milestone
11/8/2019	Initial problem statement submitted to Fox
1/22/2020	PDR (Preliminary Design Review) presented to Fox
1/21/2020	FMEA (Failure Modes and Effects Analysis) of initial design
1/30/2020	Safety Review
2/6/2020	DFMA Review
2/13/2020	Interim Design Review
2/25/2020	Detail CAD completed
2/27/2020	Manufacturing plan
3/9/2020	CDR (Critical Design Review) report delivered to Fox
3/10/2020	CDR slides presented to Fox
4/13/2020	Mechanical redesign review with Fox
4/20/2020	REV-1 Drawing packet submitted to Fox for quoting process
4/25/2020	Updated BOM with prices per machine subsystem sent to Fox for cost approval from management
4/26/2020	Control system design review with Fox
5/29/2020	Virtual Cal Poly senior project expo (website)

Date	Deliverable / Milestone
6/5/2020	Project hand-off meeting with Fox
6/8/2020	Final Design Report & CAD directory sent to Fox
6/17/2020	Control system components delivered to Fox

Blue – Major events completed on track for original project timeline

Red – Major events completed during project scope change & timeline shift

Black – Events to be completed after submittal of final design report

Once the machine is fully assembled, the Fox manufacturing engineering department will need to complete the remaining project details:

- Sorting out open-protocol communication between the PF6000 & the PLC
- Programming task #3 / the home-return function for the torque driver once Fox has acquired the new version of ToolsTalk
- Potentially adding a coupling between the cylinder and the sliding carriage to prevent the body cap pallet from lifting then slamming down on the cylinder as the shock is removed (if this is found to be an issue during production)
- Add polycarbonate safety guard and add safety decals at pinch hazards

9 Conclusion

When assembling a Fox Factory shock, a linear bearing must be threaded into the shock body. This process is both an ergonomic strain on the line associate and requires multiple components to complete. One of the problems with the tightening process is that the shock shaft protrudes so high that the only option to interface with the bearing housing is to use a spanner tool and rotate the tool around the shock shaft. One of the requirements is that the solution must be safe and efficient, so that the factory does not fall behind on their goal of "getting shocks out the door". After considerable research and brainstorming, a unique and effective solution was reached. The chosen design takes inspiration from the spanner tool and combines it with a spur gear. A compact drivetrain connects this output gear with the driven gear that is to be driven by an Atlas Copco torque driver. To easily interface with the bearing housing and to avoid witness marks, an adapter tool is used to transmit the torque from the output gear of the drive train into the bearing. This adapter tool has pins which engage with the bearing and a hex protrusion that fits into a hex recess in the drivetrain system. Equally important are the supporting subsystems that make up the rest of the solution. Due to an O-ring on the bearing housing, a downward force must be applied to bring the bearing deep enough into the shock shaft to engage with the screw threads. This downward force will be supplied through a pneumatic system that will be located under the shock, connecting with the body cap pallet. The other important systems are the structures and controls system. The structure will consist of linear bearings that will allow the drivetrain assembly to move and easily engage with the shock. A tool balancer will be connected to the system allowing the line associate to easily move the machine about without having to carry the vertical weight of the drivetrain and connected torque driver. Also aiding in drivetrain movement are two handles. The handles are attached to the drivetrain and have two buttons, one on the end of each. The buttons allow the machine to received input from the operator and is how the machine moves between states. Finally, the control system will consist of a PLC, controller, and HMI. The PLC will control the peripheral devices, the Atlas Copco Controller that will control the torque driver and will allow data to be collected directly from the torque driver, and the HMI will allow the operator to view information about the current operation and troubleshoot the machine.

Due to the recent shutdown of the Cal Poly Camus, and subsequently the Mustang '60 and Aero Hangar machine shops, the team moved away from manufacturing and assembling a completed machine. Instead all the CAD files and necessary technical drawings will be presented to the sponsor at the conclusion of this project.

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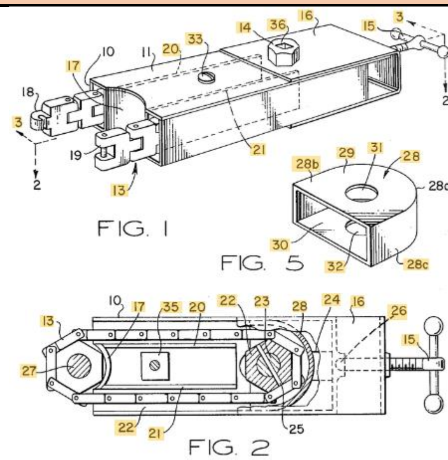
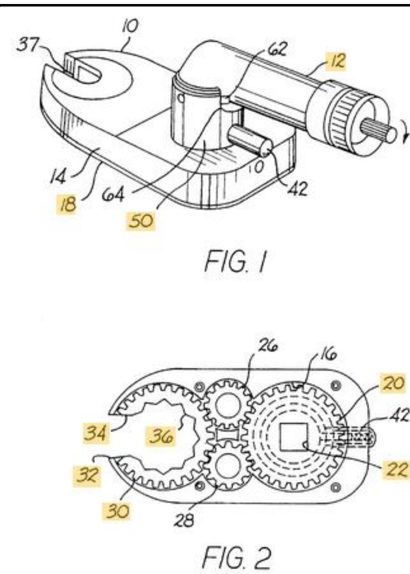
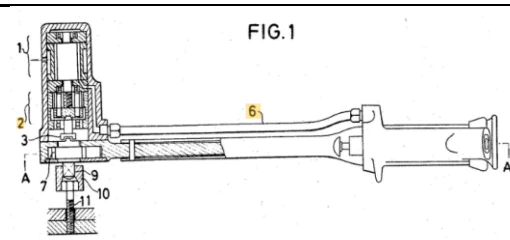
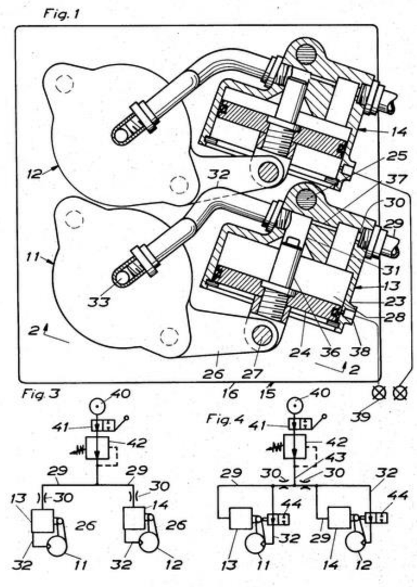
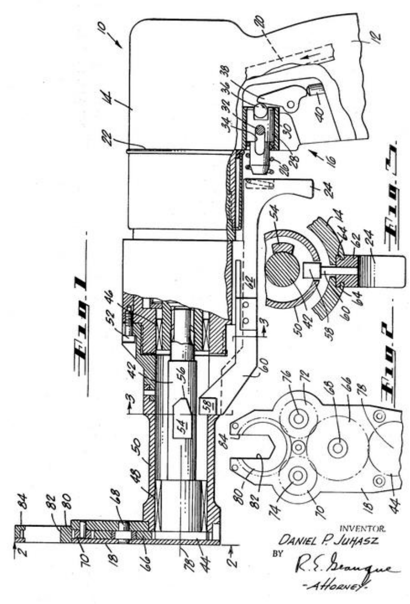
[25] Monogram Ind Inc, "Offset wrench apparatus". United States Patent US3602071A, 24 February 1970.

Appendix A. Patent Search Findings:

Patent Number	Title	Description	Drawing
US3913428A [23]	"Off-set nut runner with open-end access and socket-like drive capability"	A drive mechanism consisting of short lengths of belt arranged in a chain where the chain is closed around the nut to be driven.	
US5544553A [13]	"Off-set geared nutrunner attachment"	An open-ended, off-set geared nut runner with a non-threaded drive coupling, in which the drive gear is driven by a rotating stud, the driven gear is open-ended to align with the housing opening for shaft removal, and there are idler gears between.	
US3733935A [24]	"Torque wrench with a nut runner"	A combination manual torque wrench and powered, low-torque ratchet drive nut runner to seat the screw before manually being torqued to spec.	

Patent Number	Title	Description	Drawing
US3812744A [19]	"Torque control device for a nut runner of the continuous torque type"	A frame mounted multiple nut runner in which several coaxial nut runners are rotatably mounted. Each nut runner's pneumatic motor is shut off from the master cylinder by a control valve when desired torque is reached.	
US3602071A [25]	"Offset wrench apparatus"	A driveshaft assembly driven by pneumatic motor in which the shaft rotates an open gear assembly similar to the above mentioned "off-set geared nutrunner attachment" (cites US5544553A).	

Appendix B. QFD House of Quality

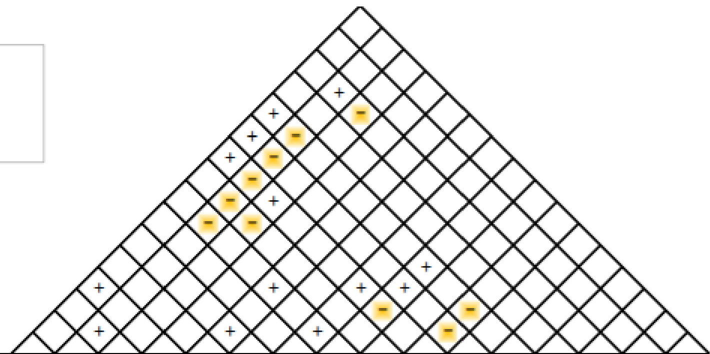
Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: Bearing Torque Automation
Revision Date: 11/30/19



Row #	Weight Chart	Relative Weight	Will (Mfg Engineer)/Tech Tear	Dan (Process Engineering)	Machine Operators		Maximum Relationship	Column # / Direction of Improvement / WHAT: Customer Requirements (Needs/Wants) — HOW: Engineering Specifications (Tests)	1 Torque Repeatability Measusre	2 Foot Print L*W*H	3 Safety	4 User Feedback	5 Scalability	6 DFMA Rules	7 Machine Quotes	8 80% Standard components	9 Operator Intervention Time	10 Cost	11 Setup Time	12 Cycle Time	13 Visual Inspection	14 Average time before failure/ (S	15 Failure Modes	16	NOW: Curr. Products — Our Current Product	Atlas Copco Torque Driver	Tool Balancer			Row #
								Direction of Improvement	◇	▼	▲	◇	◇	◇	▼	▲	▼	▼	▼	▼	◇	▼	▼							
1		11%	4	5	4		9	Torque Repeatability	●																5					1
2		6%	2	3	2		9	Short Cycle Time									○		●	●					2					2
3		12%	5	5	5		9	Safe for Operator			●	○					○								3					3
4		11%	5	5	4		9	Ergonomic			○	●					○								2					4
5		9%	5	3	3		9	Scalability					●			●		○							2					5
6		6%	3	2	2		9	Manufacturability					○	●	○	○		○							5					6
7		8%	3	2	5		9	Foot Print		●															3					7
8		7%	5	1	3		9	80/20 Rule.								●									5					8
9		3%	2	2	0		9	Cost							○	○		●							4					9
10		6%	3	3	2		9	No Witness Marks													●				3					10
11		12%	5	5	5		9	Reliability	●				○			○									4					11
12		9%	5	5	2		9	Maintainability								●						○	●		4					12
13		0%																												13
14		0%																												14
15		0%																												15

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
HOW MUCH: Target Values	Within 5%	1.5X Product	Complys With Standards	Ergonomic? Y/N?	Works with entire shock family	DFMA Rules	Minimize	80% Standard (FOX or Purchase)	Minimal	Less than $10,000	<1.5*Original	<1.5*Original	Yes	2 months	Minimize and Optimize the fix	
Max Relationship	9	9	9	9	9	9	3	9	3	9	9	9	9	3	9	
Technical Importance Rating	203.6	74.32	142.7	137.3	131.2	50	25.8	288.6	86.97	70.13	50.93	50.93	57.32	28.24	84.72	0
Relative Weight	14%	5%	10%	9%	9%	3%	2%	19%	6%	5%	3%	3%	4%	2%	6%	0%
Curr. Products: Current Product																
Atlas Copco Torque Driver																
Tool Balancer																
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Appendix C. Current Gantt Chart

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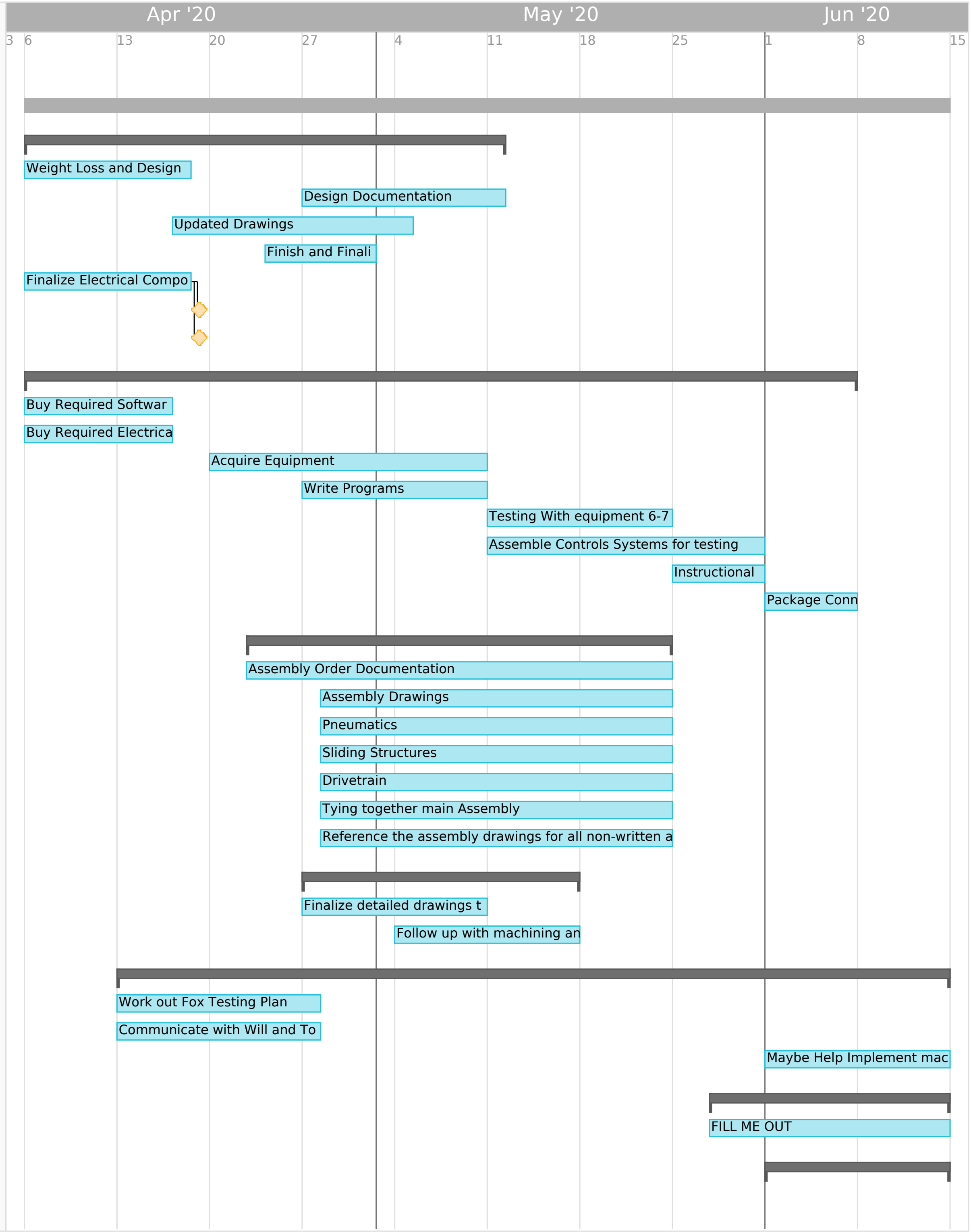
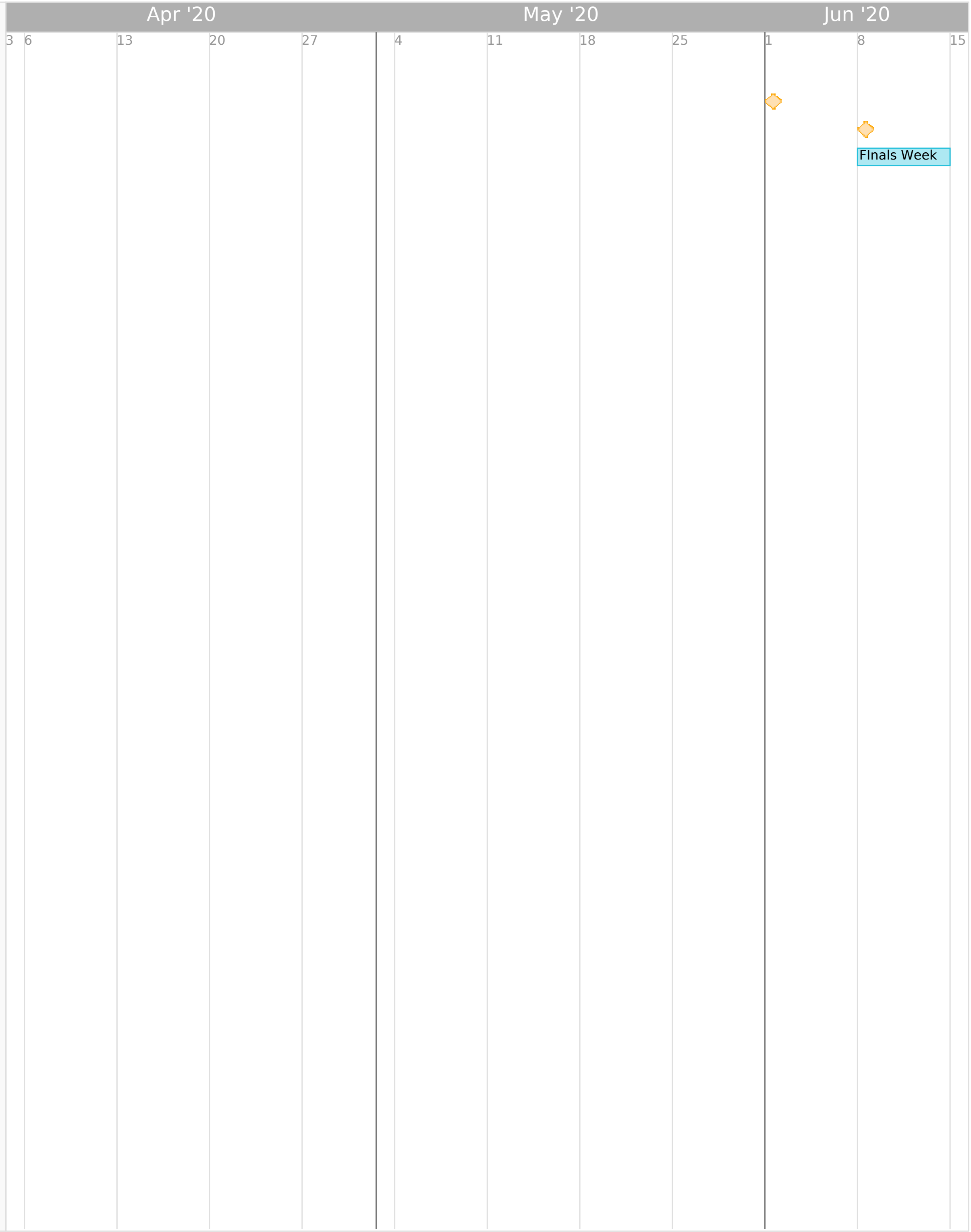
F23 - FOX Spring 2020	**0h**	**0%**
Drivetrain and Structures Redesign	**0h**	**0%**
Weight Loss and Design Updates	0	0%
Design Documentation	0	0%
Updated Drawings	0	0%
Finish and Finalize Drawings	0	0%
Finalize Electrical Component Structu...	0	0%
Communicate With Tom about Design...	0	0%
Communicate about ordering Controls...	0	0%
Finalize Controls Design and Docu...	**0h**	**0%**
Buy Required Software/Aquire	0	0%
Buy Required Electrical Comp	0	0%
Acquire Equipment	0	0%
Write Programs	0	0%
Testing With equipment 6-7	0	0%
Assemble Controls Systems for testing	0	0%
Instructional Documentation of progr...	0	0%
Package Connected Controls System ...	0	0%
Assembly Instructions	**0h**	**0%**
Assembly Order Documentation	0	0%
Assembly Drawings	0	0%
Pneumatics	0	0%
Sliding Structures	0	0%
Drivetrain	0	0%
Tying together main Assembly	0	0%
Reference the assembly drawings for ...	0	0%
Manufacturing Plan	**0h**	**0%**
Finalize detailed drawings to be sent ...	0	0%
Follow up with machining and Waterjet	0	0%
Testing Plan	**0h**	**0%**
Work out Fox Testing Plan	0	0%
Communicate with Will and Tom bout...	0	0%
Maybe Help Implement machine on t...	0	0%
Final Report and Website Presentat...	**0h**	**0%**
FILL ME OUT	0	0%
FINALS WEEK	**0h**	**0%**



Dead Week	0	0%
FInals Week	0	0%
FInals Week	0	0%



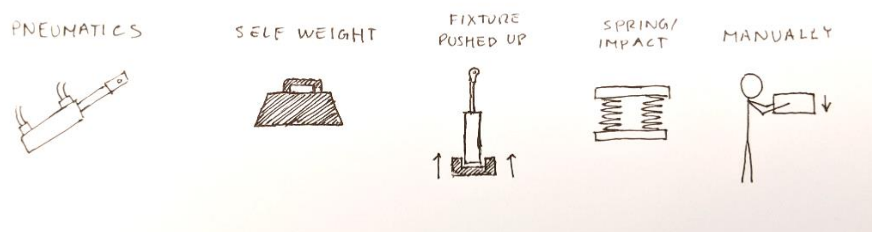
Appendix D. Functional Decomposition → Concept Ideation

Function	Description	Potential Solutions
Support Bodycap and Shock Weight	Support shock weight	• Bodycap pallets (existing) • Softjaws
Prevent Tipover and Shaft Bending	Fully constrain shock at top of body tube, take up pin bearing load	• Pneumatic clamps / softjaws on bodytube • U-shaped support w/ front latch • Magnetic latch
Initial Downward Force	Press tool and bearing housing downward while engaging initial thread	• Pneumatic cylinder • Utilize tool assm. weight • Lift fixture • Springs / Impact
Spin 10+ Revolutions (Drive Mechanism)	Thread bearing housing into body tube until fully seated	• Spur gears • Belt drive / pulley spanner • Chain drive / sprocket spanner
Torque Reliably to 50 ft*lb	Ensure torque spec. is met reliably and precisely	• Atlas-Copco / Ingersoll-Rand torque drivers • PLC cabinet integration
Hold Weight of Tool Assm.	Hold weight of rundown tool / drivetrain assembly to avoid line associate lifting fatigue	• Tool balancer (Atlas-Copco) • Lead-screw / ACME screw • Flex-arm
Resist Applied Torque	Prevent rotation of drivetrain / tool assembly due to torque reaction	• Line associate resists torque at handles • Flex-arm • Tool on rigid frame • Parallel linear bearings / rails
Position Around Shaft and Bearing Housing	Move tool or fixtured shock in all linear directions while preventing tool rotation	• Linear rails, line associate positioned (Similar to El Cajon system) • Motor driven lead screws • Flex arm
Engage Bearing Housing	Engage pin holes in top of bearing housing without leaving witness marks (spanner adaptor)	• Sawtooth profile / ratcheting • Friction engagement • Pin holes in top of adaptor • Hex adaptor, split socket spanner

Appendix E. Pugh Matrices

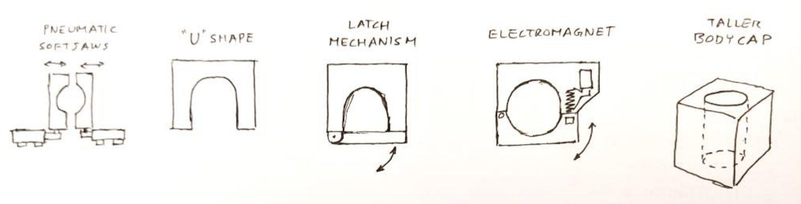
Initial Downward force

Criteria	Pneumatics	Self Weight	Fixture Pushed up	Springs/ impact	Manually
Safe	1	1	1	-1	0
Easy to service	-1	1	-1	-1	0
Easy to use	1	-1	1	1	0
Fast	1	1	1	1	0
Cost	-1	1	-1	-1	0
Total	1	3	1	-1	0



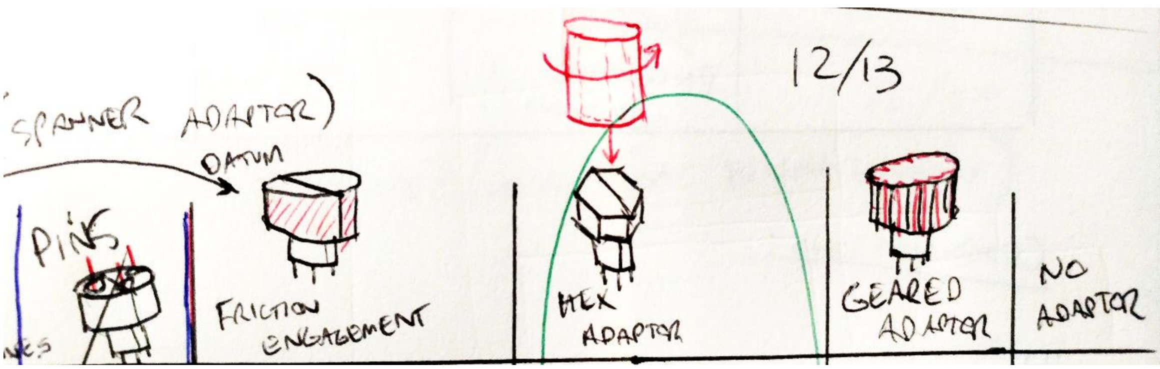
Tip prevention

Criteria	Pneumatic soft jaws	"U" shape	Latch Mechanism	Electro-magnet	Taller Bodycap
Stable	1	0	1	-1	-1
No witness marks	0	0	1	1	0
Fast	1	0	-1	1	0
Minimum user interventio	0	0	-1	1	1
Simplicity	-1	0	0	-1	1
Total	1	0	0	1	1



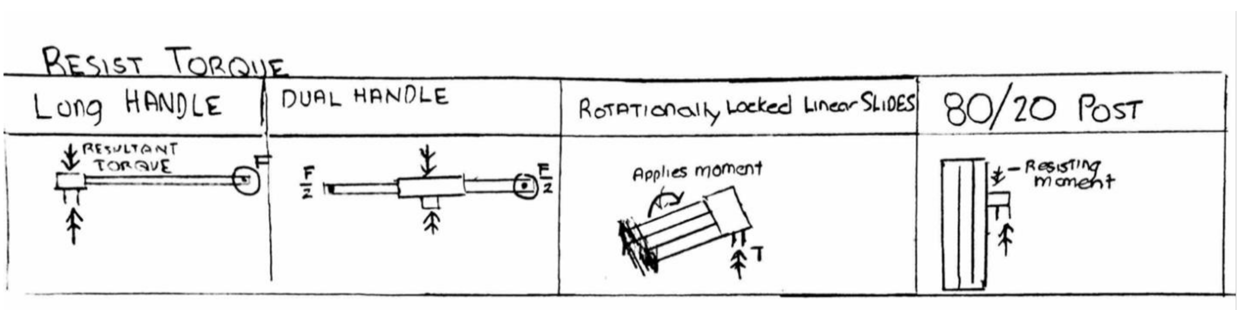
Engagement w/ Bearing Housing: (Spanner Adaptor)

Criteria	Pins	Friction Engagement	Hex Adaptor	Geared Adaptor	No Adaptor
No Witness Marks	0	0	0	0	-1
Indexing req. w/ spanner	-1	0	0	-1	-1
Manufacturability / Cost	-1	0	-1	-1	1
Reliability	1	0	1	-1	-1
Ease of loading	0	0	0	-1	1
Effect on spanner	-1	0	1	-1	0
Total	-2	0	1	-5	-1



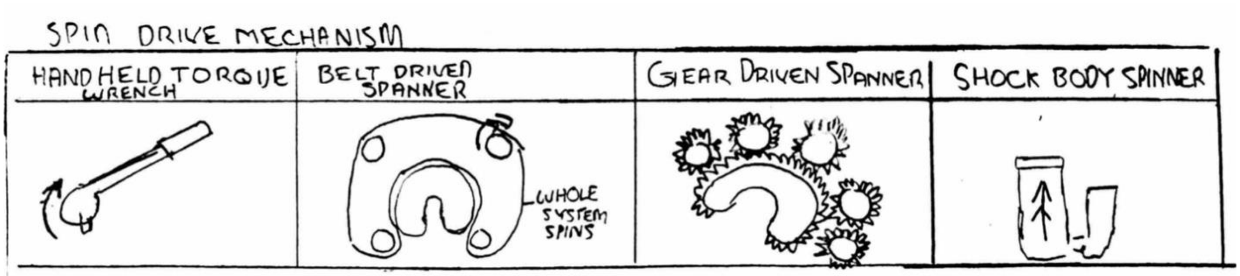
Resist Torque

Criteria	Long Handle	Dual Handle Resistance	Rotationally Locked Linear	80/20 Post
Ergonomic	0	1	1	-1
Safe	0	0	1	1
Low user fatigue	0	1	1	1
Minimum user interventio	0	0	0	1
Simplicity	0	0	0	-1
Total	0	2	3	1



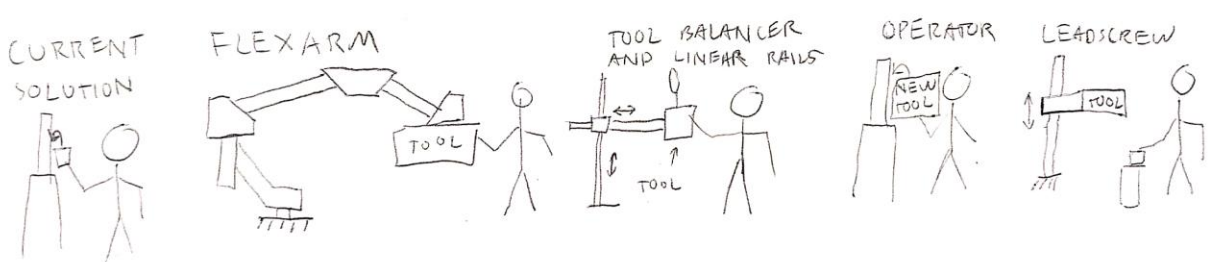
Spin/ Drivetrain

Criteria	Hand held torque wrench	Belt driven spanner	Gear Driven spanner	Spinning Shock body
Ergonomic	0	1	1	1
Safe	0	1	1	0
Low user fatigue	0	1	1	1
Minimum user interventio	0	0	0	0
Reliable	0	0	0	0
Ease of Maintenance	0	0	0	0
Simplicity	0	-1	-1	-1
Total	0	2	2	1



Hold Weight of Tool Assembly and Positioner

Criteria	Current Solution	Flexarm	Tool Balancer and Linear Rails	Operator	Leadscrew
Cost	0	-1	-1	0	-1
Ergonomics	0	1	1	-1	1
Reach	0	1	1	0	-1
Versatility	0	1	1	-1	-1
Total	0	2	2	-2	-2



Appendix F. Weighted Decision Matrix

		Option 1		Option 2		Option 3		Option 4	
		Linear Rail / Balancer		Min. Automation		Spin Shock		Flex Arm	
Criteria (from QFD)	**Weight**	**Score**	**Total**	**Score**	**Total**	**Score**	**Total**	**Score**	**Total**
Torque Repeatability	10.5	4	42.0	2	21.0	3	31.5	4	42.0
Short Cycle Time	5.7	3	17.0	2	11.3	3	17.0	3	17.0
Safe for Line associate	12.1	5	60.6	1	12.1	3	36.3	5	60.6
Ergonomic	11.2	5	56.1	1	11.2	5	56.1	4	44.9
Scalability	8.7	5	43.4	2	17.4	3	26.1	4	34.8
Manufacturability	5.6	4	22.2	5	27.8	3	16.7	5	27.8
Foot Print	8.3	4	33.0	5	41.3	2	16.5	3	24.8
80/20 Rule.	7.1	5	35.3	5	35.3	3	21.2	5	35.3
Cost	3.0	4	12.2	5	15.2	3	9.1	3	9.1
No Witness Marks	6.4	5	31.8	4	25.5	5	31.8	5	31.8
Reliability	12.1	3	36.3	3	36.3	5	60.6	3	36.3
Maintainability	9.4	5	47.1	5	47.1	4	37.7	4	37.7
Total			437.1		301.5		360.6		402.0

Appendix G. Gear Sample Calculations

k_o → Light Shock + MODERATE SHOCK

$$\boxed{k_o = 1.5}$$

OVERLOAD FACTORS

Dynamic FACTOR

$$k_v = \left(\frac{A + \sqrt{V}}{A}\right)^B$$

$$A = 50 + 56(1 - B) = 59.77$$

$$B = .25(12 - Q_v)^{2/3} = .82$$

$$V = 785$$

$$\boxed{k_v = 1.37}$$ → VARIES w/ DIAMeter

$k_t = 1.00$ → FOR STANDARD OPERATING TemperATURES

$k_r = 1.00$ FOR STANDARD OP

$N_p = 30T$ $\quad$ Rpm = 60

$N_G = 30T$ $\quad$ T = 50 lbft

$P = 6$ TPI

Bending

$$S = \omega^T k_o k_v k_s \frac{P_d}{F} \frac{k_m k_B}{J}$$

$$S = \frac{240\,lbf}{1.5\,in}(1.37)(1.5)(1)\frac{(6)(1.3)(1.0)}{(.4)}$$

$$S = 6.44$$

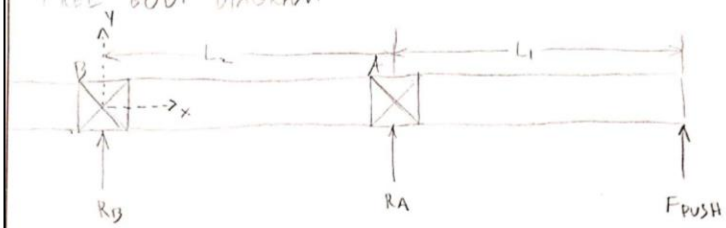
$$FOS = \left(\frac{S}{S_{UT}}\right)^{-1} = \left(\frac{6.44}{30.69}\right)^{-1} =$$

$$\boxed{FOS = 4.8}$$

Appendix H. Sample Beam Calculations

HORIZONTAL ARM SAMPLE CALCULATION

FREE BODY DIAGRAM



$L_1 = 8''$ $D_{Arm} = 1''$

$L_2 = 6''$

$F = 100\ lbf$

REACTIONS:

$R_B = \frac{F L_1}{L_2}$

$= \frac{100\ lbf \cdot 8\ in}{6\ in}$

$R_B = 133.3\ lbf$

TWO BEARINGS AT B, SO $R_B = 66.7\ lbf$

$R_A = \frac{-F}{L_2}(L_2 + L_1)$

$= \frac{-100\ lbf}{6\ in}(6\ in + 8\ in)$

$R_A = -233.3\ lbf$

TWO BEARINGS AT A, SO $R_A = -116.7\ lbf$

DEFLECTIONS:

SIMPLE SUPPORT - OVERHANGING LOADS

$D_{hMAX} = \frac{F L_1}{3 E I_{TOTAL}}(L_2 + L_1)$

$I_H = \frac{\pi}{4} R^4$

$= \frac{\pi}{4}(\frac{1}{2} in)^4$

$I_H = 0.0491\ in^4$

2 SHAFTS IN SAME PLANE, SO

$$I_{TOTAL} = 2I_{H}$$

$$= 2(0.0491\ in^4)$$

$$I_{TOTAL} = 0.0982\ in^4$$

HARDENDED STEEL SHAFT,
ASSUME $E = 29 \cdot 10^6$ psi

$$D_{hMAX} = \frac{100\ lbf\ (8\ in)^2}{3(29 \cdot 10^6\ psi)(0.0982\ in^4)}(6\ in + 8\ in)$$

$$\boxed{D_{hMAX} = 0.010\ in}$$

Appendix I. Design Hazard Checklist

DESIGN HAZARD CHECKLIST

Team: Fox Factory Faculty Coach: P. Schuster

Y	N	
X		1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
	X	2. Can any part of the design undergo high accelerations/decelerations?
	X	3. Will the system have any large moving masses or large forces?
	X	4. Will the system produce a projectile?
X		5. Would it be possible for the system to fall under gravity creating injury?
	X	6. Will a user be exposed to overhanging weights as part of the design?
	X	7. Will the system have any sharp edges?
	X	8. Will any part of the electrical systems not be grounded?
	X	9. Will there be any large batteries or electrical voltage in the system above 40 V?
X		10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	X	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	X	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
	X	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	X	14. Can the system generate high levels of noise?
	X	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
	X	16. Is it possible for the system to be used in an unsafe manner?

X	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

Description of Hazard	Planned Corrective Action / Action(s) Taken	Planned Date	Actual Date
(1) Potential for pinch hazard: open gear rotating in/out of drivetrain housing under power could pinch fingers placed on/around bearing housing	Buttons included on both drivetrain handles which must be held for machine to be powered. Pinch hazard decals to be placed on drivetrain housing near opening.	6/15/2020	
(5) Potential for machine tipping when drivetrain system is fully extended away from vertical column in any direction. Potential for shock tipping out of fixture if hit by drivetrain.	CG not found to extend past base plate for machine. Upper fixturing with toggle clamp added to design to prevent shock tip. Base plate to be c-clamped to table when installed at factory.	N/A	N/A
(10) Stored energy in the system: pneumatic lines at 105-120psi could shoot assembly grease or shock oil towards eyes. Hanging weight of drivetrain assembly and sliding structures.	Pneumatics: No corrective action needed beyond standard safety glass policy already in effect at factory. Hanging weight: Tool balancer sized for hanging components combined weight.	N/A	N/A

Appendix J. Failure Modes and Effects Analysis (FMEA)

System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurance	Current Detection Activities	Detection	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Action Results				
												Actions Taken	Severity	Occurrence	Detection	RPN
Downward Force / Drive bearing onto 1st thread	Not enough downward force to lower bearing far enough	bearing not threaded	8	Pneumatics are too small/weak	Verify pneumatics' output	2	Pressure Gauge / regulator	1	16							
	Too much downward force	thread damage, bcp insert damage	6	Pneumatics are too large/strong	Verify pneumatics' output	1	Pressure Gauge / regulator	1	6							
	Force output not time with torque driver cycle	bearing not threaded	8	Control system setup incorrectly	Verify no leaks, verify programming	2	Test timing of machine	1	16							
Downward Force / Help clamp/fixture shock	Fixturing systems leave witness marks	replace components	4	Sharp edges on fixture scrape shock body	Chamfer sharp edges	2	Routinely feel for sharp edges	2	16							
	Takes too long to fixture	long cycle time	4	Fixture mechanism is overly complicated	Design latch to be simple	5	Measure cycle time	1	20							
	Fixture too lose and there's wobble	thread binding	3	Fixture is oversized and shock can wobble within it	Use stock body cap pallet	3	Test fit shock in fixture	2	18							
Fixturing / Support shock weight	Does not support shock weight	Broken bcp insert	7	Tool balancer is too strong or weak	Design structures with factor of safety	1	Test fit shock in fixture	1	7							
Fixturing / Prevent tip-over towords user	Shock can tip	Operator injury	9	Insufficient fixturing	Shock pinched between BCP & drivetrain	2	Shock wobbling during cycle	3	54	Add U-shaped support w/ QR latch	David 1/18/2020	Toggle clamp & delrin Jaw added 2/25	1	1	1	1
		Shock shaft assm. damage	6	Body cap pallet not correctly sized	Change out BCP insert routinely	1	Test fit shock in pallet	1	6							
Structures / Allow sliding & z-rotation (4 DOF) of drivetrain	Rail binding	under torque	4	Drivetrain is angled/offset causing binding in the bearing	Large linear beaings w/ adjustment	5	Check w/ operator for binding	2	40	Check parallelism of shafts w/ indicator	Riley 5/1/2020		4	3	1	12
Structures / Hold drivetrain stationary for torque cycle	Rail slippage	1st thread not engaged	5	Air breaks do not provide enough clamping force	Buy correct breaks for shaft	2	Measure reaction force of break	1	10							
Drivetrain / Interface with bearing (adapter)	Wobble between male/female hex (size issue)	High rate of adapter wear	3	Male hex is too small/female hex is too large	Verify fit and tolerances	4	Measure male hex w/ calipers routinely	1	12							
	Premature rounding of hex corners (material issue)	High rate of adapter wear	3	HRC values for adapter components insufficient	Choose high/low wear materials	2	Change adapter material if excessive wear occurs	3	18							
Drivetrain / Rundown 10+ revolutions	Doesn't rundown far enough	Under torque	7	Bearing housing isn't rundown fully/driver attemps to rundown housing too far	Code torque threshold/ clear debris	3	Double check torque w/ manual wrench	2	42	Test machine before installing in factory	Chris 5/1/2020		7	1	2	14

Continued Failure Modes and Effects Analysis (FMEA)

Drivetrain / Torque to 50 ft*lbs	Consistently misses torque	Under/over torque	8	1) Drivetrain mechanism isn't calibrated properly and correct torque is not delivered (losses) 2) Error with actual torque driver and correct torque is not delivered	1) Calibrate machine with torque sensor or against known value 2) Verify torque driver with sensor or against known value	3	Verify w/ manual wrench routinely	2	48	Test machine before installing in factory	Chris 5/1/2020		8	1	2	16
	Torque applied too quickly	ergo impact on operator	5	Programming issue with PF4000 controller	Plot torque output over time in programming software	1	Check w/ operator about machine kick-back	2	10							
	Randomly misses torque	Back bearing off, re-torque	3	Trigger sensitivity, debris in drivetrain	Implement programming solution, check drivetrain	6	Operator notices increase in cycle errors	2	36	Check for gear break-in debris & grease flow	Eric 5/1/2020		3	2	1	6
Drivetrain / Negotiate around shaft & over bearing	Drivetrain doesn't index for shock removal	Bottlenecks entire assembly line	8	PF4000 programming issue	Research programming documentation	1	Visually verify indexed properly	1	8							
Drivetrain / Support and integrate with torque driver	Torque driver isn't mounted securely on housing	Under torque	6	Torque driver is loose/misalligned	Fasten torque driver fixture plate to sufficient preload	2	Inspect for any driver deflection	3	36	Check deflection at end of driver w/ dial indicator, loctite mounting plate fasteners	Riley 5/1/2020		6	1	1	6
General / Fasten systems together	Fastener shears	Machine down until fastener replaced	8	Fatigued fastener, load at fastener not corretly analyzed	Basic Analysis of load on each fastener	1	Visually inspect machine	2	16							

Appendix K. Design Verification Plan

Senior Project DVP&R														
Date:	FOX FACTORY BEARING RUNDOWN AND TORQUE	FOX FACTORY			Description of System: RUNDOWN AND TORQUE OF LINEAR BEARING INTO SHOCK SHAFT					FOX FACTORY TEAM				
TEST PLAN										TEST REPORT				
Item No	Specification #	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES		TIMING		TEST RESULTS			NOTES
						Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	1	New torquing method will be tested against the current system ton ensure proper torque is hit	Torque is within 1% of target	Eric	CP/FP	30	Sys	5/1/2020					
2	2	Foot print will be compared to the original foot print of the manual system	Foot print no larger that 1.5X the original footprint	Riley	CP/SP/FP	1	Sys	2/25/2020	3/1/2020	Pass	1	-	
3	3	Safety hazards will be minimized through risk and hazard assessment	Maximum of 2 low risk hazards/ further minimized by notices	David	CP/SP/FP	1	Sys	2/27/2020	3/1/2020	Pass	-	-	Keep an eye out to ensure more hazards arent introduced
4	4	Cycle time will be compared to the manual system when done at a pace that can be kept for 1 hour of assembly	1.5xOriginal time length Max	David	FP	10	Sys	5/5/2020					
5	5	Set up time will be measured with a stopwatch and compared to the original	1.5X the original time	Eric	FP	10	Sys	5/5/2020					
6	6	Utilize 8020 and Fox Standard parts where possible	Possibility to be modified for other shock families without modifying the overall concept	Riley	SP/FP	1	Sys	2/15/2020	2/22/2020	Pass	-	-	Will not be proceeding with other shock implementation. Confident it can be done with minimal design change
7	7	Using Minimal new components	Adhere to the 80/20 rule where applicable	Riley	FP	1	Sys						
8	8	Follow the DFMA guidelines to design parts for Machines available. Machine parts	If parts are successfully machined	Team	CP/FP	1	Sys	3/20/2020					
9	9	Develop a shopping list including all material and machining costs	Not exceeding 20,000	Eric	FP	1	Sys	2/29/2020	3/10/2020				
10	10	Utilize fatigue analysis tests to estimate failure time and plan maintenance prior	Time before major maintenance no sooner than 3 months	Chris	FP	1	Sys	2/15/2020	3/7/2020	-	-		Maintenance driven by shock assembled. At current rate, intervals will be greater than 3 months
11	11	Design the system to wear/break in specfic regions	Limit failure modes to 3 easy to maintain and replace areas	David	FP	1	sub	2/1/2020	3/7/2020	-	-		
12	12	Utilize DFA to ensure failure points are easily accessible. Meausre time to replace a component	No more than 2 hours after failure diagnosis	Eric	FP	1	sub	5/5/2020					

Continued Design Verification Plan:

13	13	Compare the line assosciate intervention to the intervention with the manual method	No more than the same amount of Intervention	Riley	FP	5	Sys	5/1/2020					
14	10	Test the drivetrain to analyze grease rejection to set maintenance intervals for applying more grease to the zerks	-	Eric	FP	5	Sys	5/1/2020					
15	12	Measure times for assembly and disassembly of major sub-systems	2 hours Per sub-system average	Team	FP	3	Sys	4/20/2020					
16	4	Pancake air cyclinder will be tested to ensure the downward force is consistently strong enough for a number of different lubricant amounts	Should provide enough force for all amounts of lubricant. Potentially not enough for no lubricant	David	FP	20	sub	4/20/2020					
17	3	Polycarbonate guard should protect from possibly breakage and part ejection from all angles except in line with operator.	Guard Manages to block random part ejection in all directions except in line with operator	David	FP	30	sub	5/1/2020					
18	3	Shock to maintain fixtured. Apply force in all directions to the shock fixture, simulating the shock, in order to ensure shock will not become unfixtured	Must withstant 150lbs in all directions	Chris	FP	10	sub	4/20/2020					

Appendix L. Indented Bill of Materials

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Indented Bill of Materials

Assembly Level	Part Number	Level	1	2	3	4	Description	Make or Buy	Material	Qty.	Unit Price	Qty Per Pack	More info	Total	SUBSYSTEM (LEVEL 1) TOTAL
0	01	**Final Assembly**												$ 61,050.36	
1	02		**Drive Train Assembly**												$ 23,864.89
2	001			Slotted Gear_6325K52			Slotted gear machined from 6325k52	Make	1144 Steel	1	$200.00	-	George	$ 200.00	
2	002			Slotted Bearing_6338k614			Slotted bearing machined from 6338k614	Make	841 Bearing Bro	2	$225.00	1	A51	$ 450.00	
2	003			Bottom Case Half				Make	7075 Alum	1	$2,450.00	-		$ 2,450.00	
2	009			Top Case Half				Make	7075 Alum	1	$1,920.00	-		$ 1,920.00	
2	05-XXX			**Idler Shaft Assembly**											
3	10-XXX				399-50-925-010-XXX		Idler shaft	Make	1144 Steel	2	$187.75	1	A51	$ 375.50	
3	-				97633A320		External Retaining Ring for 1-1/8" OD, Black	Buy		4	$5.83	25		$ 0.93	
3	-				5709K82		Tapered-Roller Bearing with Steel Ring Trade	Buy		4	$26.53	1		$ 106.12	
3	-				6343K16		Bearing Locknut 1215 Carbon Steel, 0.969"-	Buy		2	$8.02	1		$ 16.04	
3	018				Idler Gear_6325K49		Metal Gear - 14-1/2 Degree Pressure Angle	Make	1144 Steel	2	$150.00	1	George	$ 300.00	
3	-				95053A595		Rounded Machine Key Zinc-Plated 1018-104	Buy		2	$7.22	5		$ 2.89	
3	-				97633A300		External Retaining Ring for 1" OD, Black-Pho	Buy		2	$9.27	50		$ 0.37	
2	07			**Drive Shaft Assembly**											
3	016-XXX				399-50-925-016-XXX		Drive Shaft	Make		1	$263.00	1	A51	$ 263.00	
3	-				97633A320		External Retaining Ring for 1-1/8" OD, Black	Buy		4	$5.83	25		$ 0.93	
3	-				97633A300		External Retaining Ring for 1" OD, Black-Pho	Buy		2	$9.27	50		$ 0.37	
3	-				95053A595		Rounded Machine Key Zinc-Plated 1018-104	Buy		2	$7.22	5		$ 2.89	
3	008				Drive Gear_6325K52			Make	1144 steel	1	$175.00	1	George	$ 175.00	
3	-				5709K82		Tapered-Roller Bearing with Steel Ring Trade	Buy		4	$26.53	1		$ 106.12	
3	-				6343K16		Bearing Locknut 1215 Carbon Steel, 0.969"-	Buy		2	$8.02	1		$ 16.04	
2	017			Shaft Caps			Shaft Caps	Make		5	$75.00	1		$ 375.00	
2				91255A245			Button Head Hex Drive Screw Black-Oxide A	Buy		15	$8.99	50		$ 2.70	
2	019			Torque Driver Adapter			Attaches the torque Driver	Make		1	$1,310.00	1	A51	$ 1,310.00	
2	044			Bump Stops			Delrin bump stops for machine wear	Make		2	$100.00	1	George	$ 200.00	
2	-			8433218205 torquedriver			Torque Driver	Buy		1	$14,139.00	1		$ 14,139.00	
2	-			42203607_Driver_Cord			5m torque driver cord	Buy		1	$1,400.00	1		$ 1,400.00	
2	-			91290A434			Black-Oxide Alloy Steel Socket Head Screw N	Buy		3	$8.87	50		$ 0.53	
2	-			91255A582			Button Head Hex Drive Screw Black-Oxide A	Buy		4	$11.64	50		$ 0.93	
2	-			91251A542			Black-Oxide Alloy Steel Socket Head Screw 1	Buy		10	$8.55	50		$ 1.71	
2	-			91251A242			Black-Oxide Alloy Steel Socket Head Screw 1	Buy		10	$11.19	100		$ 1.12	
2	-			98381A626			Dowel Pin 4037 Alloy Steel, 3/8" Diameter,	Buy		2	$7.13	10		$ 1.43	
2	-			1095K65			Zinc-Plated Steel Grease Fitting Straight, 1/8	Buy		2	$3.51	10		$ 0.70	
2	-			90201A415			Extreme-Strength Grade 9 Steel Hex Head S	Buy		1	$6.95	5		$ 1.39	
2	013			Ground Socket_5552A63			6-Point Impact Socket Standard, 3/4" Square	Make		1	$18.72	1		$ 18.72	
2	-			6436K18			Clamping Two-Piece Shaft Collar for 1" Diam	Buy		4	$5.96	1		$ 23.84	
2	-			98306A179			1004-1045 Carbon Steel Clevis Pin 1/4" Dian	Buy		2	$13.18	25		$ 1.05	
2	-			98335A044			Zinc-Plated 1050-1095 Spring Steel Cotter Pi	Buy		2	$6.07	100		$ 0.12	
2	-			91251A194			Black-Oxide Alloy Steel Socket Head Screw 8	Buy		4	$11.12	100		$ 0.44	
1	04		**Adapter Piece Assembly**												$ 826.21
2	005			Adapter Body				Make		1	$375.00	1	A51	$ 375.00	
2	006			Adapter Delrin				Make		1	$450.00	1	A51	$ 450.00	
2	-			91251A240			Black-Oxide Alloy Steel Socket Head Screw 1	Buy		3	$11.00	100		$ 0.33	
2	-			98381A542			Dowel Pin 4037 Alloy Steel, 1/4" Diameter,	Buy		3	$7.31	25		$ 0.88	
2	399-50-780-30_340-3		**Body Cap Pallet Assembly**												
2	03		**Structures**												$ 6,971.24
3	039			Foot Plate				Make		1	$150.00	1	George	$ 150.00	
3	040			Head Plate				Make		1	$150.00	1	George	$ 150.00	
3	043			Top Wear Pad				Make		1	$100.00	1	George	$ 100.00	
3	042			Shaft Wear Collar				Make		6	$100.00	1	George	$ 600.00	
3	-			RLN-100200MXO			Rail Brake	Buy		3	$440.00	1		$ 1,320.00	
3	041			Rodlock Mount				Make		3	$200.00	1	George	$ 600.00	
3	035			Side Plate				Make		2	$225.00	1	A51	$ 450.00	
3	036			Front Plate				Make		1	$300.00	1	A51	$ 300.00	
3	034			Back Plate				Make		1	$600.00	1	A51	$ 600.00	
3	037			Bottom Plate				Make		1	$200.00	1	George	$ 200.00	
3	056			Linear Bearing_9338T11			Mounted Linear Ball Bearing Fixed Alignmer	Make		3	$183.90	1		$ 551.70	
3	-			47065t906			Gusset Bracket 3" Long for 3" High Double/(	Buy		9	$18.94	1		$ 170.46	
3	-			47065t215			T-Slotted Framing End-Feed Single Nut with	Buy		88	$2.38	4		$ 52.36	
3	-			47065T227			T-Slotted Framing Locking Inline/Perpendicu	Buy		4	$78.86	1		$ 315.44	
3	-			47065T264			T-Slotted Framing Silver Surface Bracket, 6"	Buy		2	$10.80	1		$ 21.60	
3	049			6061K25_Vertical Motion			Linear Motion Shaft 1566 Carbon Steel, 1" D	Buy		1	$25.08	1		$ 25.08	
3	-			47065T215			T-Slotted Framing End-Feed Single Nut with	Buy		20	$2.38	4		$ 11.90	
3	-			91255A540			Button Head Hex Drive Screw Black-Oxide A	Buy		26	$9.46	50		$ 4.92	
3	-			91255A582			Button Head Hex Drive Screw Black-Oxide A	Buy		8	$11.64	50		$ 1.86	
3	-			91251A580			Black-Oxide Alloy Steel Socket Head Screw 5	Buy		32	$9.09	50		$ 5.82	
3	-			92018A650			High-Strength Steel Nylon-Insert Flange Loc	Buy		2	$6.18	10		$ 1.24	
3	-			6436K23			Clamping Two-Piece Shaft Collar for 1-1/2" D	Buy		3	$9.22	1		$ 27.66	

3	-			3018T18			Galvanized Steel Eyebolt with Nut and with	Buy		2	$25.65	1		$ 51.30	
3	-			91251A242			Black-Oxide Alloy Steel Socket Head Screw 1	Buy		1	$11.19	100		$ 0.11	
3	050			6007K66_Horizontal Motion			Hollow Linear Motion Shaft 1566 Carbon Ste	Make		2	$150.89	1		$ 301.78	
3	-			91251A600			Black-Oxide Alloy Steel Socket Head Screw 5	Buy		12	$8.22	10		$ 9.86	
3	-			98306A310			1004-1045 Carbon Steel Clevis Pin 3/8" Diam	Buy		1	$8.30	5		$ 1.66	
3	-			98306A161			1004-1045 Carbon Steel Clevis Pin 1/4" Diam	Buy		2	$6.32	25		$ 0.51	
3	-			91251A581			Black-Oxide Alloy Steel Socket Head Screw 5	Buy		12	$9.11	50		$ 2.19	
3	-			98335A044			Zinc-Plated 1050-1095 Spring Steel Cotter Pi	Buy		2	$6.07	100		$ 0.12	
3	-			98335A069			Zinc-Plated 1050-1095 Spring Steel Cotter Pi	Buy		1	$9.97	50		$ 0.20	
3	-			5779K108			Push-to-Connect Tube Fitting for Air Straigh	Buy		3	$3.16	1		$ 9.48	
3	057-001			8020 Structure bottom brace			47065T109 32.16"	Make		2	$75.00	1	George	$ 150.00	
3	057-002			8020 Structure top brace			47065T109 29.44	Make		2	$75.00	1	George	$ 150.00	
3	045-001			8020 Structure bottom upright			47065T502_34.5"	Make		2	$75.00	1	George	$ 150.00	
3	045-002			8020 Structure top horizontal			47065T502_25"	Make		1	$75.00	1	George	$ 75.00	
3	045-003			8020 Structure bottom horizonta			47065T502_19"	Make		1	$75.00	1	George	$ 75.00	
3	045-004			8020 Structure foot strut			47065T502_4.5	Make		1	$75.00	1	George	$ 75.00	
3	045-005			8020 Structure tool balancer mou			47065T502_13.5" PLUS DRILL	Make		1	$75.00	1	George	$ 75.00	
3	045-006			8020 Structure top upright			47065T502_36	Make		1	$75.00	1	George	$ 75.00	
3	-			1865K6			Easy-Access Base-Mounted Shaft Support fo	Buy		2	$26.83	1		$ 53.66	
3	-			57745K23			Flange-Mounted Shaft Support for 1" Shaft D	Buy		1	$55.34	1		$ 55.34	
2	933-076		**Fox Live Valve Shock Assembly**							1					
2	06		**Fixturing**												**$ 2,437.68**
3	-			6709K120			Ball Bearing Carriage for 15 mm Wide Rail	Buy		4	$118.97	1		$ 475.88	
3	011			Fixturing Carriage Plate				Make		1	$200.00	1	George	$ 200.00	
3	015			Lower Fixturing Body Cap Pallet Plate				Make		1	$100.00	1	George	$ 100.00	
3	012			Lower Fixturing rail plate				Make		1	$200.00	1	George	$ 200.00	
3	007			Lower Fixturing Gusset				Make		4	$75.00	1	George	$ 300.00	
3	023-001			Fixturing 8020 Long			18.75 inches 47065T103	Make		1	$50.00	1	George	$ 50.00	
3	023-002			Fixturing 8020 Short			5 inches 47065T103	Make		1	$50.00	1	George	$ 50.00	
3	027			Fixturing clamp block short				Make		1	$150.00	1	George	$ 150.00	
3	028			Fixturing clamp block long				Make		1	$200.00	1	George	$ 200.00	
3	029			Fixturing Delrin v-block				Make		1	$450.00	1	A51	$ 450.00	
3	-			47065T229			T-Slotted Framing Drop-in Nut with Spring T	Buy		6	$1.58	1		$ 9.48	
3	-			91255A537			Button Head Hex Drive Screw Black-Oxide A	Buy		4	$7.08	50		$ 0.57	
3	-			91255A535			Button Head Hex Drive Screw Black-Oxide A	Buy		4	$8.34	50		$ 0.67	
3	-			91251A581			Black-Oxide Alloy Steel Socket Head Screw 5	Buy		1	$9.11	50		$ 0.18	
3	-			91290A140			Black-Oxide Alloy Steel Socket Head Screw M	Buy		16	$9.93	100		$ 1.59	
3	-			91290A168			Black-Oxide Alloy Steel Socket Head Screw M	Buy		10	$10.86	100		$ 1.09	
3	-			91251A541			Black-Oxide Alloy Steel Socket Head Screw 1	Buy		8	$8.82	50		$ 1.41	
3	-			91251A542			Black-Oxide Alloy Steel Socket Head Screw 1	Buy		4	$8.55	50		$ 0.68	
3	-			92395A030			Brass Screw-to-Expand Inserts for Plastic, 5/	Buy		1	$6.95	10		$ 0.70	
3	-			91255A582			Button Head Hex Drive Screw Black-Oxide A	Buy		4	$11.64	50		$ 0.93	
3	-			91251A542			Black-Oxide Alloy Steel Socket Head Screw 1	Buy		4	$8.55	50		$ 0.68	
3	-			6709K302			15 mm Wide x 280 mm Long Guide Rail for B	Buy		2	$89.60	1		$ 179.20	
3	-			47065T679			T-Slotted Framing Silver Gusset Bracket, 1-1	Buy		5	$7.58	1		$ 37.90	
3	-			50225A120			Dual-Mount Hold-Down Toggle Clamp	Buy		1	$26.72	1		$ 26.72	
2	10		**Pneumatics**												**$ 734.89**
3	-			61975K31			1/8 NPTF 2 Station Manifold for Modular Air	Buy		1	$29.95	1		$ 29.95	
3	-			62005K224			Air Flow Control Valve Elbow, 1/8 NPT Inlet	Buy		1	$12.77	1		$ 12.77	
3	-			61975K552			Air Directional Control Valve 3-Way Single S	Buy		2	$55.53	1		$ 111.06	
3	-			5779K108			Push-to-Connect Tube Fitting for Air Straigh	Buy		2	$3.16	1		$ 6.32	
3	-			4452K141			316 Stainless Steel Threaded Pipe Fitting Lov	Buy		2	$2.80	1		$ 5.60	
3	-			4450K1			Muffler 1/8 NPT Male, Steel, 11 scfm @ 100	Buy		2	$2.07	1		$ 4.14	
3	-			60115K250			End Block Set for Modular Compressed 1/4	Buy		2	$16.45	1		$ 32.90	
3	-			4927K26			Wilkerson Compressed Air Regulator Manifo	Buy		2	$29.38	1		$ 58.76	
3	-			60115K210			Joiner Clamp for 1/8 and 1/4 NPT Lubricator	Buy		3	$6.62	1		$ 19.86	
3	-			60115K720			Wilkerson Air Filter Series F08, 1/4 NPT Fem	Buy		1	$26.04	1		$ 26.04	
3	-			6148k320			Safety Lockout Valve for Compressed Air FR	Buy		1	$27.64	1		$ 27.64	
3	-			9767T211			Miniature Pressure Gauge with Nickel-Plate	Buy		2	$15.13	1		$ 30.26	
3	-			4452K161			316 Stainless Steel Threaded Pipe Fitting Lov	Buy		2	$3.47	1		$ 6.94	
3	-			5779K152			Push-to-Connect Tube Fitting for Air 90 Deg	Buy		3	$3.58	1		$ 10.74	
3	-			4452K142			316 Stainless Steel Threaded Pipe Fitting Lov	Buy		1	$2.80	1		$ 2.80	
3	-			2945n21			Electrical Air Directional Control Valve Simu	Buy		1	$96.74	1		$ 96.74	
3	-			5779K151			Push-to-Connect Tube Fitting for Air 90 Deg	Buy		2	$3.25	1		$ 6.50	
3	-			91251A242			Black-Oxide Alloy Steel Socket Head Screw 1	Buy		4	$11.19	100		$ 0.45	
3	-			91251A201			Black-Oxide Alloy Steel Socket Head Screw 8	Buy		5	$8.12	50		$ 0.81	
3	-			4450K2			Muffler 1/4 NPT Male, Steel, 21 scfm @ 100	Buy		1	$2.43	1		$ 2.43	
3	-			47065T215			T-Slotted Framing End-Feed Single Nut with	Buy		4	$2.38	4		$ 2.38	
3	-			3FFY9			DIN Type B Solenoid Coil Connector with Plu	Buy		2	$19.90	1	Grainger	$ 39.80	
3	033			Pneumatics back plate				Make		1	$200.00	1	George	$ 200.00	
2			8494T32				Black-Oxide Steel Shackle with Safety Pin - fo	Buy		1	$29.28	1		$ 29.28	
2			ATLAS COPCO 8202_0780_02				Tool Balancer_COST EST MCMASTER	Buy		1	$1,620.83	1		$ 1,620.83	

2	14		**Magnetic Bearing Cap**												$ **25.43**
3	-			7132T24			Nonmarring Encased Neodymium Magnet w	Buy		1	$23.16	1		$ 23.16	
3	-			57455K510			Plastic Tapered Handle High-Temperature, v	Buy		1	$2.27	1		$ 2.27	
2	11		**Ram Mount Assembly**												$ **100.13**
3	025			Ram Mount Screwscrew				Make		1	$50.00	1	George	$ 50.00	
3	026			Ram Plate				Make		1	$50.00	1	George	$ 50.00	
3	-			96640A132			Black-Oxide 18-8 Stainless Steel Phillips Flat	Buy		1	$6.46	50		$ 0.13	
2	004		Machine Base Plate					Make	6061-t6	1	$710.00	1	A51	$ 710.00	
2	053		Joining Plate					Make	6061-t6	1	$200.00	1	George	$ 200.00	
2	054		Fixtures Mounting Plate					Make	6061-t6	1	RFQ	1		RFQ	
2	-		**Table_Height Assist**				Not sure if we were going to use	Buy		1					
2	030		**Polycarb Guard**				Design Incomplete	Make		1					
2			6212K222				Round Body Air Cylinder for Narrow Spaces	Buy		1	$110.85	1		$ 110.85	
2			91251A347				Black-Oxide Alloy Steel Socket Head Screw 1	Buy		4	$8.85	50		$ 0.71	
2			8492A408				Press-Fit Drill Bushing with Head 0.5" ID, 7/8	Buy		2	$16.62	1		$ 33.24	
2	09		**Handle Assembly**												$ **1,712.17**
3	021			Handle bottom plate				Make	6061-t6	2	$112.50	1	A51	$ 225.00	
3	022			Handle back plate				Make	6061-t6	2	$150.00	1	A51	$ 300.00	
3	020			Handle cap				Make	6061-t6	2	$150.00	1	A51	$ 300.00	
3	047			Handle connector plate				Make	6061-t6	4	$100.00	1	George	$ 400.00	
3	051			Handle				Make	6061-t6	2	$225.00	1	A51	$ 450.00	
3	-			91251A542			Black-Oxide Alloy Steel Socket Head Screw 1	Buy		12	$8.55	50		$ 2.05	
3	-			6023T130			Flush-Mount Panel-Mount Push-Button Swit	Buy		2	$15.18	1		$ 30.36	
3	-			7565K46			Cable Holders Adhesive-Back, Nylon, 1" Long	Buy		8	$8.54	25		$ 2.73	
3	-			90044A125			Black-Oxide Alloy Steel Socket Head Screw 1	Buy		6	$8.42	25		$ 2.02	
2	-		5779K108				Push-to-Connect Tube Fitting for Air Straight	Buy		1	$3.16	1		$ 3.16	
2	-		91251A542				Black-Oxide Alloy Steel Socket Head Screw 1	Buy		4	$8.55	50		$ 0.68	
2	-		4450K1				Muffler 1/8 NPT Male, Steel, 11 scfm @ 100	Buy		1	$2.07	1		$ 2.07	
2	-		91251A583				Black-Oxide Alloy Steel Socket Head Screw 5	Buy		16	$11.48	50		$ 3.67	
2	-														
2	12		**PF Mount**												$ **21,663.23**
3	-			PF6000				Buy		1	$6,553.00	1		$ 6,553.00	
3				PF6000 IAM				Buy		1	$10,342.00	1		$ 10,342.00	
3	-			EA9-T7CL-R_HMI			Recommended HMI interface	Buy		1	$487.00	1		$ 487.00	
3	09-11279-000_REV_2			Micrologix PLC System and Enclosure				Buy		1	$3,977.00	1		$ 3,977.00	
3	-			HMI control box			FOX standard HMI control box e-stop	-	-	1	-	-	Part number required	-	
3				8382k45			Normally Closed E-stop	Buy		1	$38.33	1	HMI control boc	$ 38.33	
3				BG5933-22-61-24			Dold safety relay, two-hand control, 2-chann	Buy	-	1	$146.00	1	Automation Direct	$ 146.00	
3				HCTR3			Edison fuse, HCTR series, Class CC, current-li	Buy	-	1	$94.00	10	Automation Direct	$ 9.40	
3				EHCC1DU			Edison modular fuse holder, accepts Class C	Buy	-	1	$10.50	1	Automation Direct	$ 10.50	
3				Assorted ferrules and wiring			Assorted Ferrules and Wiring	Buy	-	1	$100.00	1	Automation Direct	$ 100.00	

Appendix M. Generic python code

```python
# Software generic code:

# variable declarations
State = 0
Button_1 = 0 # 1 if button is pressed
Button_2 = 0 # 1 if button is pressed
Rail_break = 0
Revolutions_reached = 0
Rundown_reached = 0
Button_event = 0
Low_torque_met = 0
Torque_met = 0
Restart = 0

while True:
    if State == 0: # ready state
        if Button_1 == True and Button_2 == True: # if both buttons have been pressed
            State = 1 # go to next state

    elif State == 1: # slow rotation of torque driver
        if Button_1 == False and Button_2 == False: #if either button prematurely released
            State = 2 # go to next state

    elif State == 2: # stopped state
        if Button_1 == True and Button_2 == True: # if both buttons have been momentarily released
            Rail_break= True # engage rail breaks
            Pneumatics = True # engage pneumatic cyclinder
            State = 3 # go to next state

    elif State == 3: # rundown
        if Low_torque_met == True: # if the torque requirement has been met
            State = 4 # go to the next state
        elif Button_1 == False or Button_2 == False: # if either button prematurely released
            State = 7 # go to error state
            # Command to stop torque driver goes here

    elif State == 4: # waiting for torque
        if Button_Event == True: # wait until machine is ready to restart
            State = 4=5 # go to next state

    elif State == 5: # torque operation
        if Torque_met == True:
            State = 6 # go to next state
        elif Button_1 == False or Button_2 == False:
            State = 7 # go to error state
            # Command to stop torque driver goes here

    elif State == 6: # torque op completed
        if Button_1 == False and Button_2 == False:
            Rail_break = False # disengage rail breaks
            Pneumatics = False # disengage pneumatic cylinder
            State = 0 # go to ready state

    elif State == 7: # error state
        if Button_event == True:
            Rail_breaks = False # disengage rail breaks
            Pneumatics = False # disengage pneumatic clinder
            State = 0 # go to ready state

```

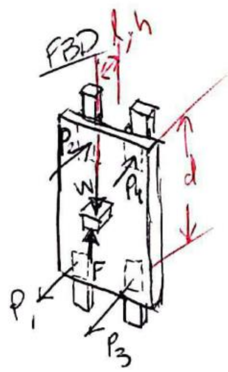
Appendix N. Fixturing Linear Rail Sizing Hand Calcs

→ HIWIN LINEAR GUIDEWAYS: HG SERIES (HEAVY LOAD BALL TYPE)

– LUBRICATION: GREASE NIPPLE OPTIONS (PG. 29 PDF MANUAL/CATALOG)

– BASIC LOAD RATINGS [1-3] CATALOG

NOMINAL LIFE CALC: $L = \left(\frac{C}{P}\right)^3 \cdot 31\ \text{MILE}$



C ≡ BASIC DYNAMIC LOAD RATING

P ≡ ACTUAL LOAD

$$P_1 \approx P_4 = -\frac{W \cdot h}{2d} + \frac{F \cdot l}{2d} = \frac{(-80\,\text{LB}_f)(5'')}{2(12'')} = (16.7\ \text{LB}_f)$$

$(10'') \Rightarrow 20\ \text{LB}_f$

(254mm)

→ ASSUMING WEIGHT & FORCE APPLIED ALONG SAME AXIS

→ LOOKS LIKE HIWIN RECOMMENDS 2 // RAILS!

→ WORST LOAD CASE: SUPPORTING ASSM. WEIGHT WHILE CYLINDER RETRACTS (F=0, W ≈ 80)

31

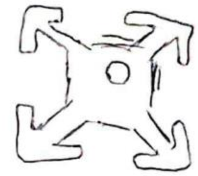
Appendix O. Fixturing Stiffness Hand Calcs

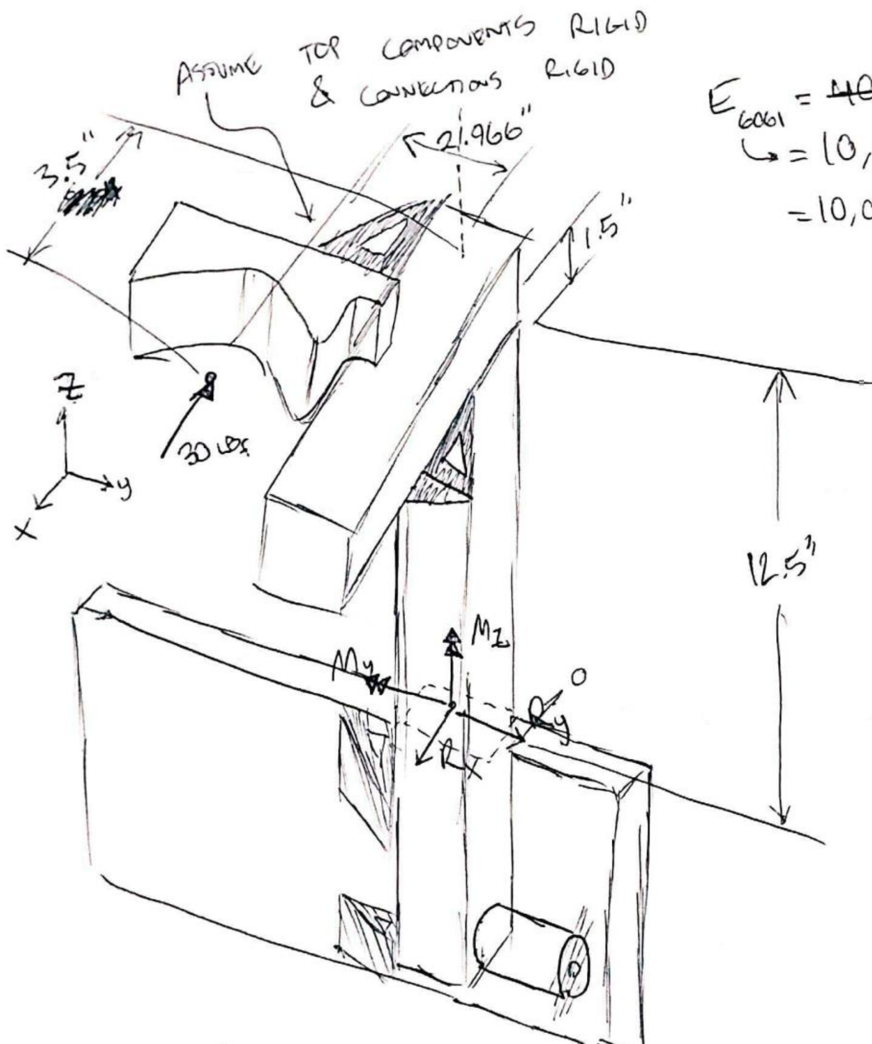
2/29

1.5" SINGLE 8020 AREA M.O.I :

$A = 1.155\ \text{IN}^2$

$I_{xx} = I_{yy} = .256\ \text{IN}^4$





$E_{6061} = \sout{40{,}000}\ \text{LBF}/\text{IN}^2$

$\hookrightarrow = 10{,}000\ \text{KSI}$

$= 10{,}000{,}000\ \text{PSI}$

→ FAIRLY RIGID LOWER CONNECTION

↳ TREAT AS CANTILEVER

$M_y = -(30\,\text{LBF})(14.0")$

$M_z = (30\,\text{LBF})(2.966")$

X-DEFL:

$$X_{MAX} = \frac{-F\ell^3}{3EI} = \frac{(30\,\text{LBF})(14.0")^3}{3(10000\ \text{KSI})(.256\ \text{IN}^4)} = 0.0107"$$

Appendix P. Electrical wiring diagram

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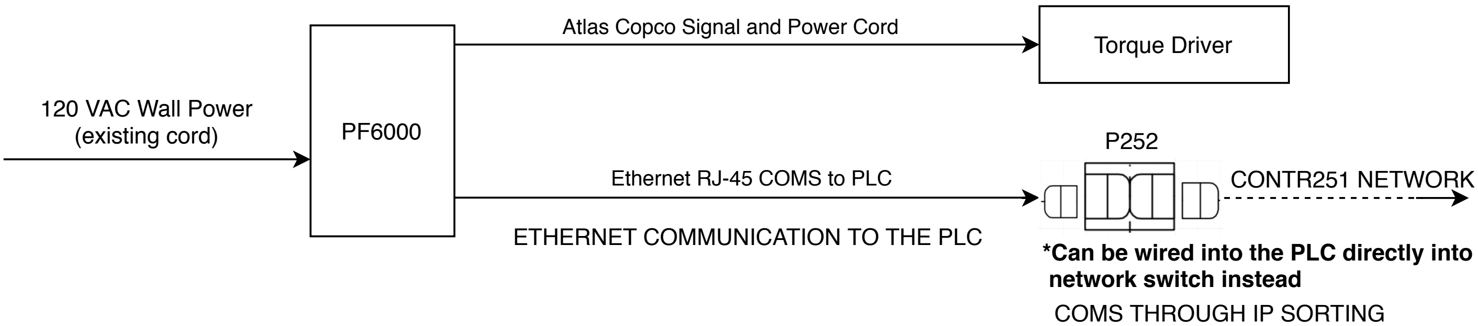
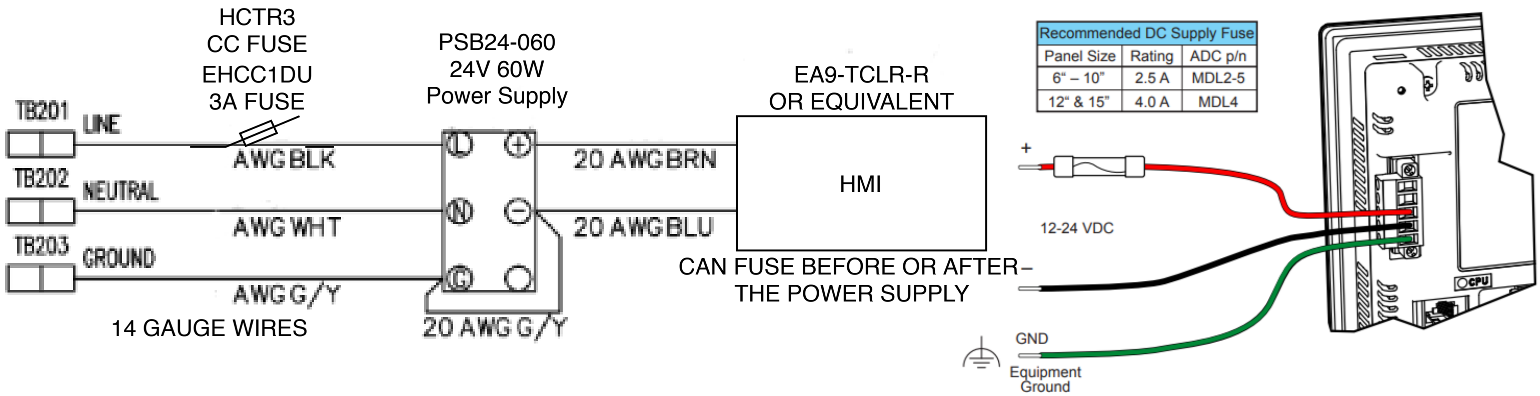
PF6000



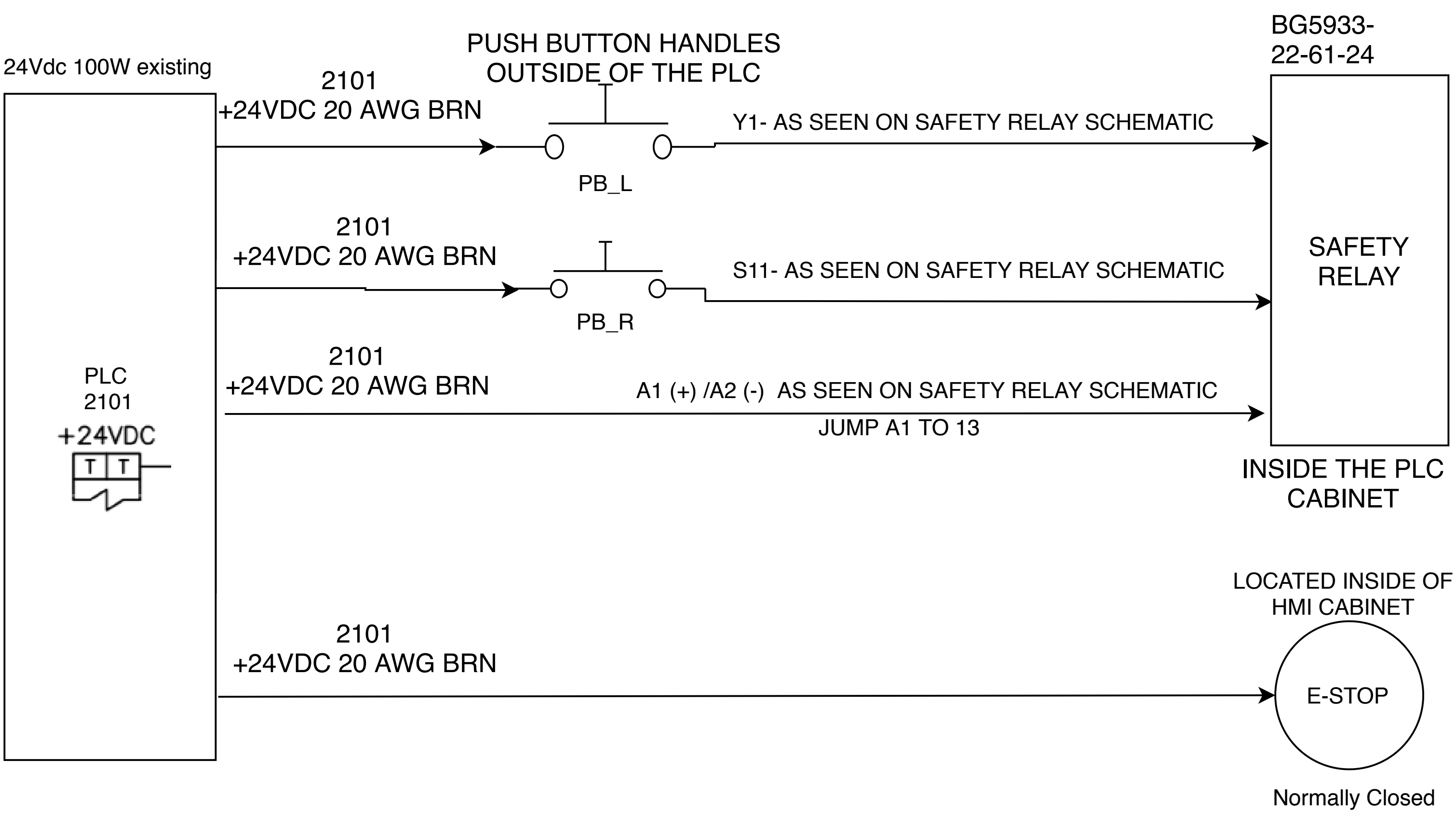
PLC CABINET

SEE EXISTING AREIAS PN 02-11270-000
SHEMATIC 09-11279-000

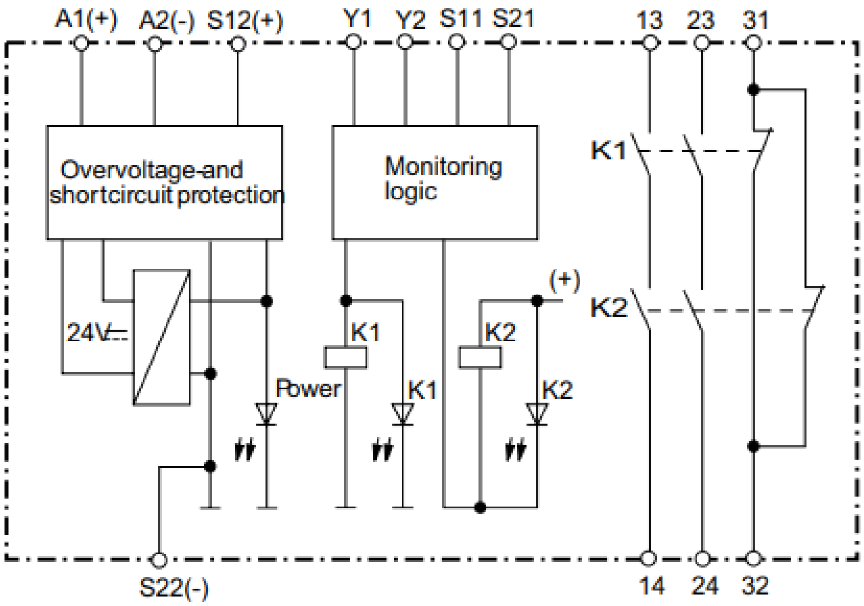


STEMMING OFF OF THE EXISTING TERMINAL BLOCKS A 14 GAUGE BLACK WILL BE FUSED BEFORE THE POWER SUPPLY. FROM THE POWER SUPPLY, 24V CAN BE BROUGHT DIRECTLY INTO THE HMI CABINET AND INTO THE HMI. AN EQUIPTMENT GROUND WILL ALSO NEED TO BE BROUGHT TO THE HMI

A SIMPLE MODIFICATION CAN BE MADE TO THIS BY LANDING THE 24Vdc FROM THE POWER SUPPLY INTO A TERMINAL BLOCK (MCMASTER PART #: 8841T22) BEFORE WIRING INTO THE HMI SUB-PANEL.
IF CHOOSING TO FUSE DC POWER MAKE SURE TO USE THE RECOMMENDED FUSE SIZE FOR THE PANEL SIZE.

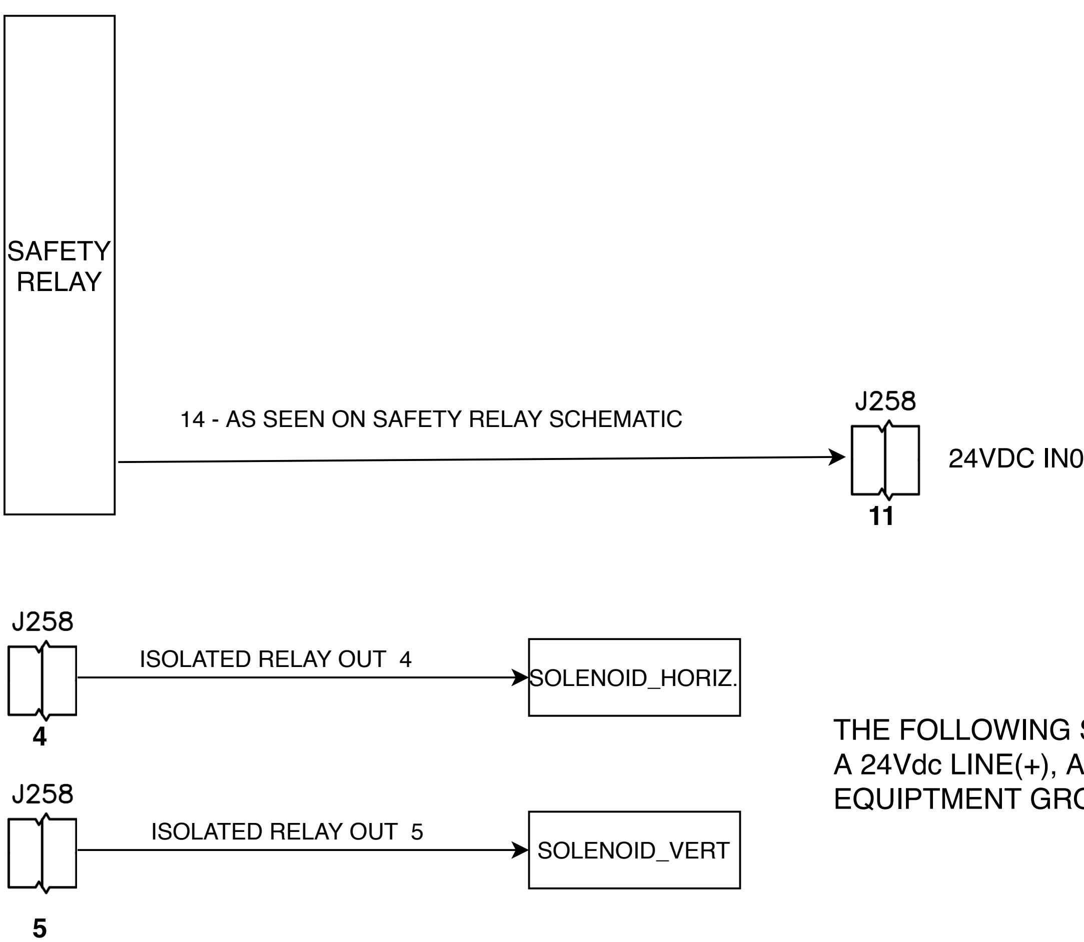


SAFETY RELAY SCHEMATIC

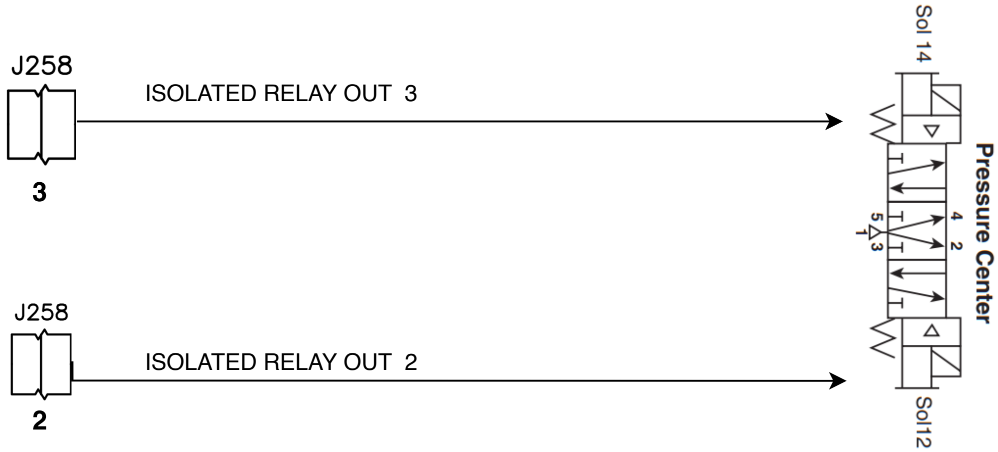


MY UNDERSTANDING OF THIS SAFETY RELAY IS THAT A1 AND A2 ARE CONTROL POWER WIRES. 13/23/31 ARE LINE SIDE IN INTO THE LOGIC CONTROLLED SWITCHES. THEY CAN RECEIVE POWER JUMPED FROM THE A1 TERMINAL.
THE BUTTONS ARE WIRED TO Y1 AND S11. THIS MAY NEED EXPERIMENTATION. THEY MAY NEED TO BE WIRED TO Y1 AND Y2. BUT IM PRETTY SURE THIS IS CORRECT

BG5933-
22-61-24



THE FOLLOWING SOLENOIDS WILL NEED A 24Vdc LINE(+), A COMMON(-), AND AN EQUIPTMENT GROUND(-)



PANCAKE CYLINDER SOLENOID VALVE.
SOL14: PRESS
SOL12: EXHAUST
SEE PNEUMATICS DIAGRAM FOR FURTHER DETAIL

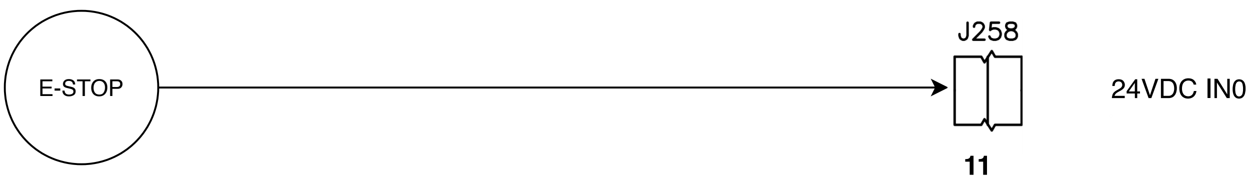
SOLENOID PAN

How will exhaust solenoid be used in comparison to neutral solenoid

HMI CABINET

THE HMI CABINET WILL CONSIST OF THE MOUNTED HMI AND THE EMERGENCY STOP.
THE POWER SUPPLY TO THE HMI WAS DETAILED ABOVE

***CAN BE WIRED IN THROUGH THE PLC CABINET INTO THE NETWORK SWITCH ITSELF. WILL ALLOW THE ETHERNET SWITCHED TO BE HARDWIRED INSTEAD OF BEING OUTSIDE OF EACH CABINET**



Appendix Q. Existing PLC wiring diagram

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	REVISIONS
1	INITIAL RELEASE
2	CHANGE IN WIRE NUMBERING

NOTES

1 MACHINE PLATE DATA:

Manufacturer:	Areias Systems, Inc. NITW.E325382
Serial Number:	PENDING
Supply:	120VAC 20A
Max Load:	120VA
Interupt Rating:	5KA

2 Unit to be manufactured per UL508A and NFPA79 standards.

3 All wires to be rated for 300V and 90°C or higher.

4 Wires shall be terminated so as to prevent fraying by the use of lugs, ferrules, or other hardware as appropriate.

5 Lock–out tag–out mechanism not required.

6 Enclosure border represented by dash–dot line. Remainder of system shown for reference only.

7 Wire colors:

BLACK	120VAC
WHITE	NEUTRAL
GREEN/YELLOW	GROUND
BROWN	24VDC AND SIGNAL
BLUE	COMMON

8 TERMINAL BLOCKS WITH SAME DESIGNATION ARE JUMPED TOGETHER. EXAMPLE: 24VDC, COM, 24EMO

SYMBOLS

CIRCUIT BREAKER

CONNECTORS

CONTROLLERS
PROGRAMABLE DEVICES
POWER SUPPLIES
PRINTED CIRCUIT BOARDS

Pin numbers shown in circles.

DIODES

FUSE, FIXED

FUSE, SWITCHING

RELAY COIL

RELAY CONTACT

TERMINAL BLOCK

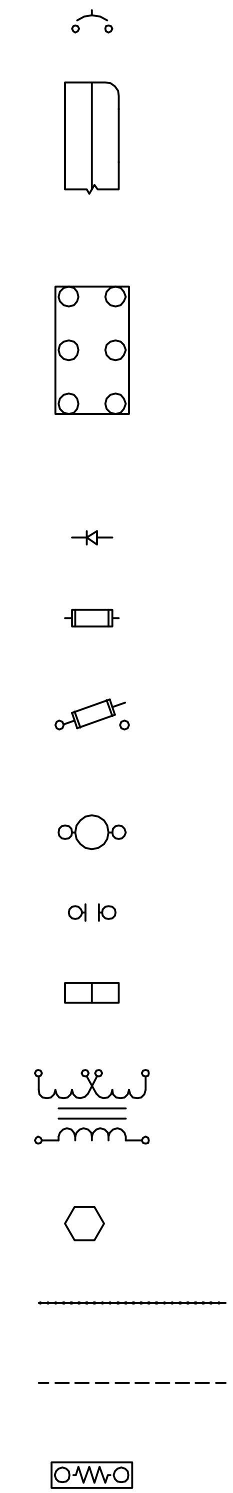
TRANSFORMER

WIRE REFERENCE

TERMINAL BLOCK JUMPER

EXTERNAL WIRING OR POSSIBLE JUMPER

RESISTOR



QTY -00	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL	REF ID	ITEM NO

INTERPRETATION PER ANSI Y14.5 WORKMANSHIP STD 74–032409–00
FIRST USED ON ASSY
FINISH
RAW MATERIAL
THIRD ANGLE PROJECTION

Areias Systems
Electro-Mechanical Design and Prototyping
5900 Butler Lane, Scotts Valley, CA 95066
(831) 439-9299 fax (831) 439-9295

DIMENSIONS ARE IN INCHES UNLESS OTHERWISE NOTED
TOLERANCE
.x ±
.xx ± .01
.xxx ± .005
ANGLES ± 1°

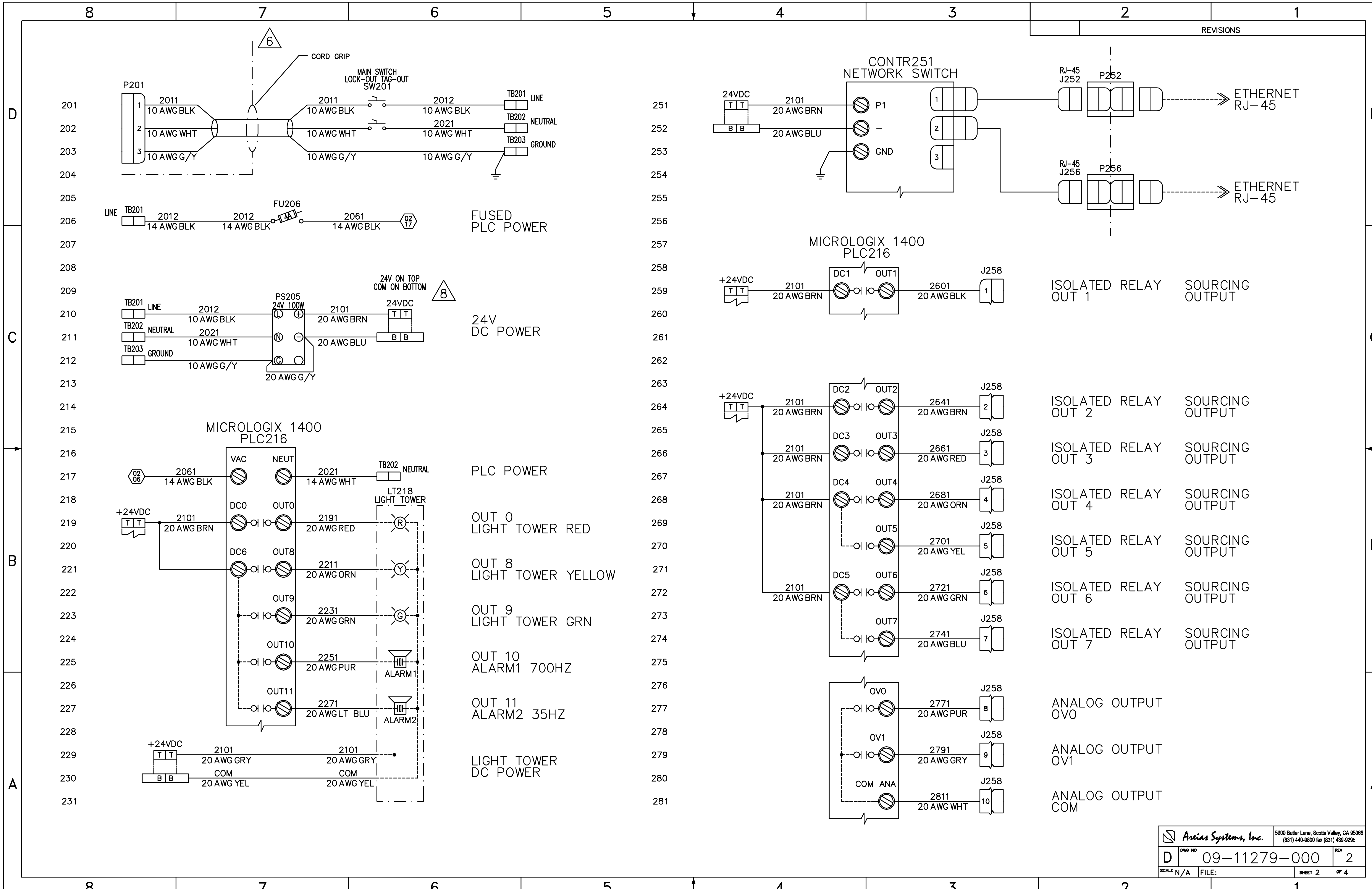
APPROVALS		DATE
DRAWN	STELOY	12/02/2011
CHK	DANRYA	12/02/2011
ENGR		
ENGR		

DO NOT SCALE DRAWING

TITLE SCH,CONTROL BOX,FOX RACING SHOX

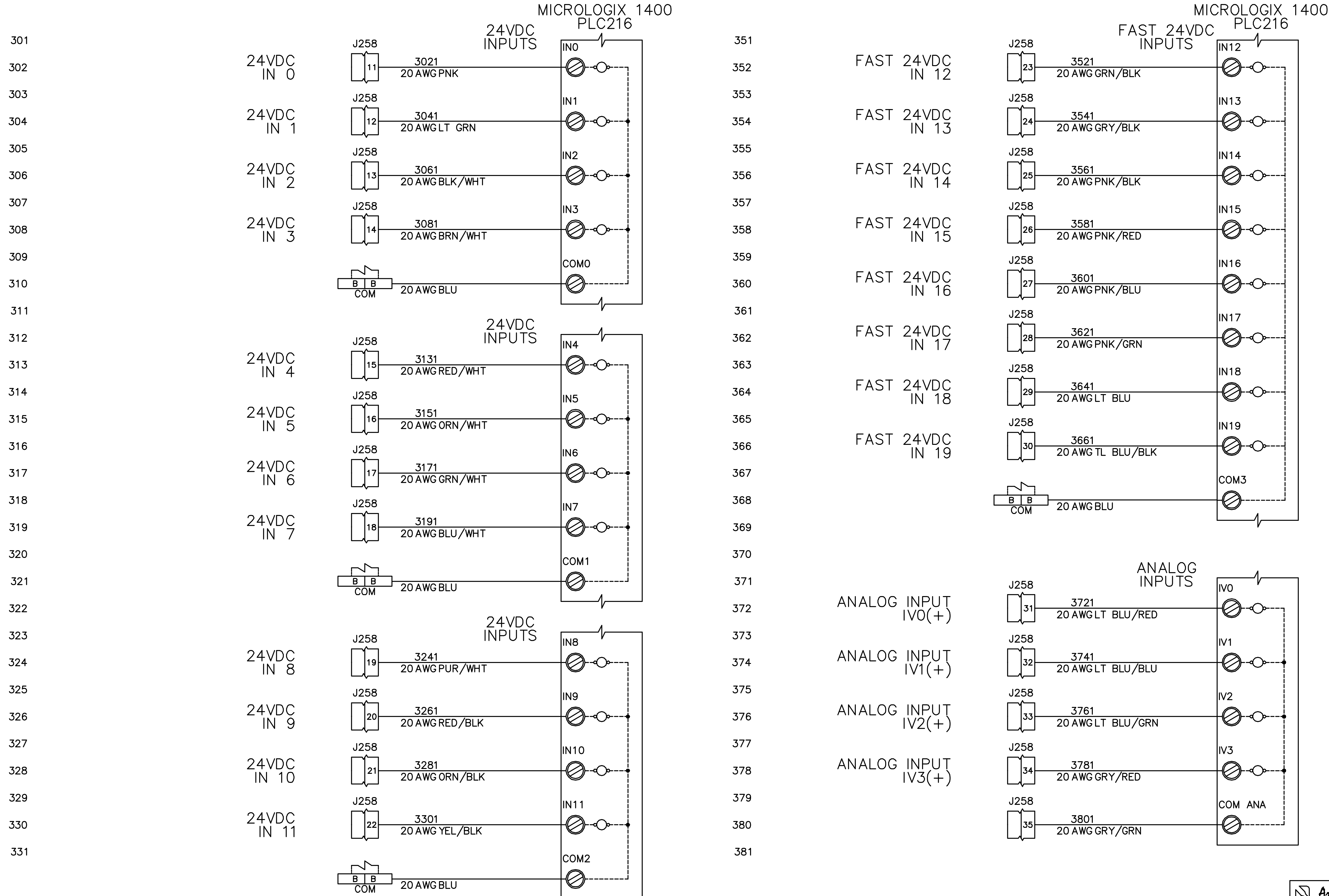
D DWG NO 09–11279–000 REV 2

SCALE N/A FILE: SHEET 1 OF 4



REVISIONS
CORD GRIP
MAIN SWITCH LOCK-OUT TAG-OUT SW201
P201
2011 10 AWG BLK
10 AWG WHT
10 AWG G/Y
2012 10 AWG BLK
2021 10 AWG WHT
TB201 LINE
TB202 NEUTRAL
TB203 GROUND
FU206 4A
2061 14 AWG BLK
FUSED PLC POWER
24V ON TOP COM ON BOTTOM
PS205 24V 100W
2101 20 AWG BRN
20 AWG BLU
20 AWG G/Y
24VDC
24V DC POWER
MICROLOGIX 1400 PLC216
VAC NEUT
2021 14 AWG WHT
PLC POWER
+24VDC
DC0 OUT0 DC6 OUT8 OUT9 OUT10 OUT11
LT218 LIGHT TOWER
2191 20 AWG RED
2211 20 AWG ORN
2231 20 AWG GRN
2251 20 AWG PUR
2271 20 AWG LT BLU
ALARM1 ALARM2
OUT 0 LIGHT TOWER RED
OUT 8 LIGHT TOWER YELLOW
OUT 9 LIGHT TOWER GRN
OUT 10 ALARM1 700HZ
OUT 11 ALARM2 35HZ
2101 20 AWG GRY
COM 20 AWG YEL
LIGHT TOWER DC POWER
CONTR251 NETWORK SWITCH
P1 – GND
RJ-45 J252 P252
RJ-45 J256 P256
ETHERNET RJ-45
ETHERNET RJ-45
DC1 OUT1 J258
2601 20 AWG BLK
ISOLATED RELAY OUT 1 SOURCING OUTPUT
DC2 OUT2 DC3 OUT3 DC4 OUT4 OUT5 DC5 OUT6 OUT7
2641 20 AWG BRN
2661 20 AWG RED
2681 20 AWG ORN
2701 20 AWG YEL
2721 20 AWG GRN
2741 20 AWG BLU
ISOLATED RELAY OUT 2 SOURCING OUTPUT
ISOLATED RELAY OUT 3 SOURCING OUTPUT
ISOLATED RELAY OUT 4 SOURCING OUTPUT
ISOLATED RELAY OUT 5 SOURCING OUTPUT
ISOLATED RELAY OUT 6 SOURCING OUTPUT
ISOLATED RELAY OUT 7 SOURCING OUTPUT
OV0 OV1 COM ANA
2771 20 AWG PUR
2791 20 AWG GRY
2811 20 AWG WHT
ANALOG OUTPUT OV0
ANALOG OUTPUT OV1
ANALOG OUTPUT COM
Areias Systems, Inc.
5800 Butler Lane, Scotts Valley, CA 95066 (831) 440-9800 fax (831) 439-9295
D DWG NO 09-11279-000 REV 2
SCALE N/A FILE: SHEET 2 OF 4

REVISIONS



Areias Systems, Inc.
5900 Butler Lane, Scotts Valley, CA 95066
(831) 440-9800 fax (831) 439-9295

D DWG NO 09–11279–000 REV 2

SCALE N/A FILE: SHEET 3 OF 4

REVISIONS

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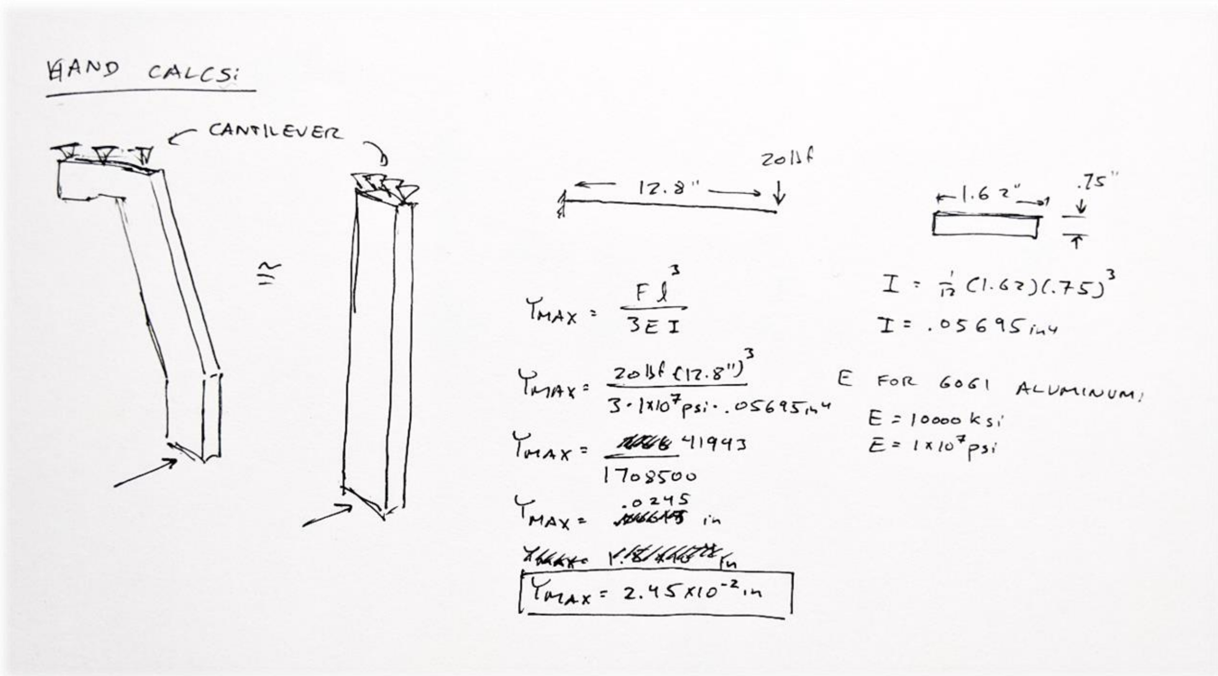
Areias Systems, Inc.	5800 Butler Lane, Scotts Valley, CA 95066 (831) 440-9800 fax (831) 439-9295	
D	DWG NO 09–11279–000	REV 2
SCALE N/A	FILE:	SHEET 4 OF 4

Appendix R. Handle Stiffness Hand Calculations



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203-00-099 BEARING ASSEMBLY RUNDOWN & TORQUE MACHINE (Fox Mfg. P/N 399-50-925)

Operator's Manual

June 2020

David Daley

Riley O'Connor

CAL POLY

SAN LUIS OBISPO

California Polytechnic State University

Mechanical Engineering Department

FOX

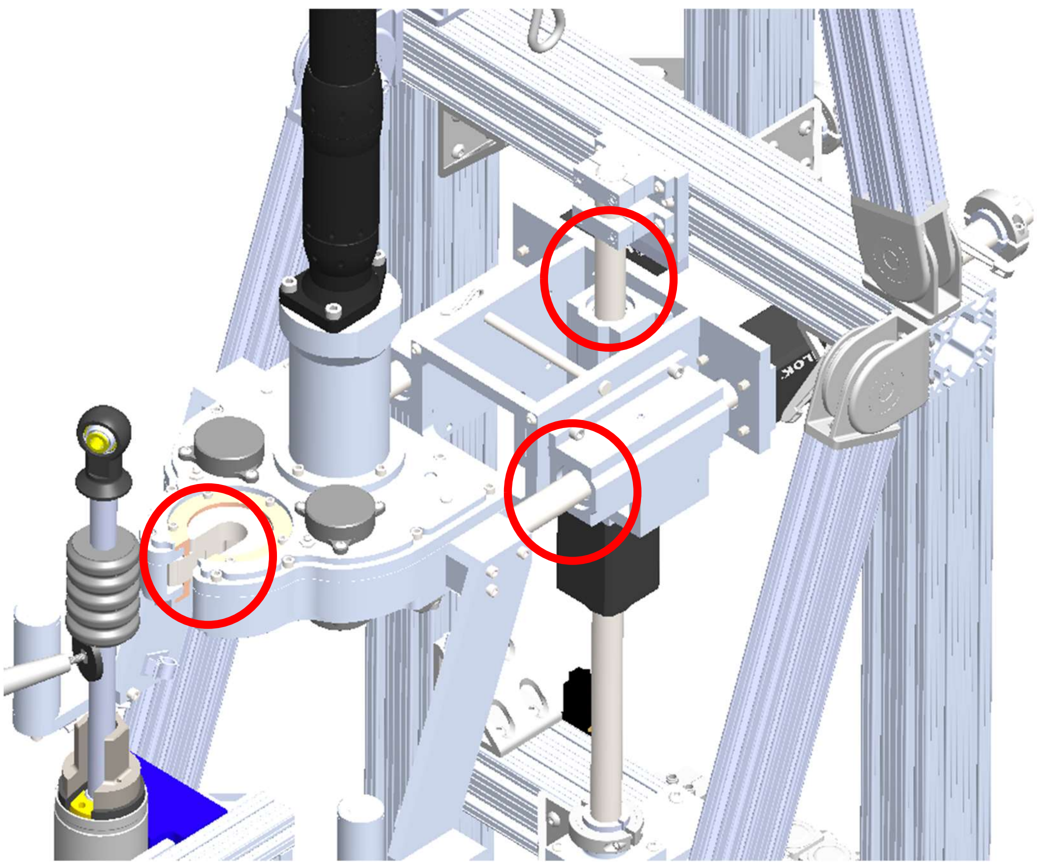
FOX Factory Inc.

Watsonville, CA

Table of Contents

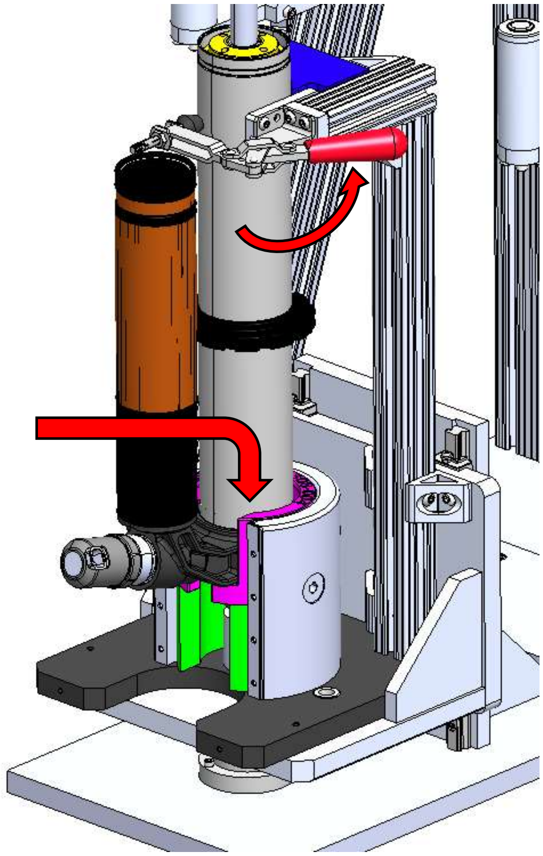
Safety Information

- Read the operators manual before using the machine for the first time
- Never place hands or fingers near driving gear while the machine is on
- Do not place hands or fingers near machine pinch points, shown below in red
- Engage toggle clamp before rundown cycle
- Firmly grasp both handles using both hands during machine operation
- Do not set any items (tools, shock parts, etc.) on top of the drivetrain housing
- Wear Z87+ eye protection at all times while operating the machine
- Do not lift body cap pallet carriage off of pneumatic cylinder or place hands near cylinder
- Inspect air lines for leaks before use
- Inspect torque driver power cord for damage before use
- Ensure nothing is blocking the drivetrain before use

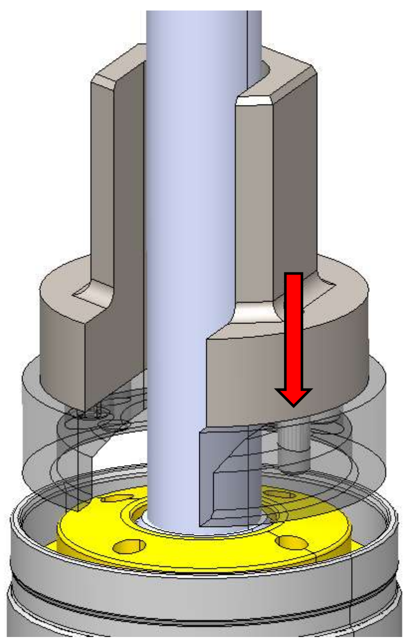


Machine Operation

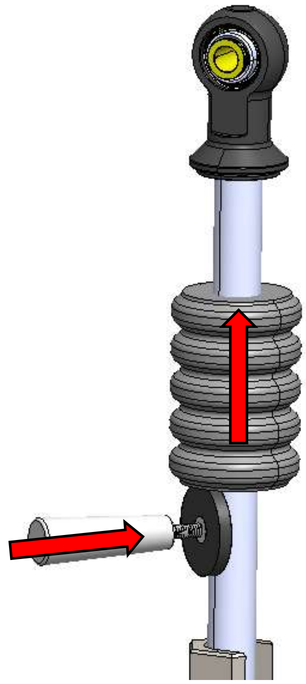
1) With the shaft assembly loosely assembled into the shock body, place the shock into the body cap pallet & secure the body tube by closing the toggle clamp.



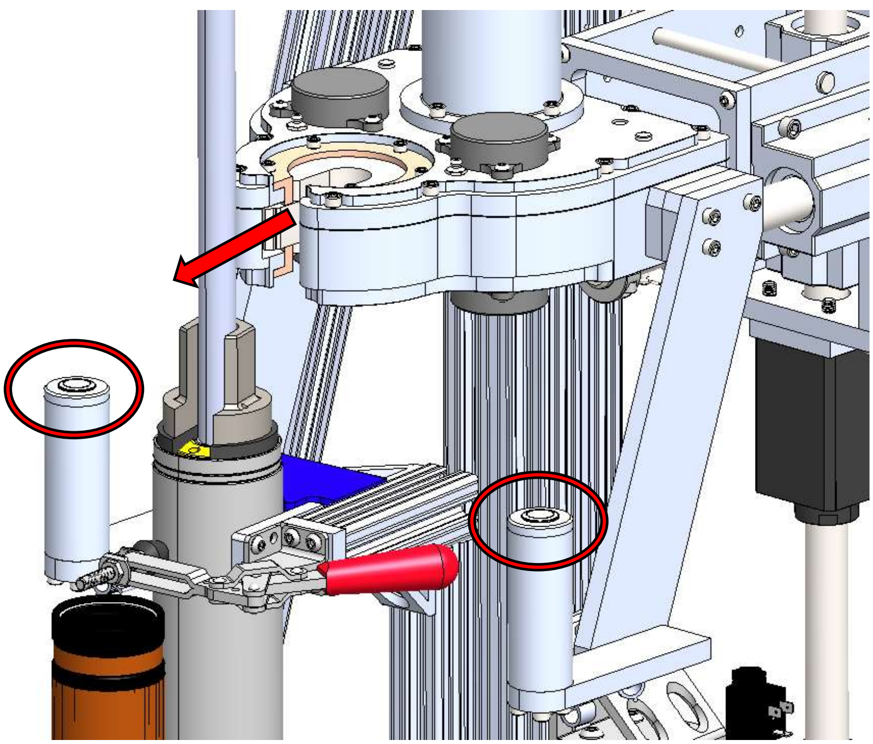
2) Place the hex adapter on the bearing housing, taking care not to scratch the bearing with the pins.



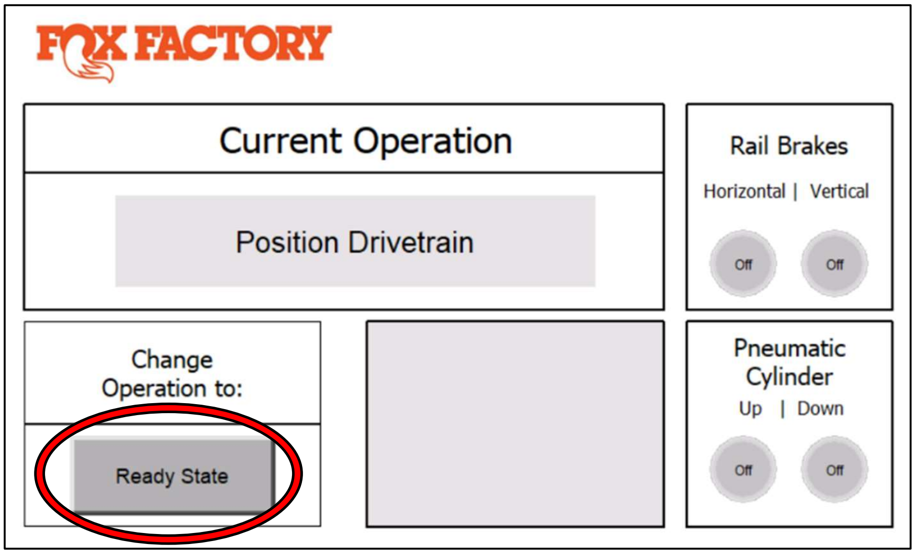
3) Raise the body tube cap and shaft bumper out of the way until bumped up against the eyelet. Clip the magnet assembly to the shaft to keep them away from the bearing.



4) Press & hold the buttons on the drivetrain handles to release the brakes. Slide the drivetrain into place around the shock shaft. Ensure the shaft is centered in the gear, then release the buttons.

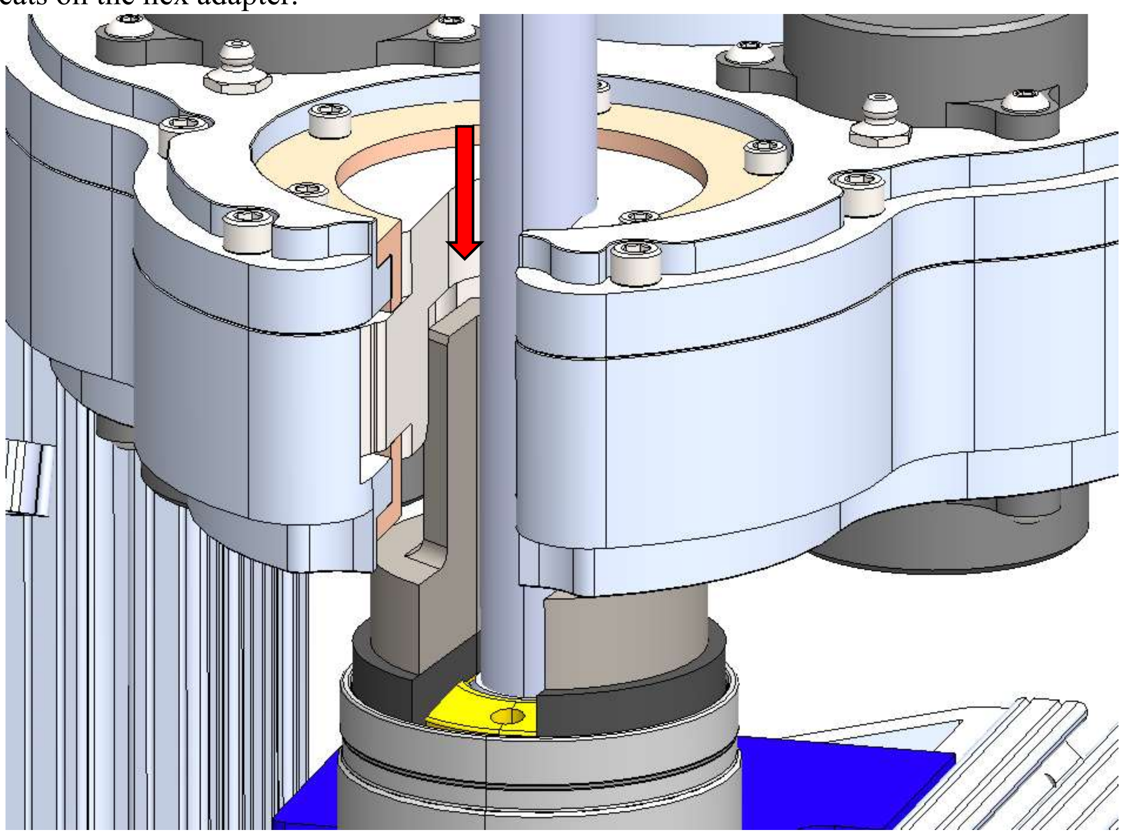


→ *Note*: if either / both of the buttons were released prematurely, press the option on the HMI labeled "Ready State" (under "Change operation to") to re-attempt positioning

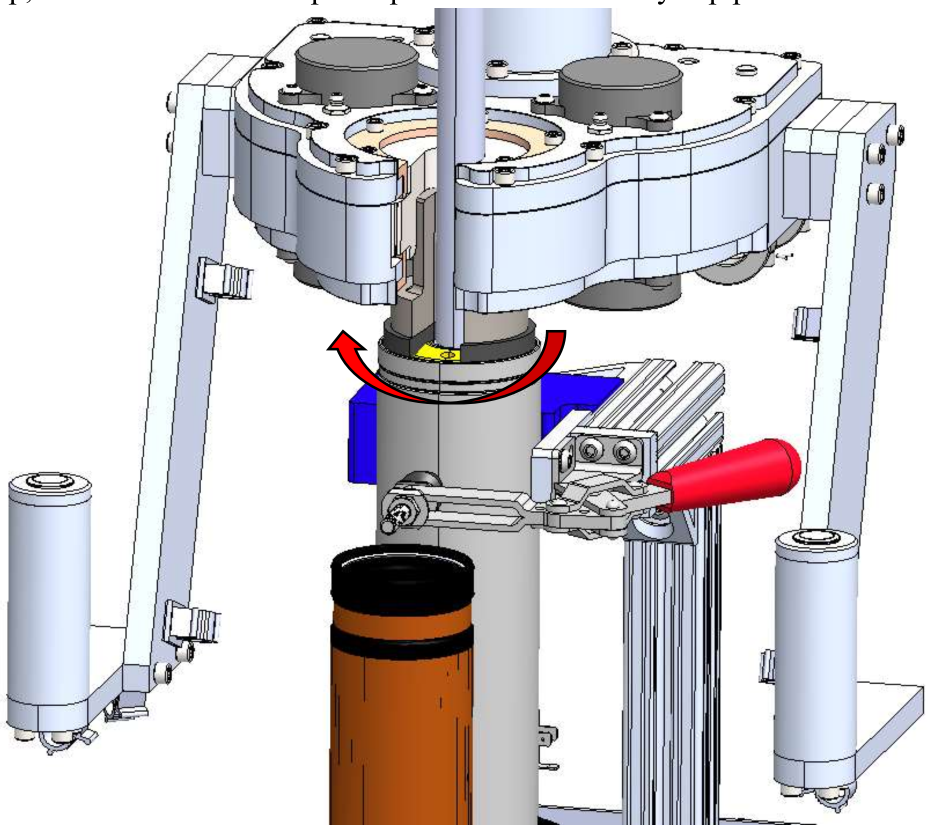


5) Make sure any nearby line associates have their hands clear of the rotating gear. Press both buttons again to start the machine spinning at a low RPM. Lightly pull the handles down until the gear begins to spin the hex adapter. Release the buttons once this engagement occurs.
→ If the gear stops spinning but did not engage correctly, press the HMI option to resume the slow rotation. You will have 5 seconds to return to holding the buttons down.

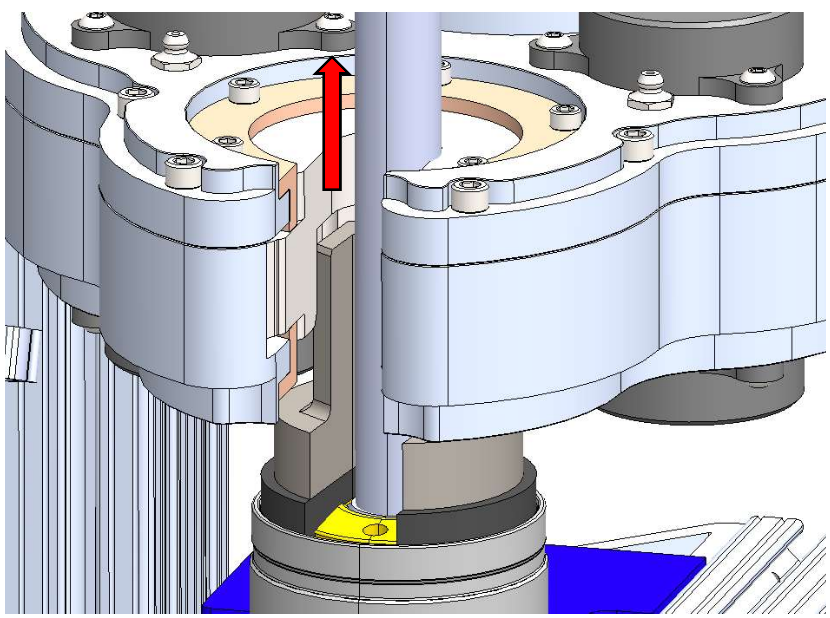
6) With the buttons released & the hex engaged, pull down on the handles until the gear fully seats on the hex adapter.



7) Press the buttons again to initiate the torque & rundown cycle. Ensure that no objects are set on the drivetrain housing, and make sure any nearby line associates have their hands clear of the rotating gear. The pneumatic cylinder beneath the shock will also engage during this step, so take care to avoid pinch points below the body cap pallet.

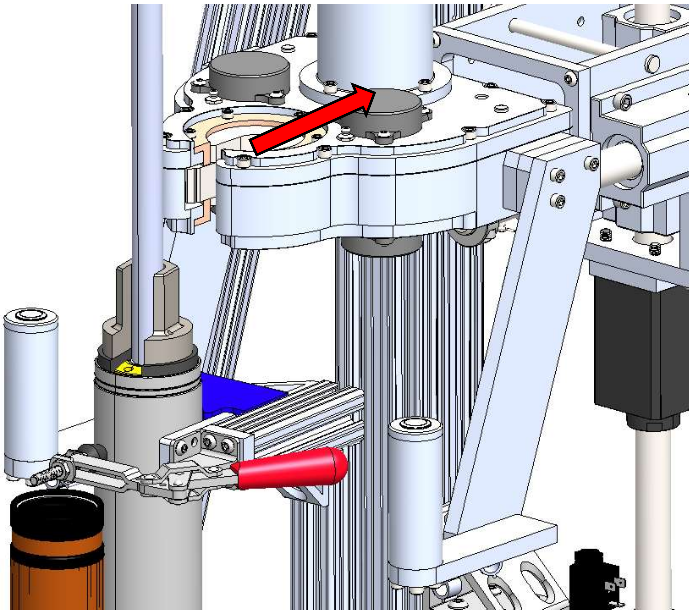


8) The torque driver will stop automatically once the correct torque value is reached. Release the buttons after it stops spinning and pull up on the handles to retract the drivetrain away from hex adapter / bearing. Note that the cylinder will be retracting at this point.

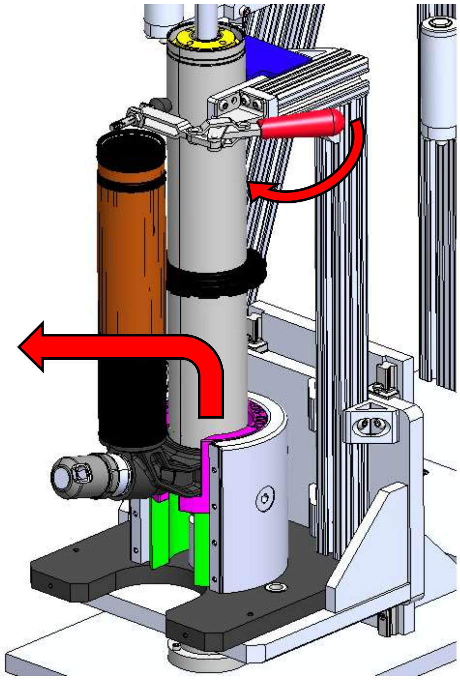


9) With the gear clear of engagement, press the buttons again. This will spin the gear back to its home position, aligning the gear opening with the drivetrain opening.

10) Push the drivetrain back away from the shock, then release the buttons. The machine will again lock drivetrain travel.



11) Remove the hex adapter from the bearing and open the toggle clamp. Remove the new shock assembly from the body cap pallet.



→ Note: for a new body cap pallet insert with a snug fit, the pallet base plate may need to be held down while removing the shock.

Possible Errors & Reset Options

Below is a table of possible errors and other problem situations with the according procedure to follow. The step number in the left most column corresponds to the above steps from the machine operation.

Step # / Description	Error / Situation	Reset / Solution
Any step	**Emergency situation** (object caught in gear, broken machine component, etc.)	**Hit emergency stop**. Get tech team involved to activate machine maintenance mode.
4 / Drivetrain positioning	Buttons released before shaft fully within gear (drivetrain needs to be repositioned)	1) HMI "Change operation to" → "Ready State" 2) Press buttons again to reposition
5 / Slow rotation & 6 / Check for full hex engagement	Buttons released before hex engagement	HMI "Change operation to" → "Slow Rotation." Press & hold the handle buttons down within 5 seconds of selecting this HMI option.
	Non-negligible torque encountered by the gear	Release buttons & re-press. Gear will go into homing process (see step 9). Return to step 4 once gear is in home position.
	Buttons not released / hex not engaged for 10 revolutions	Machine will automatically return to the ready state. Return to step 4.
7 / Torque & Rundown	Buttons released before final torque value reached.	If shock damaged or another problem has occurred, and the shock needs to be removed → HMI "Shock Removal" option. Press buttons again to return gear to home position. Advance to step 9.
		If buttons were released accidentally, re-press buttons to continue torqueing & rundown process.
	Torque limit exceeded	Warning message will occur on HMI. Press HMI option to begin shock removal process. Advance to step 9. Over-torqued shock should go to quality control and tech team should be consulted to adjust machine.
9 / Gear homing	Buttons released before home position reached	Re-press buttons to continue homing process

Note to tech team & engineering: the step numbers from the above table do not correspond to state numbers from the machine state diagram or PLC programming states.

Appendix T. Universal Design Measures

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Universal Design Performance Measures - Fox Senior Project - April 2020

	Principle One | Equitable Use	Not applicable	Stongly Disagree	Disagree	Neutral	Agree	Stongly Agree	Comments
1A.	All potential users could use this product in essentially the same way, regardless of differences in their abilities				X			
1B.	Potential users could use this product without feeling segregated or stigmatized because of differences in personal capabilities					X		
1C.	Potential users of this product have access to all features of privacy, security, and safety, reguardless of personal capabilites						X	
1D.	This product appeals to all potential users	X						

	Principle Two | Flexibility in Use	Not applicable	Stongly Disagree	Disagree	Neutral	Agree	Stongly Agree	Comments
2A.	Every potential user can find at least one way to use this product effectively					X		Still need training manual for operation
2B.	This product can be used with either the right or left hand alone.	X						Need both hands for operation
2C.	This product facilitates (or does not require) user accuracy and precision.			X				
2D.	This product can be used at whatever pace (quickly or slowly) the user prefers.						X	

	Principle Three | Equitable Use	Not applicable	Stongly Disagree	Disagree	Neutral	Agree	Stongly Agree	Comments
3A.	This product is as simple and straightforward as it can be				X			Could possibly make work with 1 push of buttons instead of 2, but would add controls complication
3B.	An untrained person could use this product without instructions			X				
3C.	Any potential user can understand the language used in this product	X						
3D.	The most important feature of this product are the most obvious					X		
3E.	This product provides feedback to the user						X	

Neutral

	Principle Four | Equitable Use	Not applicable	Stongly Disagree	Disagree	Nuetral	Agree	Stongly Agree	Comments
4A.	This product can be used without hearing.						X	
4B.	This product can be used without sight.		X					
4C.	The features of this product can be clearly described in words (e.g., in instruction manuals or on telephone help lines).					X		
4D.	This product can be used by persons who use assistive devices (e.g., eyeglasses, hearing airs, sign language, or service animals).					X		Not currently wheelchair accessible

Appendix U. Risk Assessment

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designsafe Report

Application:	Bearing Run Down Machine	Analyst Name(s):	Riley O'Connor, David Daley, Chris Hansen, Eric Forrester
Description:		Company:	Fox Factory
Product Identifier:	399-50-925 Bearing Run Down Machine	Facility Location:	130 Hangar Way, Watsonville, CA 95076
Assessment Type:	Detailed		
Limits:			
Sources:			
Risk Scoring System:	ANSI B11.0 (TR3) Two Factor		

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-1-1	All Users normal operation	mechanical : pinch point Driven gear catching finger	Serious Likely	High	Both buttons on handles need to be pushed simultaneously to drive gearhead	Serious Unlikely	Medium	Complete [3/8/2020] David
1-1-2	All Users normal operation	ergonomics / human factors : lifting / bending / twisting Drivetrain weighs more than 35 lb	Moderate Very Likely	High	Tool balancer makes structure hold weight of drivetrain	Moderate Unlikely	Low	Complete [3/8/2020] Riley
1-1-3	All Users normal operation	fluid / pressure : pneumatics rupture Leaking air lines	Moderate Likely	Medium	Train operators to inspect air lines before use	Moderate Unlikely	Low	On-going [Daily] Riley
2-1-1	maintenance technician periodic maintenance	mechanical : pinch point Driven gear catching finger	Serious Likely	High	Train technicians to keep hands away from drive gear when in maintenance mode	Serious Unlikely	Medium	On-going [Daily] Riley
2-1-2	maintenance technician periodic maintenance	ergonomics / human factors : lifting / bending / twisting Drivetrain weighs more than 35 lb	Moderate Likely	Medium	Train operators to support drivetrain and structures carraige when servicing tool balancer	Moderate Unlikely	Low	On-going [Daily] Riley
2-1-3	maintenance technician periodic maintenance	fluid / pressure : pneumatics rupture Removing airline fittings while system is pressurized	Moderate Likely	Medium	Train operators to release air pressure during maintenance	Moderate Unlikely	Low	On-going [Daily] Riley

Appendix V. Assembly Drawings

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4 3 2 1

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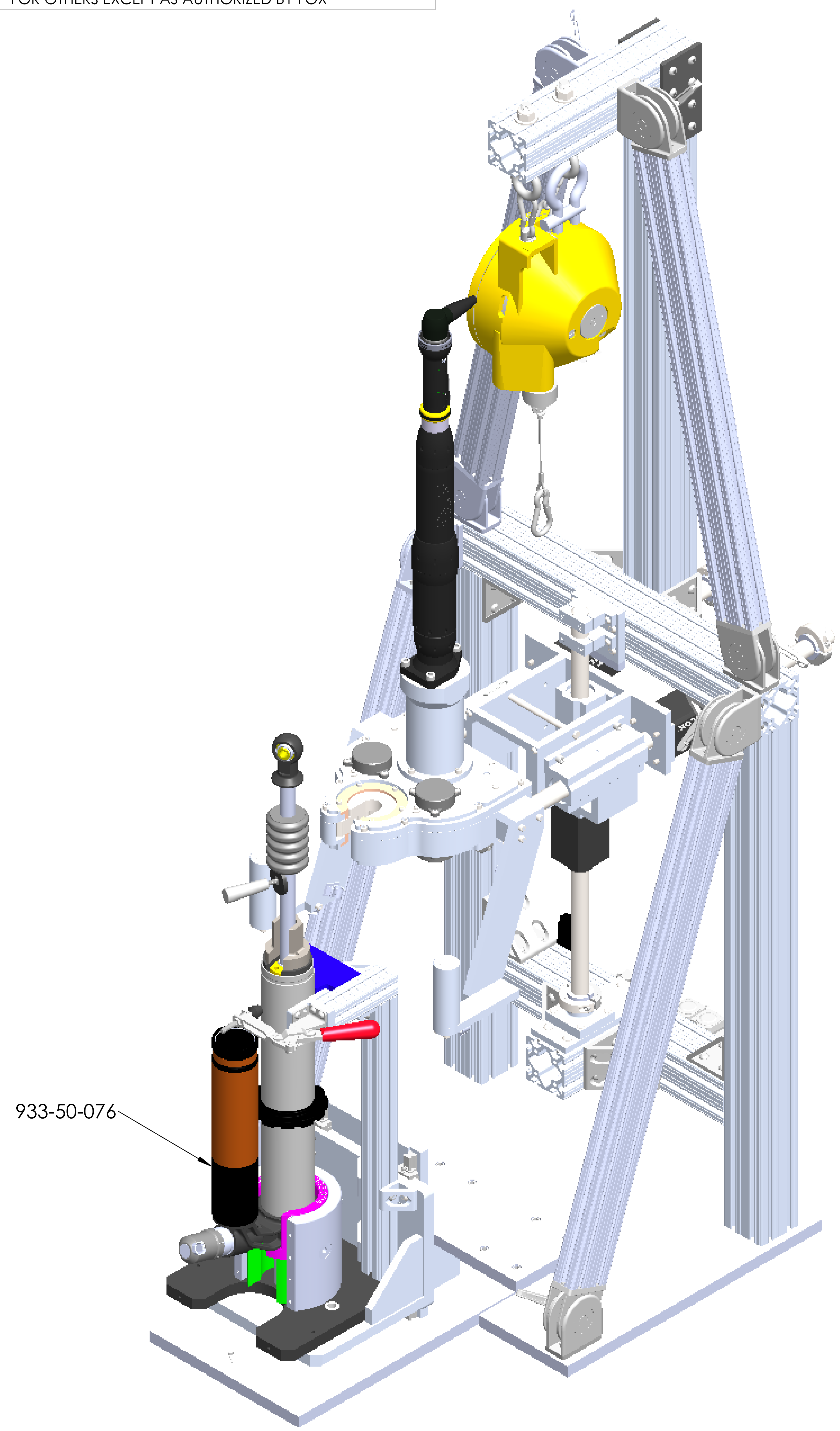
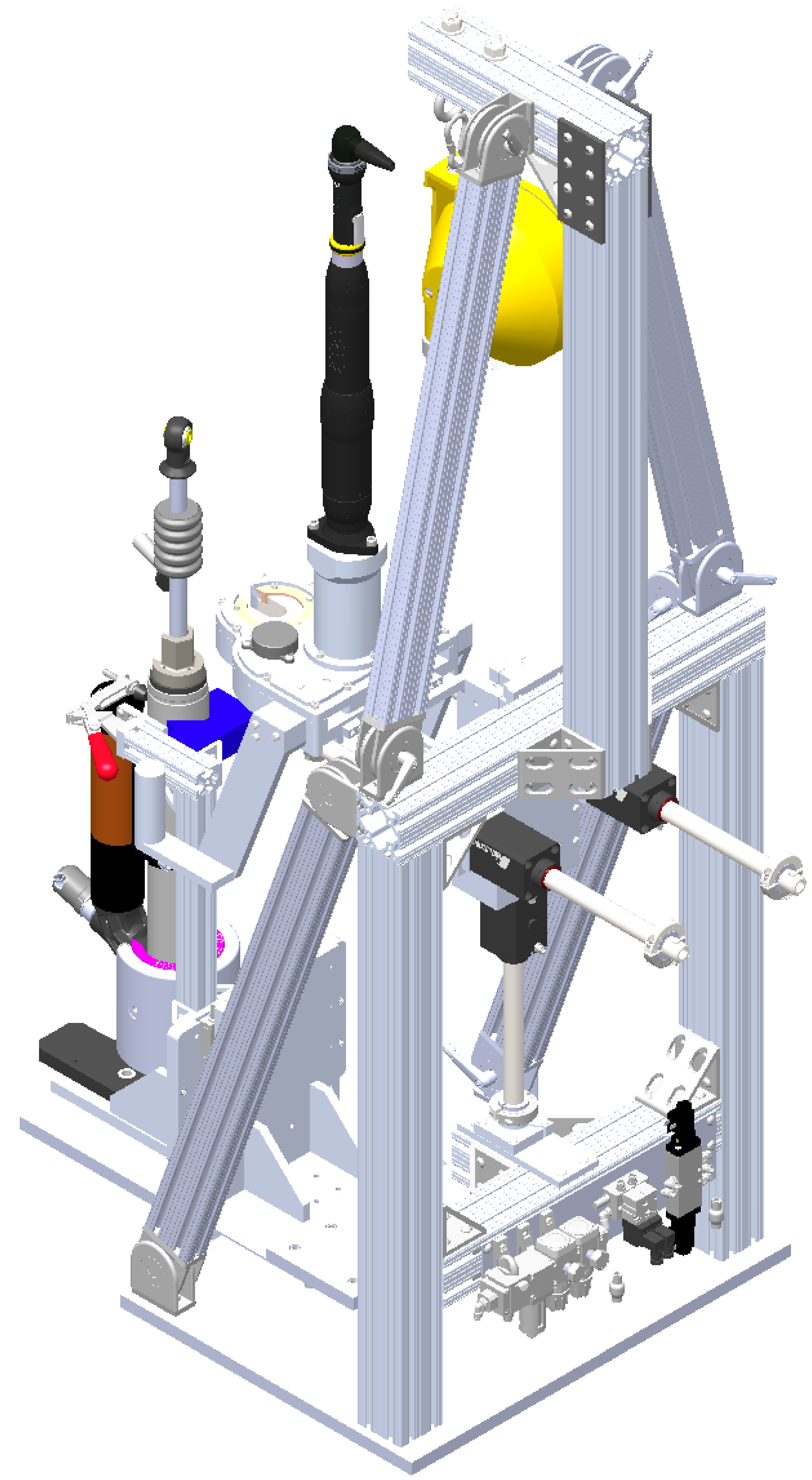
1	INITIAL	05/23/2020	R. O'CONNOR

D C B A





PER ASME Y14.5M 1994		FOX Factory, Inc. CAL POLY College of Engineering	
APPROVALS	DATE	130 Hangar Way, Watsonville, CA 95076 USA, Ph 831-768-1100, Fax 831-768-9312	
DWN. BY R. O'CONNOR	05/23/2020	BEARING RUN DOWN AND TORQUE MACHINE	
CHK. BY D. DALEY	05/23/2020		
ENG. T. MULROONEY W. CRAWFORD		SIZE C	ASSEM. NO. 399-50-925-01
MFG.		PLOT SCALE: 1:6	SHEET 1 OF 2

4 3 2 1

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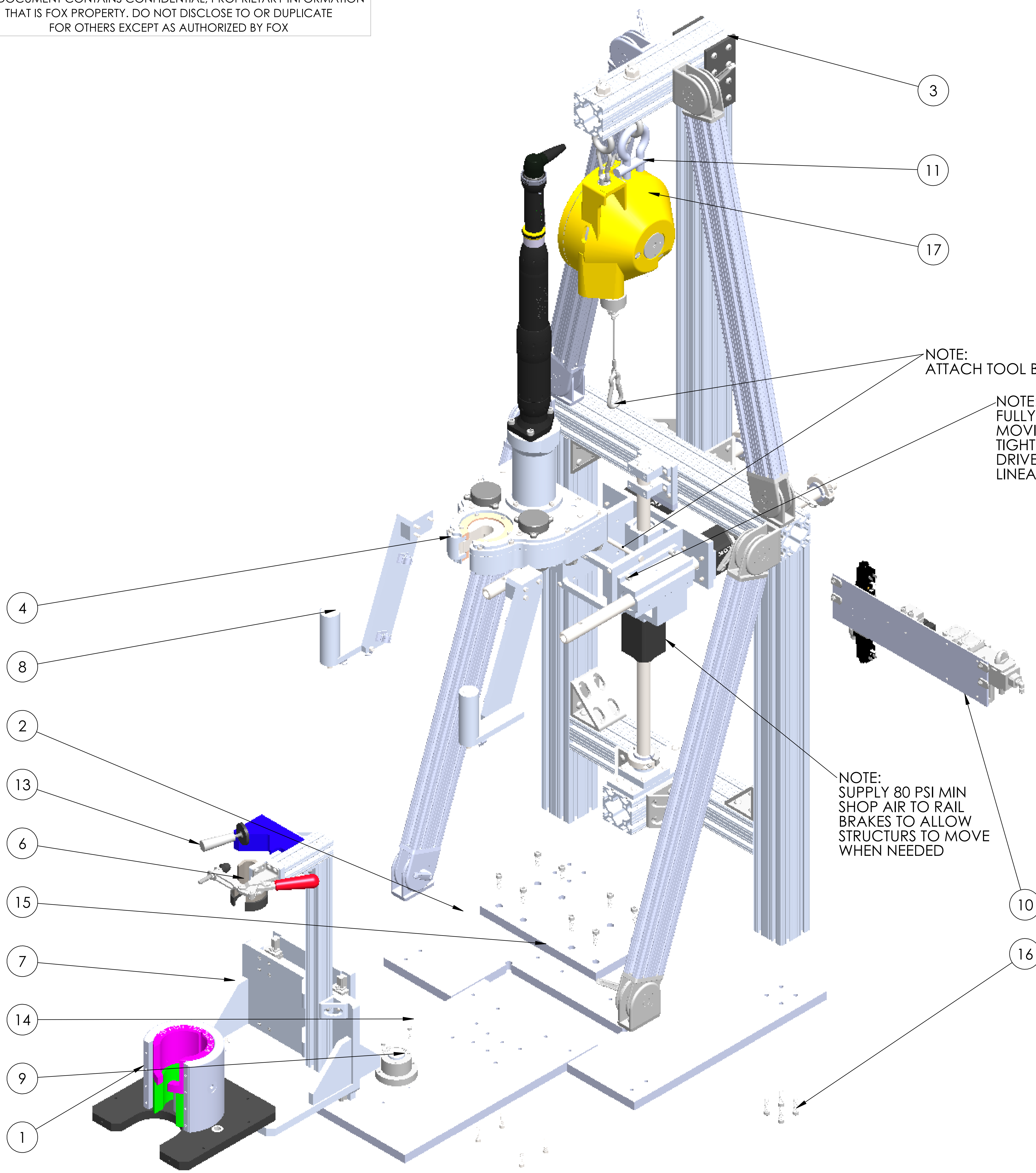

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	399-50-780-30_340-3	Body Cap Pallet	1
2	399-50-925-004	Machine Base Plate	1
3	399-50-925-03	Structures	1
4	399-50-925-02	Drivetrain	1
5	91251A347	Black-Oxide Alloy Steel Socket Head Screw 10-32 Thread Size, 1" Long	3
6	399-50-925-04	Adapter Piece Assembly	1
7	399-50-925-06	Fixturing	1
8	399-50-925-09	Handle Assembly	1
9	399-50-925-11	Air Cylinder Ram Assembly	1
10	399-50-925-10	Pneumatics Assembly	1
11	8494T32	Black-Oxide Steel Shackle with Safety Pin - for Lifting, 5-8 Thick	1
12	91251A542	1/4-20x1" SHCS	4
13	399-50-925-14	MAGNET CLIP FOR BOOT & CAP	1
14	399-50-925-054	Pallet Base Plate	1
15	399-50-925-053	Pallet Connecter Plate	1
16	91251A583	Black-Oxide Alloy Steel Socket Head Screw 5/16"-18 Thread Size, 1" Long	16
17	8202_0780_02	Tool Balancer	1

SIZE	ASSEM. NO.	REV.
C	399-50-925-01	1

PLOT SCALE: 1:6 SHEET 2 OF 2

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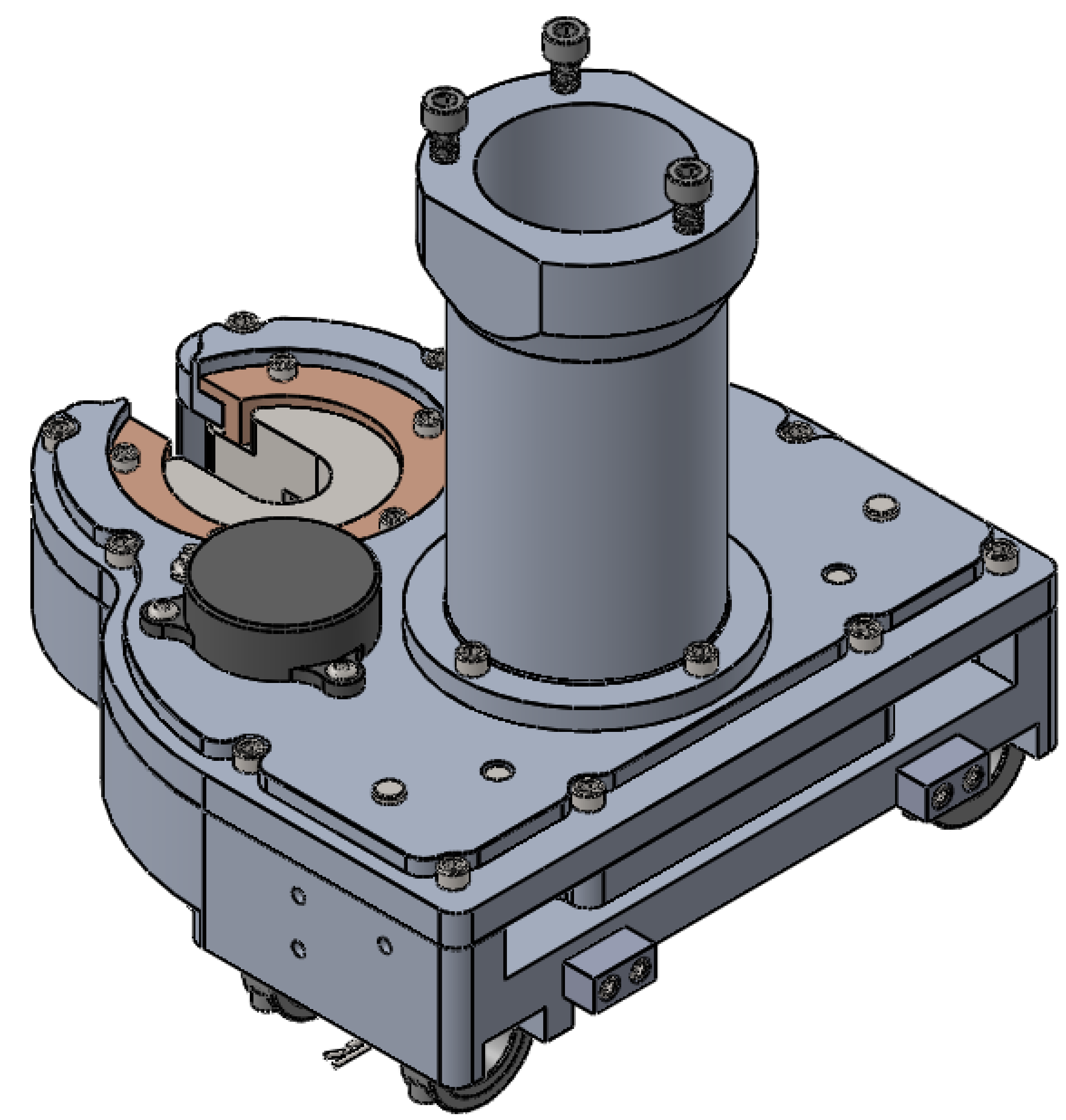
DRIVE TRAIN ASSEMBLY PACKET



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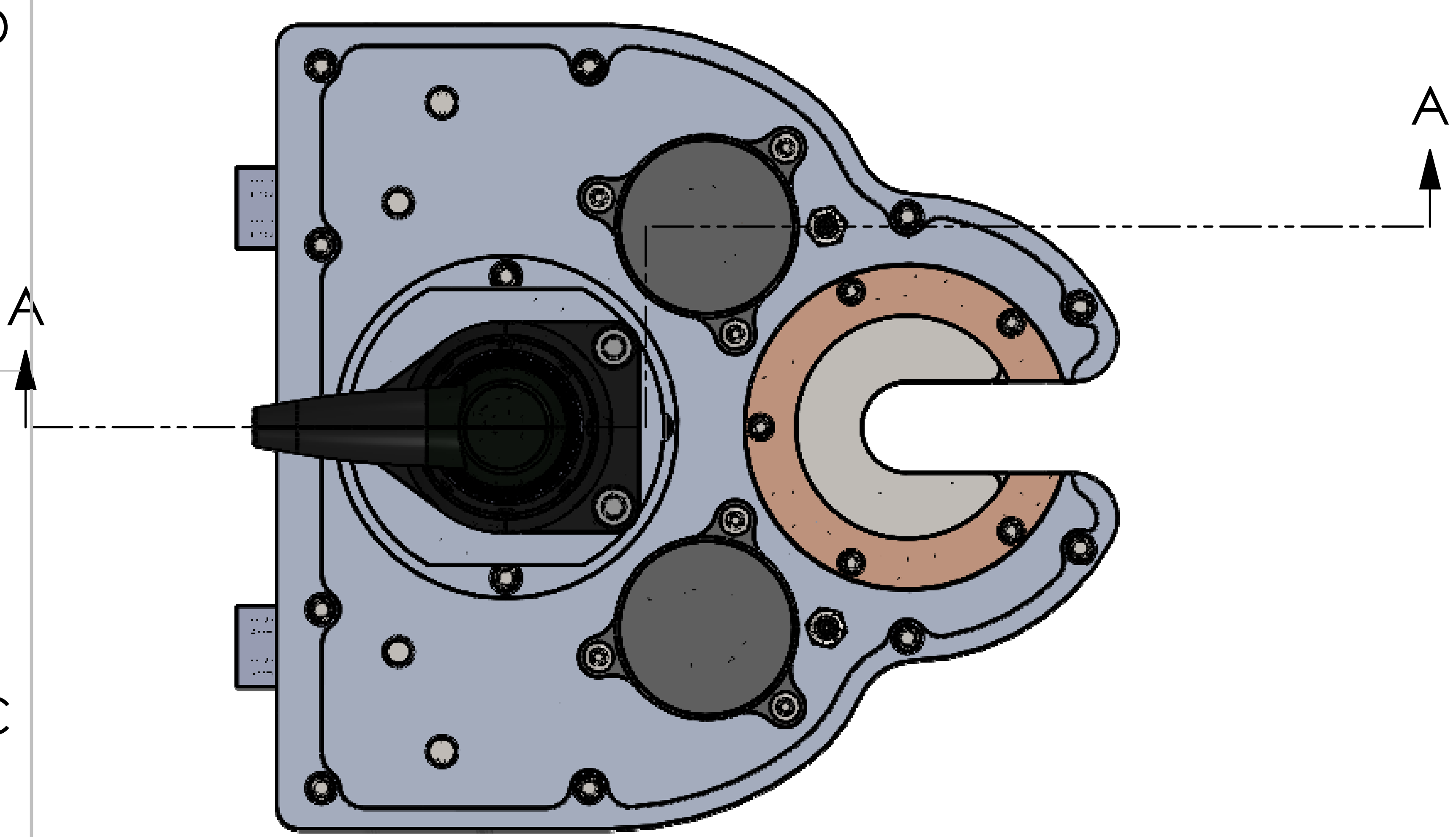
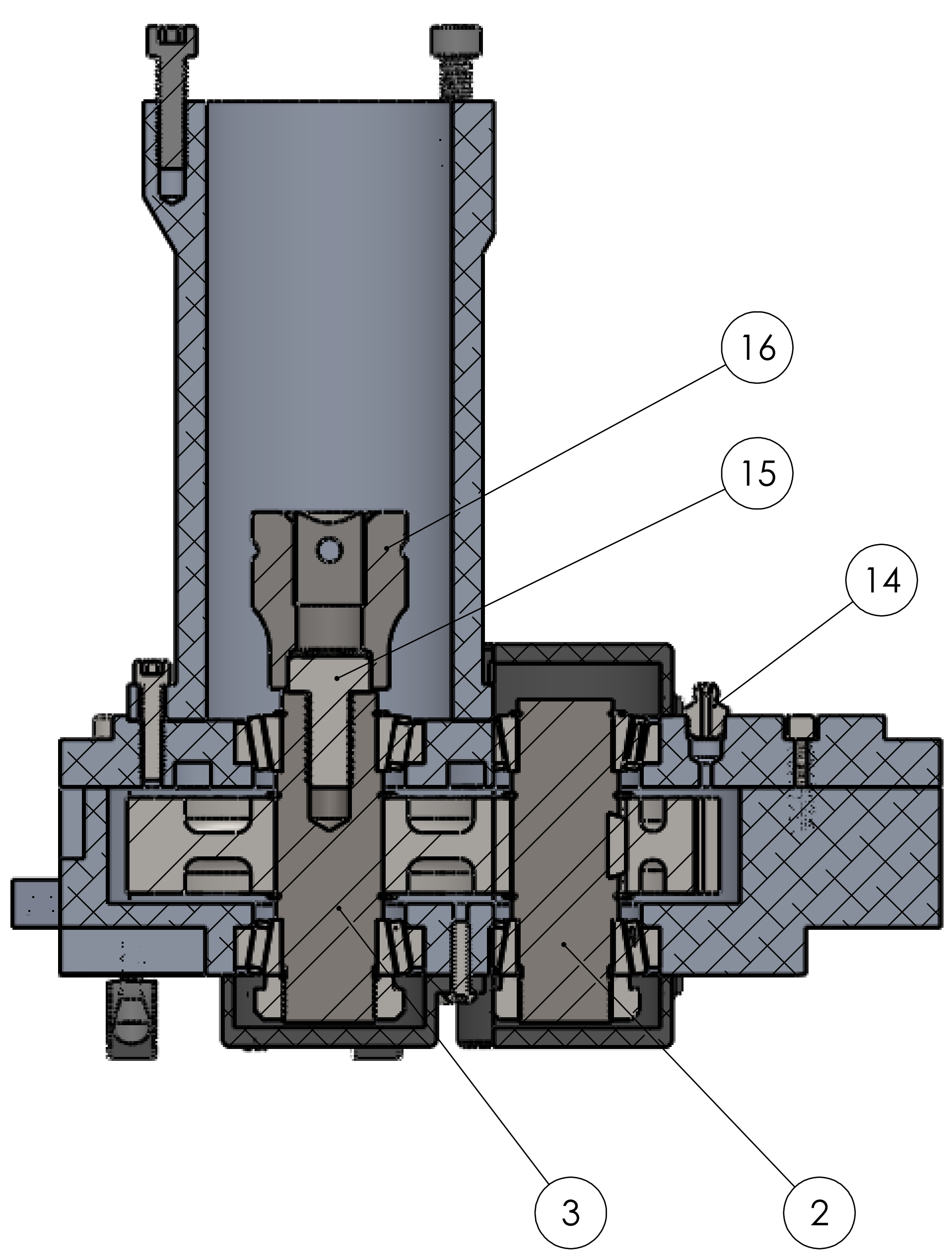
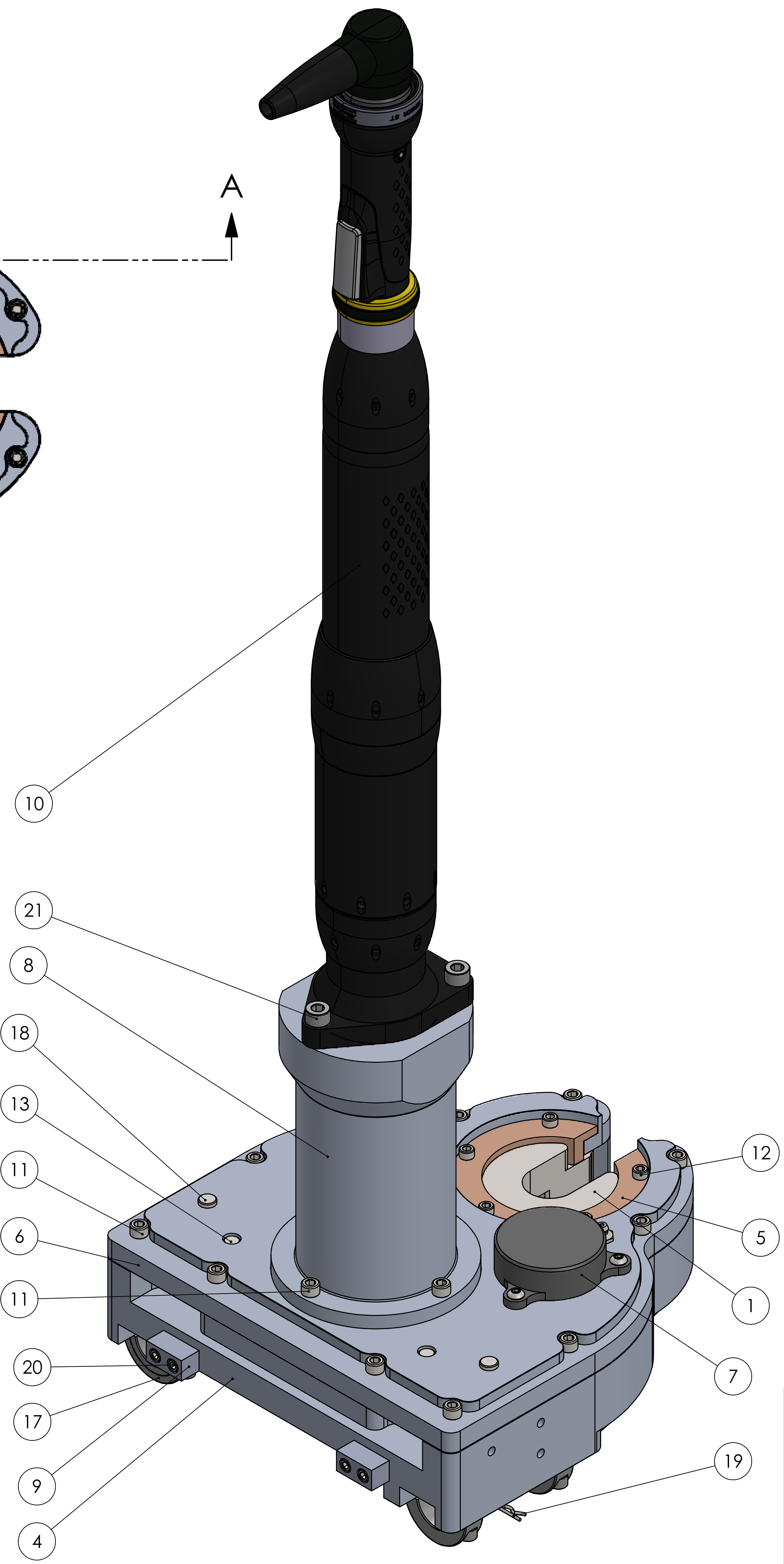
APPROVALS	DATE	130 Hangar Way, Watsonville, CA 95076 USA, Ph 831-768-1100, Fax 831-768-9312
DWN. BY E. FORRESTER	05/11/2020	DRIVE TRAIN ASSEMBLY DRIVE TRAIN ASSEMBLY PACKET
CHK. BY D. DALEY	05/15/2020	
ENG. T. MULROONEY W. CRAWFORD		SIZE C ASSEM. NO. 399-50-925-02
MFG.		PLOT SCALE: 1:2 SHEET 1 OF 11

REVISIONS			
REV	DESCRIPTION	DATE	APPROVED
1	INITIAL	05/11/2020	E. FORRESTER

DRIVE TRAIN BILL OF MATERIALS:
ASSEMBLY DETAILED OUT IN SHEETS 5-11.
UTLIZED FOR TOP LEVEL COMPONENTS AND SUBASSEMBLY.







ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	399-50-925-001	Slotted McMaster Gear_6325K52	1
2	399-50-925-05	Idler Gear Assembly	2
3	399-50-925-07	Drive Shaft Assembly	1
4	399-50-925-003_N	Bottom Case Half	1
5	399-50-925-002_N	Slotted Bushing Made from 6338K614	2
6	399-50-925-009_N	Top Case Half	1
7	399-50-925-08	Shaft Cap Assembly	5
8	399-50-925-019	Torque Driver Adapter	1
9	399-50-925-044	Front Bump Stops	2
10	8433218205 toruqe driver	Atlas Copco inline Torque Driver	1
11	91251A542	1/4-20x1" SHCS	14
12	91251A242	10-24x1/2" SHCS	10
13	98381A626	3/8x1.25" Dowel Pin	2
14	1095K65	Steel Grease Zerk	2
15	90201A415	1/2"-13x1" Grade 9 Socket Cap Screw	1
16	399-50-925-013	Made from 3/4" Square Drive 3/4" Hex	1
17	6436K18	Clamp-On Shaft Collar Top Piece	4
18	98306A179	Steel Clevis Pin	2
19	98335A044	Cotter Pin	2
20	91251A194	8-32x1/2" SHCS	4
21	91290A434	M8x1.25x30 SHCS	3

PER ASME Y14.5M 1994

FOX Factory, Inc.

CAL POLY
College of Engineering

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DWN. BY	E. FORRESTER	05/11/2020
CHK. BY	D. DALEY	05/15/2020
ENG.	T. MULROONEY W. CRAWFORD	
MFG.		

DRIVE TRAIN BILL OF MATERIALS
TOP LEVEL BILL OF MATERIALS

SIZE C | ASSEM. NO. 399-50-925-02

PLOT SCALE: 1:2 | SHEET 2 OF 11

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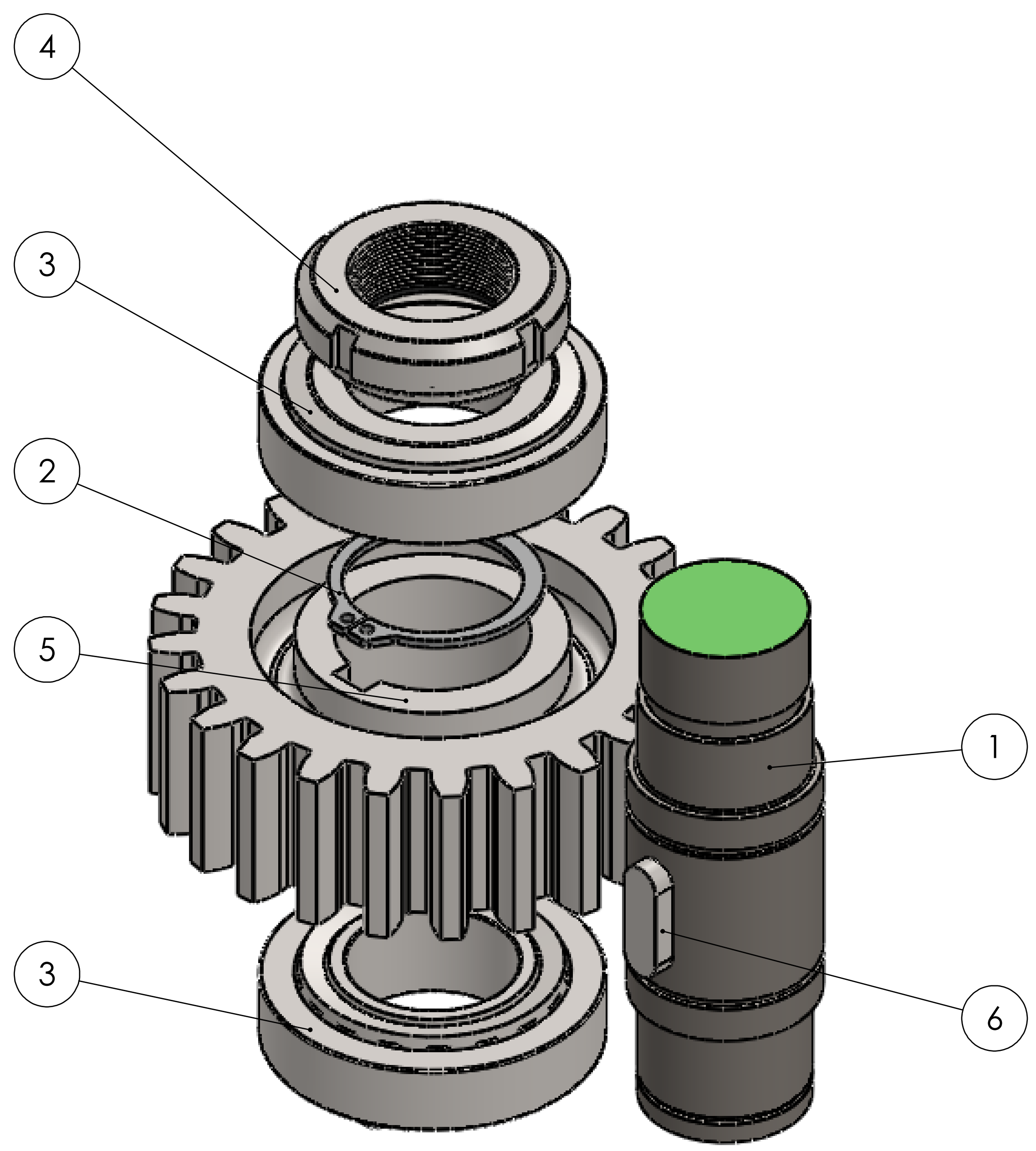

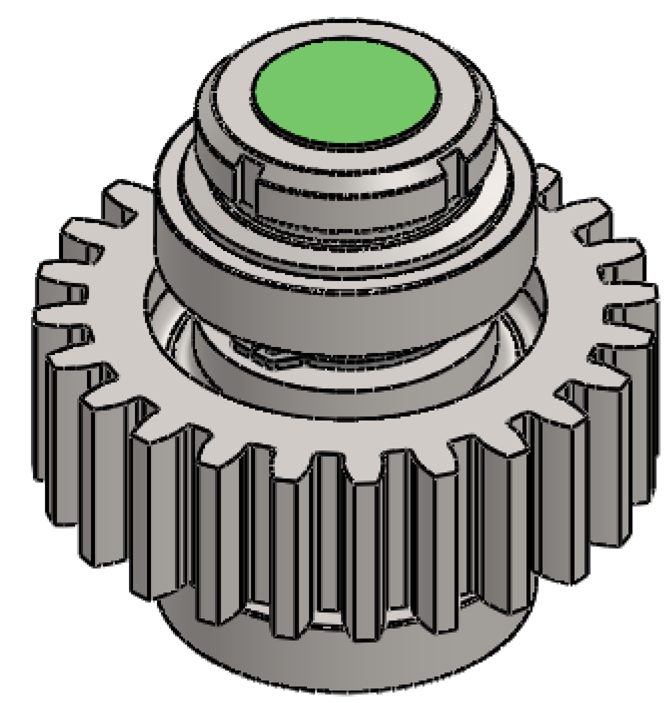

QTY: 2 Idler Shaft Assemblies Per drivetrain
Do not assemble as shown. Assembly detailed in sheets 5-11.

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	399-50-925-010-XXX	IDLER SHAFT -010-001 SHOWN. EITHER WORK	1
2	97633A320	1.125 EXTERNAL RETAINING RING	2
3	5709K82	TAPERED ROLLER BEARING	2
4	6343K16	THREADED BEARING LOCKNUT	1
5	399-50-925-018_6325K490_N	GEAR MADE FROM 6325K49	1
6	95053A595	1/4" MACHINE KEY	1
7	97633A300	1" EXTERNAL RETAINING RING	1

PER ASME Y14.5M 1994

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130 Hangar Way, Watsonville, CA 95076 USA, Ph 831-768-1100, Fax 831-768-9312

APPROVALS	DATE
DWN. BY E. FORRESTER	05/11/2020
CHK. BY D. DALEY	05/15/2020
ENG. T. MULROONEY W. CRAWFORD	
MFG.	

IDLER SHAFT BILL OF MATERIALS

SIZE C | ASSEM. NO. 399-50-925-05

PLOT SCALE: 1:1

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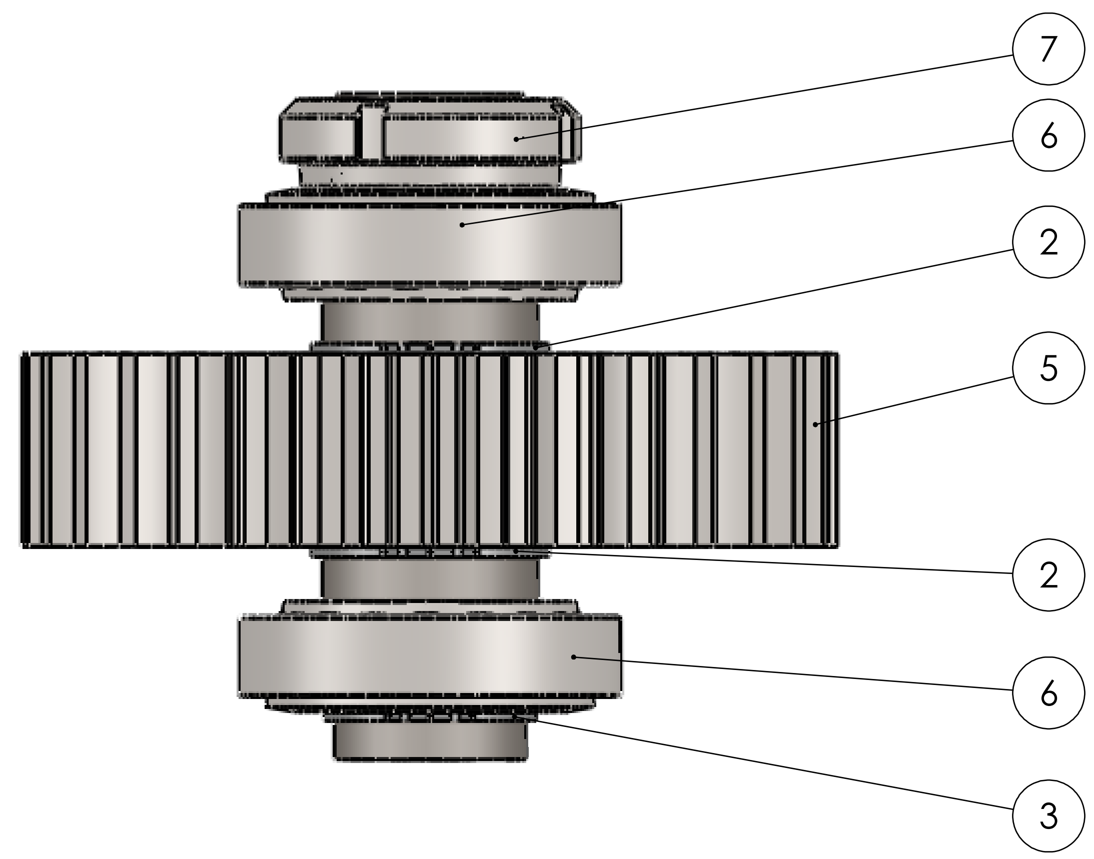
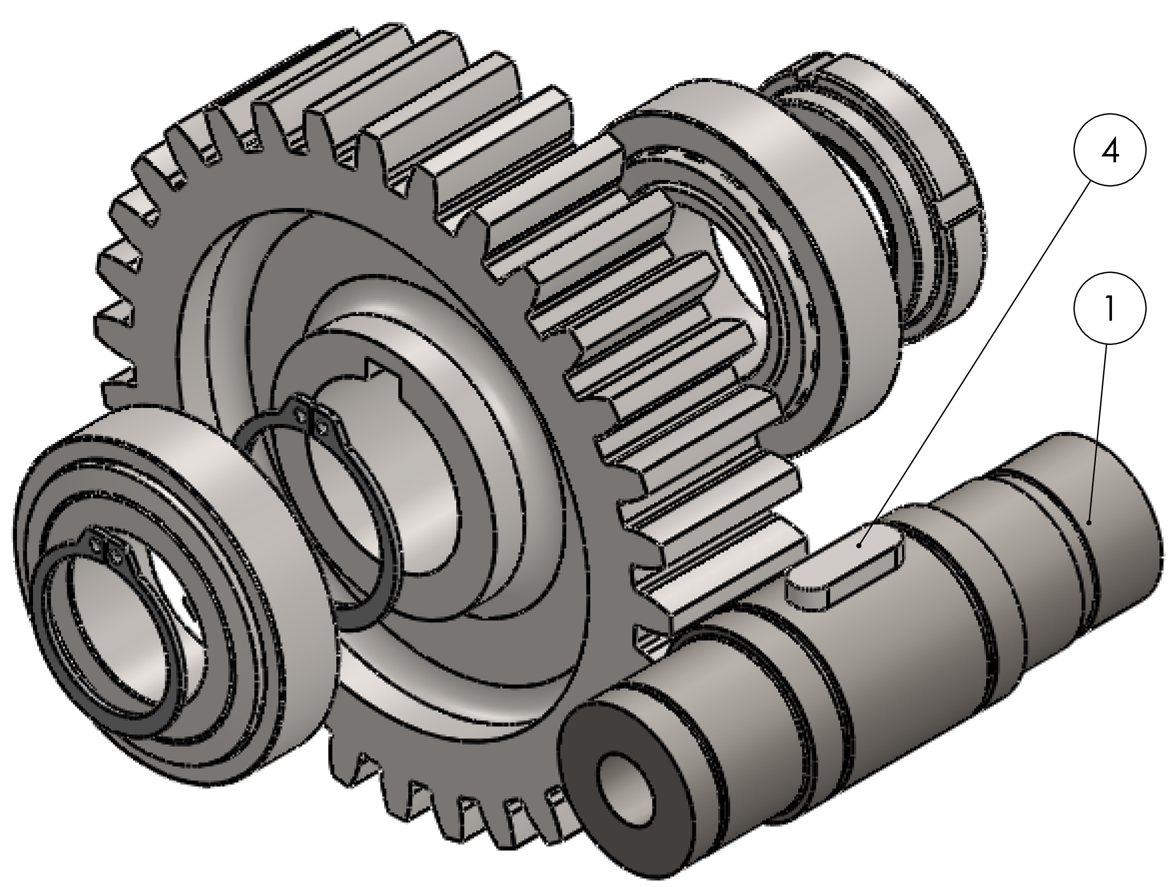
1	INITIAL	05/11/2020	E. FORRESTER





QTY: 1 Drive Shaft Assembly Per drivetrain
Do not assemble as shown. Assembly detailed in sheets 5-11

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	399-50-925-016-XXX	DRIVE SHAFT 016-001 CURRENTLY SHOWN. EITHER WORK.	1
2	97633A320	1.125 EXTERNAL RETAINING RING	2
3	97633A300	1" EXTERNAL RETAINING RING	1
4	95053A595	1/4" MACHINE KEY	1
5	399-50-925-008_6325K520_N	DRIVE GEAR. MADE FROM 6325K52	1
6	5709K82	TAPERED ROLLER BEARING	2
7	6343K16	THREADED BEARING LOCKNUT	1

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CHK. BY	D. DALEY	05/15/2020
ENG.	T. MULROONEY W. CRAWFORD	
MFG.		

DRIVE SHAFT BILL OF MATERIALS

SIZE C | ASSEM. NO. 399-50-925-08

PLOT SCALE: 1:1 | SHEET 4 OF 11

4 3 2 1

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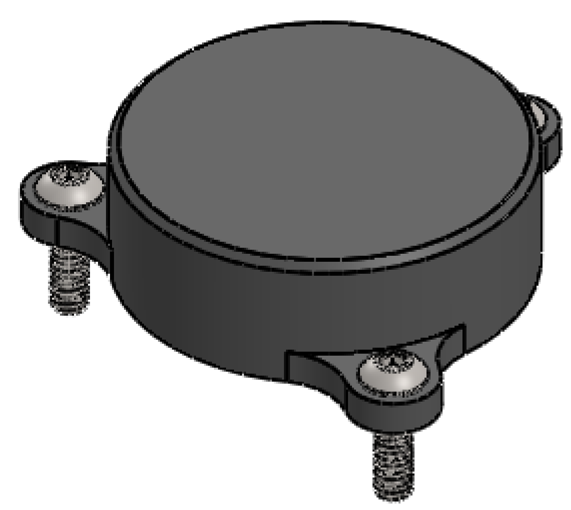
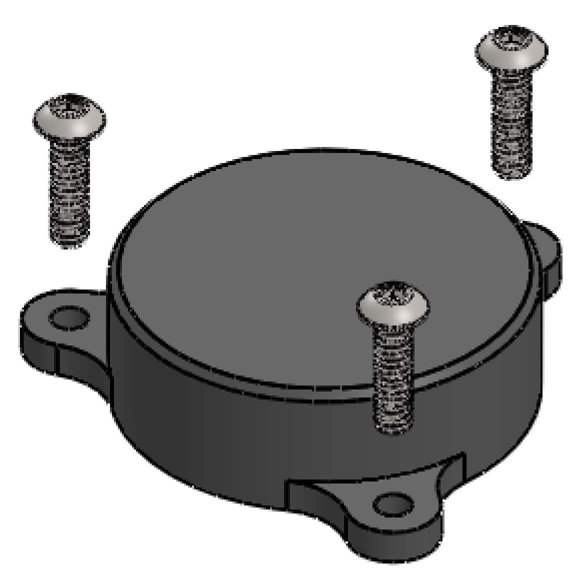


C

B



A

QTY: 5 Shaft Cap Assemblies Per drivetrain

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	399-50-925-017	Shaft Cap	1
2	91255A245	10-24 x 3/4" BHCS	3

PER ASME Y14.5M 1994

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APPROVALS	DATE
DWN. BY E. FORRESTER	05/11/2020
CHK. BY D. DALEY	05/15/2020
ENG. T. MULROONEY W. CRAWFORD	
MFG.	

SHAFT CAP BILL OF MATERIALS
ASSEMBLY DRAWINGS

SIZE C | ASSEM. NO. 399-50-925-08

PLOT SCALE: 1:1 | SHEET 5 OF 11

REVISIONS

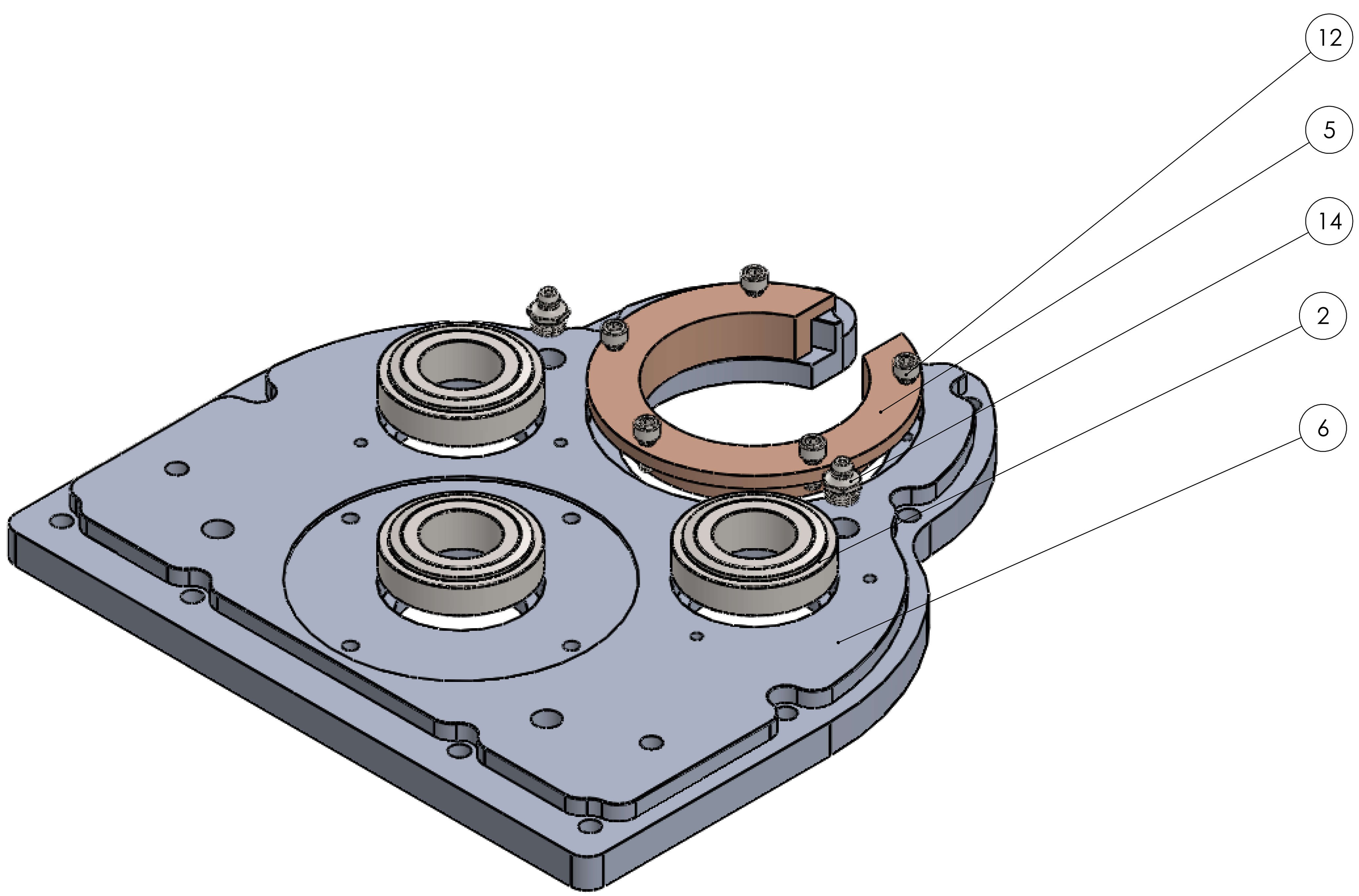
REV	DESCRIPTION	DATE	APPROVED
1	INITIAL	05/11/2020	E. FORRESTER

ENSURE THAT THE TAPERED ROLLER BEARINGS ARE PUT IN TAPER TOWARD THE INSIDE OF THE CASE

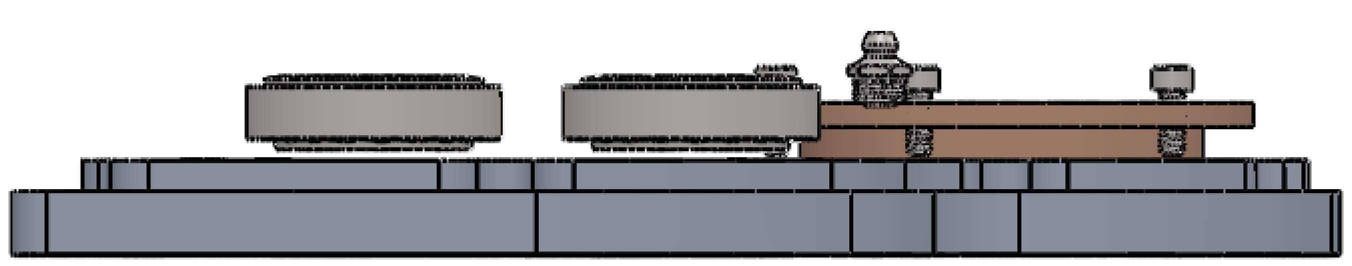
ENSURE THAT THE BEARINGS ARE PACKED WITH GREASE

USE BLUE LOCTITE ON OUTER RACE AT DISCRETION OF ASSEMBLER
*DO NOT USE FOR TEST ASSEMBLY

BEARINGS SHOULD BE A SLIP FIT



ASSEMBLE THE TOP CASE HALF AS SHOWN HERE



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	399-50-925-001	Slotted McMaster Gear_6325K52	1
2	399-50-925-05	Idler Gear Assembly	2
3	399-50-925-07	Drive Shaft Assembly	1
4	399-50-925-003_N	Bottom Case Half	1
5	399-50-925-002_N	Slotted Bushing Made from 6338K614	2
6	399-50-925-009_N	Top Case Half	1
7	399-50-925-08	Shaft Cap Assembly	5
8	399-50-925-019	Torque Driver Adapter	1
9	399-50-925-044	Front Bump Stops	2
10	8433218205 toruqe driver	Atlas Copco inline Torque Driver	1
11	91251A542	1/4-20x1" SHCS	14
12	91251A242	10-24x1/2" SHCS	10
13	98381A626	3/8x1.25" Dowel Pin	2
14	1095K65	Steel Grease Zerk	2
15	90201A415	1/2"-13x1" Grade 9 Socket Cap Screw	1
16	399-50-925-013	Made from 3/4" Square Drive 3/4" Hex	1
17	6436K18	Clamp-On Shaft Collar Top Piece	4
18	98306A179	Steel Clevis Pin	2
19	98335A044	Cotter Pin	2
20	91251A194	8-32x1/2" SHCS	4
21	91290A434	M8x1.25x30 SHCS	3

PER ASME Y14.5M 1994

FOX Factory, Inc.
CAL POLY College of Engineering
130 Hangar Way, Watsonville, CA 95076 USA, Ph 831-768-1100, Fax 831-768-9312

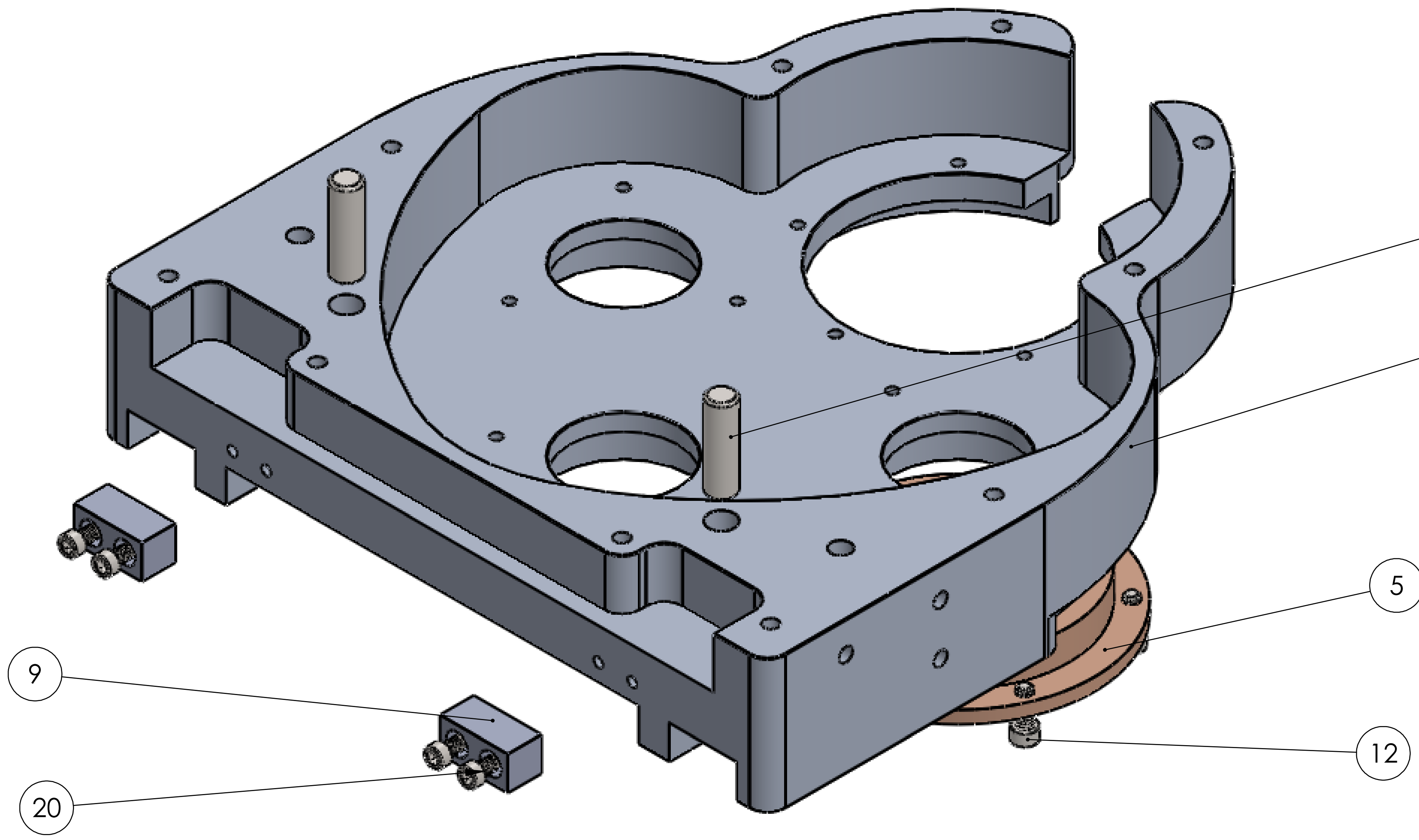
APPROVALS		DATE
DWN. BY	E. FORRESTER	05/11/2020
CHK. BY	D. DALEY	05/15/2020
ENG.	T. MULROONEY W. CRAWFORD	
MFG.		

TOP CASE HALF
ASSEMBLY 1

SIZE C
ASSEM. NO. 399-50-925-02

PLOT SCALE: 2:3

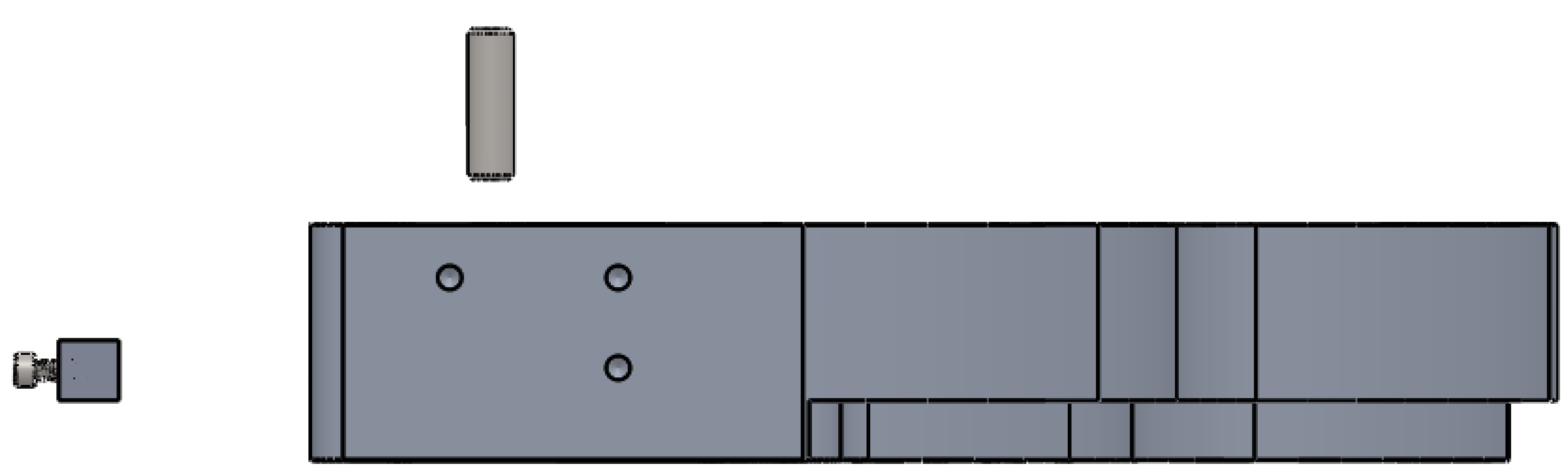
REVISIONS			
REV	DESCRIPTION	DATE	APPROVED
1	INITIAL	05/11/2020	E. FORRESTER

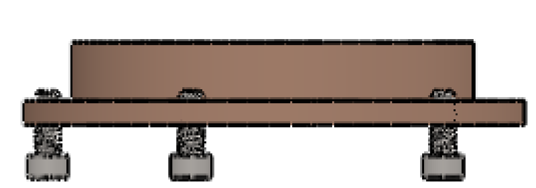


PRESS DOWEL PINS IN UNTIL THERE SHOULD BE NO LESS THAN .71 INCHES OF STICK OUT ON THE DOWEL PIN

CAREFUL OF THE INSIDE SHOULDER IN THE REAMED HOLE. DO NOT OVERPRESS/ PRESS PAST THIS SHOULD.

ASSEMBLE THE BOTTOM CASE HALF AS SHOWN HERE





ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	399-50-925-001	Slotted McMaster Gear_6325K52	1
2	399-50-925-05	Idler Gear Assembly	2
3	399-50-925-07	Drive Shaft Assembly	1
4	399-50-925-003_N	Bottom Case Half	1
5	399-50-925-002_N	Slotted Bushing Made from 6338K614	2
6	399-50-925-009_N	Top Case Half	1
7	399-50-925-08	Shaft Cap Assembly	5
8	399-50-925-019	Torque Driver Adapter	1
9	399-50-925-044	Front Bump Stops	2
10	8433218205 toruqe driver	Atlas Copco inline Torque Driver	1
11	91251A542	1/4-20x1" SHCS	14
12	91251A242	10-24x1/2" SHCS	10
13	98381A626	3/8x1.25" Dowel Pin	2
14	1095K65	Steel Grease Zerk	2
15	90201A415	1/2"-13x1" Grade 9 Socket Cap Screw	1
16	399-50-925-013	Made from 3/4" Square Drive 3/4" Hex	1
17	6436K18	Clamp-On Shaft Collar Top Piece	4
18	98306A179	Steel Clevis Pin	2
19	98335A044	Cotter Pin	2
20	91251A194	8-32x1/2" SHCS	4
21	91290A434	M8x1.25x30 SHCS	3

PER ASME Y14.5M 1994

FOX Factory, Inc. — CAL POLY College of Engineering

130 Hangar Way, Watsonville, CA 95076 USA, Ph 831-768-1100, Fax 831-768-9312

APPROVALS		DATE
DWN. BY	E. FORRESTER	05/11/2020
CHK. BY	D. DALEY	05/15/2020
ENG.	T. MULROONEY W. CRAWFORD	
MFG.		

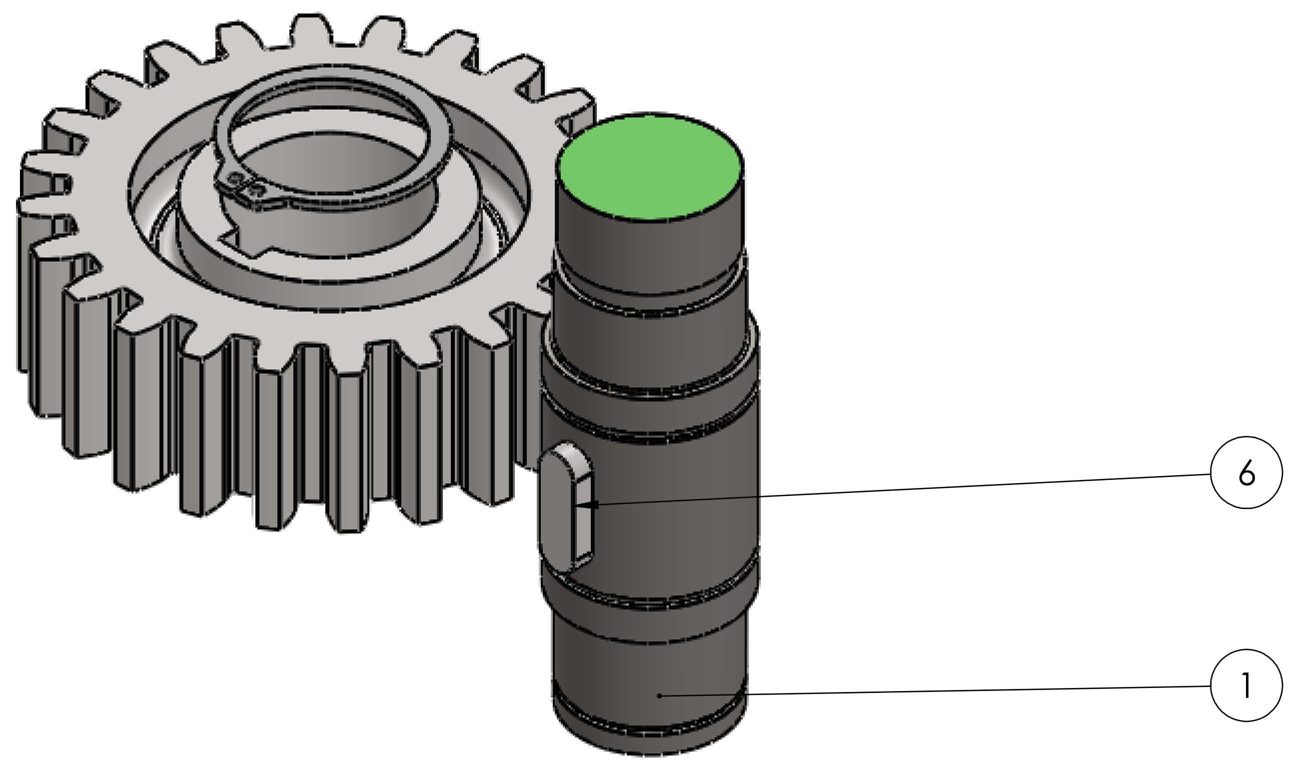
BOTTOM CASE HALF
ASSEMBLY 2

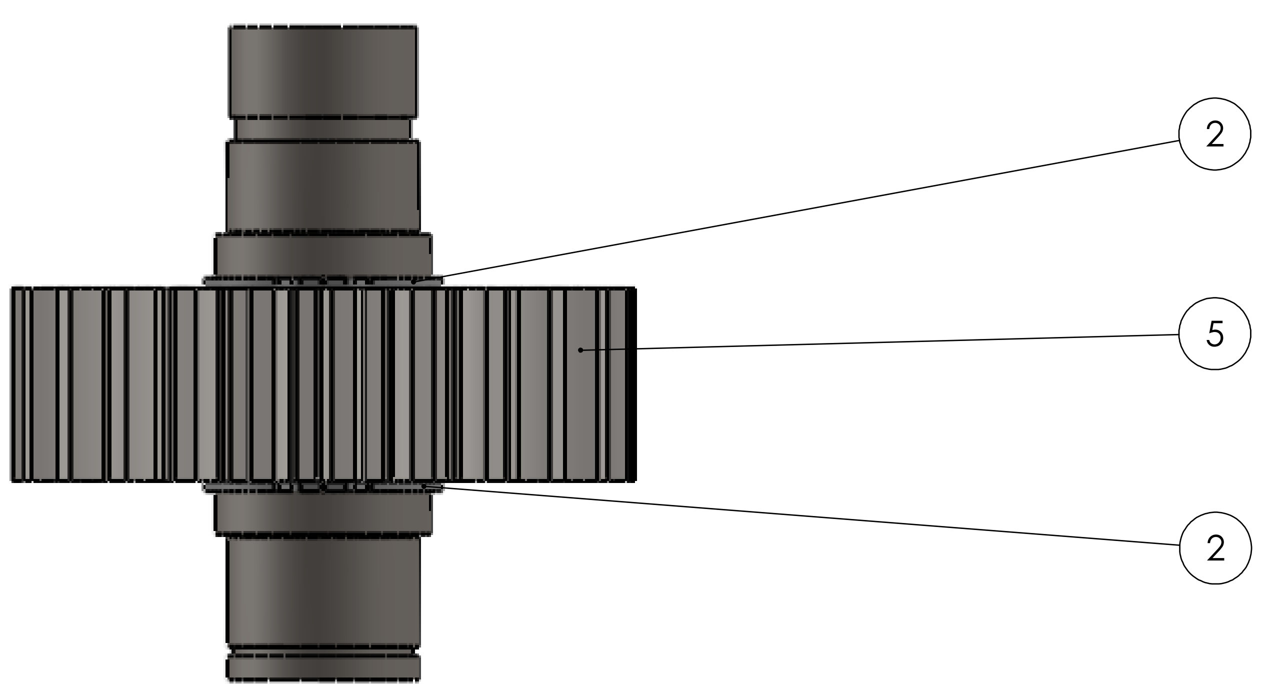
SIZE C — ASSEM. NO. 399-50-925-02

PLOT SCALE: 2:3

REVISIONS

REV	DESCRIPTION	DATE	APPROVED
1	INITIAL	05/11/2020	E. FORRESTER





ASSEMBLE 2 IDLER SHAFTS AS SHOWN HERE
FURTHER ASSEMBLY OF THESE IDLER SHAFTS
WILL RESULT IN INABILITY TO FULLY ASSEMBLE
THE DRIVETRAIN

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	399-50-925-010-XXX	IDLER SHAFT -010-001 SHOWN. EITHER WORK	1
2	97633A320	1.125 EXTERNAL RETAINING RING	2
3	5709K82	TAPERED ROLLER BEARING	2
4	6343K16	THREADED BEARING LOCKNUT	1
5	399-50-925-018_6325K490_N	GEAR MADE FROM 6325K49	1
6	95053A595	1/4" MACHINE KEY	1
7	97633A300	1" EXTERNAL RETAINING RING	1

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APPROVALS		DATE
DWN. BY	E. FORRESTER	05/11/2020
CHK. BY	D. DALEY	05/15/2020
ENG.	T. MULROONEY, W. CRAWFORD	
MFG.		

IDLER SHAFT INITIAL ASSEMBLY
ASSEMBLY 3

SIZE C — ASSEM. NO. 399-50-925-05

PLOT SCALE: 1:1 — SHEET 8 OF 11

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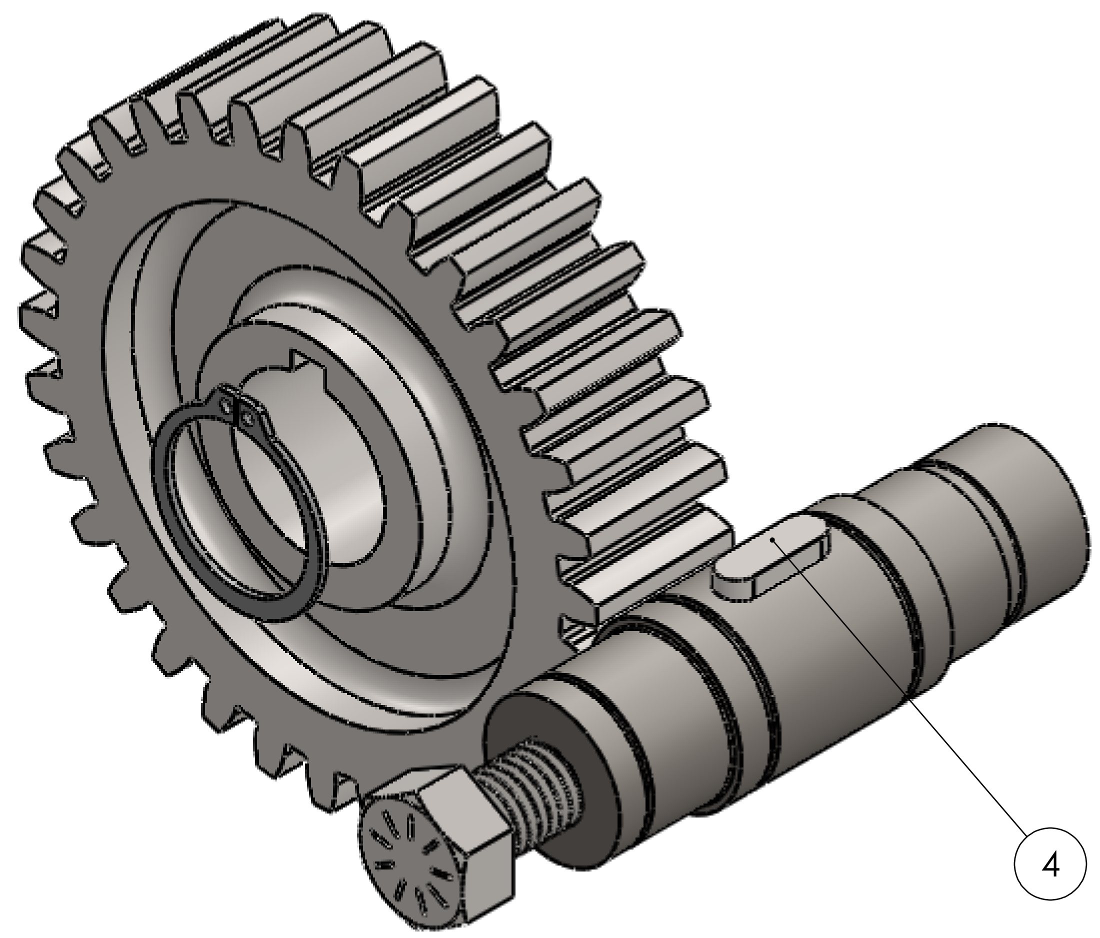
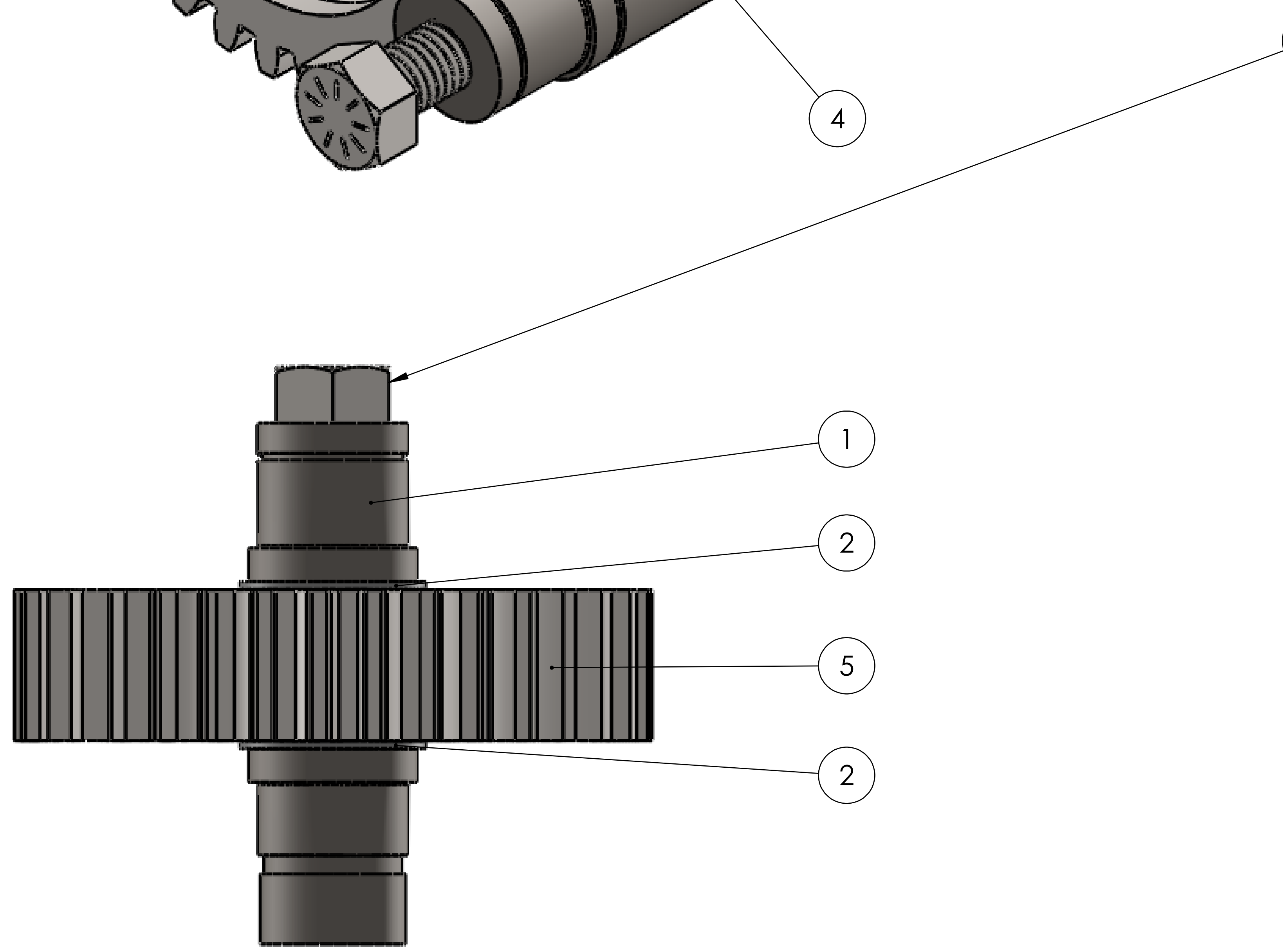
REVISIONS			
REV	DESCRIPTION	DATE	APPROVED
1	INITIAL	05/11/2020	E. FORRESTER



ASSEMBLE 1 DRIVE SHAFT AS SHOWN HERE FURTHER ASSEMBLY OF DRIVE SHAFT WILL RESULT IN INABILITY TO FULLY ASSEMBLE THE DRIVETRAIN

TORQUE BOLT TO BETWEEN 90-110 FT-LBS. UTILIZE HIGH TO MEDIUM STRENGTH THREAD LOCKER UPON THE FINAL ASSEMBLY OF THE DRIVE SHAFT



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	399-50-925-016-XXX	DRIVE SHAFT 016-001 CURRENTLY SHOWN. EITHER WORK.	1
2	97633A320	1.125 EXTERNAL RETAINING RING	2
3	97633A300	1" EXTERNAL RETAINING RING	1
4	95053A595	1/4" MACHINE KEY	1
5	399-50-925-008_6325K520_N	DRIVE GEAR. MADE FROM 6325K52	1
6	5709K82	TAPERED ROLLER BEARING	2
7	6343K16	THREADED BEARING LOCKNUT	1
8	90201A415	1/2"-13x1" Grade 9 Socket Cap Screw	1

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APPROVALS		DATE
DWN. BY	E. FORRESTER	05/11/2020
CHK. BY	D. DALEY	05/15/2020
ENG.	T. MULROONEY W. CRAWFORD	
MFG.		

DRIVE SHAFT INITIAL ASSEMBLY
ASSEMBLY 4

SIZE C | ASSEM. NO. 399-50-925-07

PLOT SCALE: 1:1 | SHEET 9 OF 11

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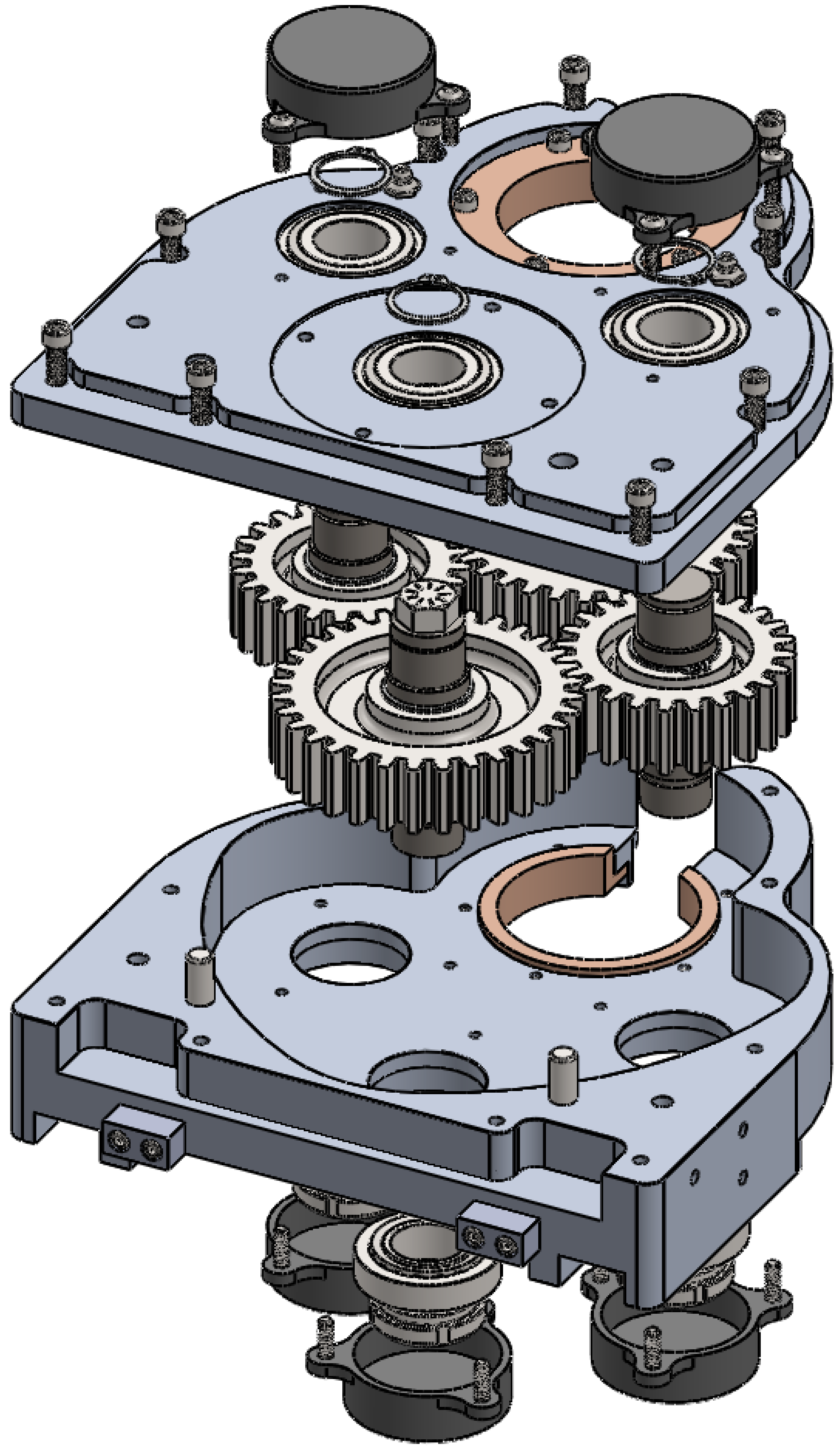
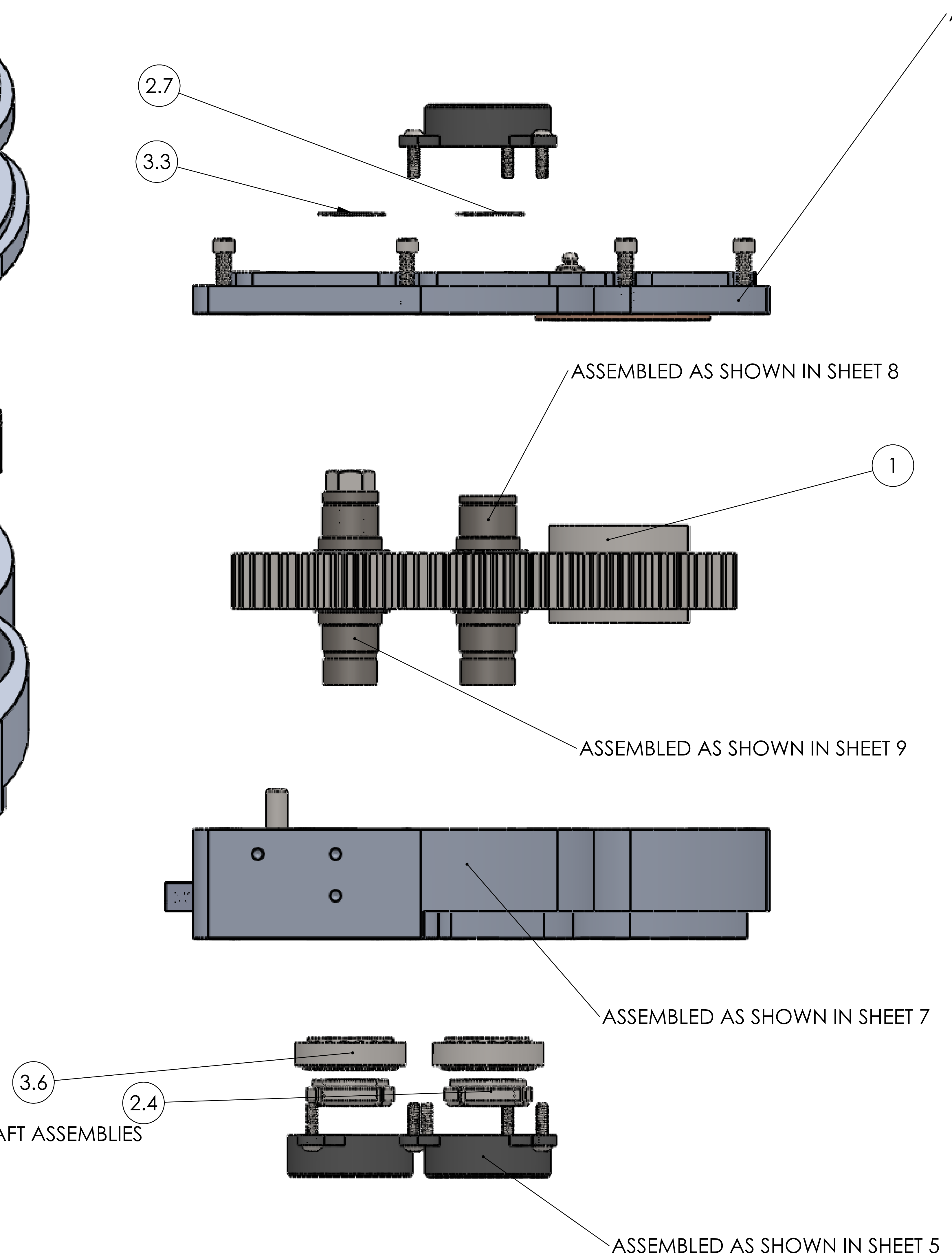
REV	DESCRIPTION	DATE	APPROVED
1	INITIAL	05/11/2020	E. FORRESTER





ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	399-50-925-001	Slotted McMaster Gear_6325K52	1
2	399-50-925-05	Idler Gear Assembly	2
2.1	399-50-925-010-XXX	IDLER SHAFT -010-001 SHOWN. EITHER WORK	1
2.2	97633A320	1.125 EXTERNAL RETAINING RING	2
2.3	5709K82	TAPERED ROLLER BEARING	2
2.4	6343K16	THREADED BEARING LOCKNUT	1
2.5	399-50-925-018_6325K490_N	GEAR MADE FROM 6325K49	1
2.6	95053A595	1/4" MACHINE KEY	1
2.7	97633A300	1" EXTERNAL RETAINING RING	1
3	399-50-925-07	Drive Shaft Assembly	1
3.1	399-50-925-016-XXX	DRIVE SHAFT 016-001 CURRENTLY SHOWN. EITHER WORK.	1
3.2	97633A320	1.125 EXTERNAL RETAINING RING	2
3.3	97633A300	1" EXTERNAL RETAINING RING	1
3.4	95053A595	1/4" MACHINE KEY	1
3.5	399-50-925-008_6325K520_N	DRIVE GEAR. MADE FROM 6325K52	1
3.6	5709K82	TAPERED ROLLER BEARING	2
3.7	6343K16	THREADED BEARING LOCKNUT	1
4	399-50-925-003_N	Bottom Case Half	1
5	399-50-925-002_N	Slotted Bushing Made from 6338K614	2
6	399-50-925-009_N	Top Case Half	1
7	399-50-925-08	Shaft Cap Assembly	5
7.1	399-50-925-017	Shaft Cap	1
7.2	91255A245	10-24 x 3/4" BHCS	3
8	399-50-925-019	Torque Driver Adapter	1
9	399-50-925-044	Front Bump Stops	2
11	91251A542	1/4-20x1" SHCS	14
12	91251A242	10-24x1/2" SHCS	10
13	98381A626	3/8x1.25" Dowel Pin	2
14	1095K65	Steel Grease Zerk	2
15	90201A415	1/2"-13x1" Grade 9 Socket Cap Screw	1
16	399-50-925-013	Made from 3/4" Square Drive 3/4" Hex	1
17	6436K18	Clamp-On Shaft Collar Top Piece	4
18	98306A179	Steel Clevis Pin	2
19	98335A044	Cotter Pin	2
20	91251A194	8-32x1/2" SHCS	4
21	91290A434	M8x1.25x30 SHCS	3

BEARING LOCKNUT USED TO TIGHTEN AND PRETENSION THE SHAFT ASSEMBLIES

ENSURE THAT THE TAPERED ROLLER BEARINGS ARE PUT IN TAPER TOWARD THE INSIDE OF THE CASE

ENSURE THAT THE BEARINGS ARE PACKED WITH GREASE

USE BLUE LOCTITE ON OUTER RACE AT DISCRETION OF ASSEMBLER
*DO NOT USE FOR TEST ASSEMBLY

BEARINGS SHOULD BE A SLIP FIT

PER ASME Y14.5M 1994

FOX Factory, Inc. CAL POLY College of Engineering
130 Hangar Way, Watsonville, CA 95076 USA, Ph 831-768-1100, Fax 831-768-9312

APPROVALS		DATE
DWN. BY	E. FORRESTER	05/11/2020
CHK. BY	D. DALEY	05/15/2020
ENG.	T. MULROONEY W. CRAWFORD	
MFG.		

DRIVE TRAIN ASSEMBLY
ASSEMBLY 5

SIZE C | ASSEM. NO. 399-50-925-02

PLOT SCALE: 1:2 | SHEET 10 OF 11

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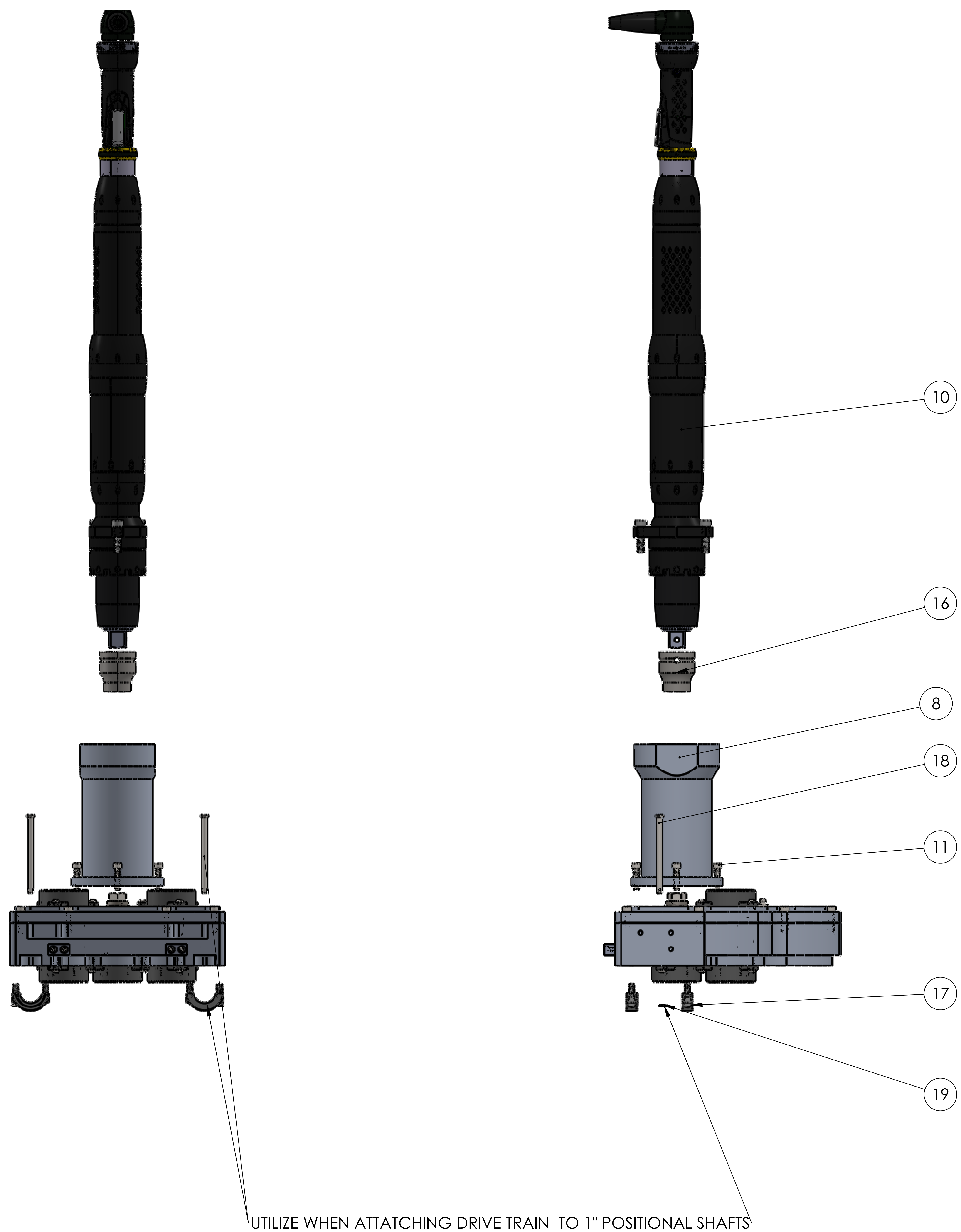
REVISIONS

REV	DESCRIPTION	DATE	APPROVED
1	INITIAL	05/11/2020	E. FORRESTER



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	399-50-925-001	Slotted McMaster Gear_6325K52	1
2	399-50-925-05	Idler Gear Assembly	2
3	399-50-925-07	Drive Shaft Assembly	1
4	399-50-925-003_N	Bottom Case Half	1
5	399-50-925-002_N	Slotted Bushing Made from 6338K614	2
6	399-50-925-009_N	Top Case Half	1
7	399-50-925-08	Shaft Cap Assembly	5
8	399-50-925-019	Torque Driver Adapter	1
9	399-50-925-044	Front Bump Stops	2
10	8433218205 toruqe driver	Atlas Copco inline Torque Driver	1
11	91251A542	1/4-20x1" SHCS	14
12	91251A242	10-24x1/2" SHCS	10
13	98381A626	3/8x1.25" Dowel Pin	2
14	1095K65	Steel Grease Zerk	2
15	90201A415	1/2"-13x1" Grade 9 Socket Cap Screw	1
16	399-50-925-013	Made from 3/4" Square Drive 3/4" Hex	1
17	6436K18	Clamp-On Shaft Collar Top Piece	4
18	98306A179	Steel Clevis Pin	2
19	98335A044	Cotter Pin	2
20	91251A194	8-32x1/2" SHCS	4
21	91290A434	M8x1.25x30 SHCS	3

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FOX Factory, Inc.

CAL POLY College of Engineering

130 Hangar Way, Watsonville, CA 95076 USA, Ph 831-768-1100, Fax 831-768-9312

APPROVALS	DATE
DWN. BY E. FORRESTER	05/11/2020
CHK. BY D. DALEY	05/15/2020
ENG. T. MULROONEY W. CRAWFORD	
MFG.	

DRIVE TRAIN FINAL ASSEMBLY
ASSEMBLY 6

SIZE C — ASSEM. NO. 399-50-925-02

PLOT SCALE: 1:2 — SHEET 11 OF 11

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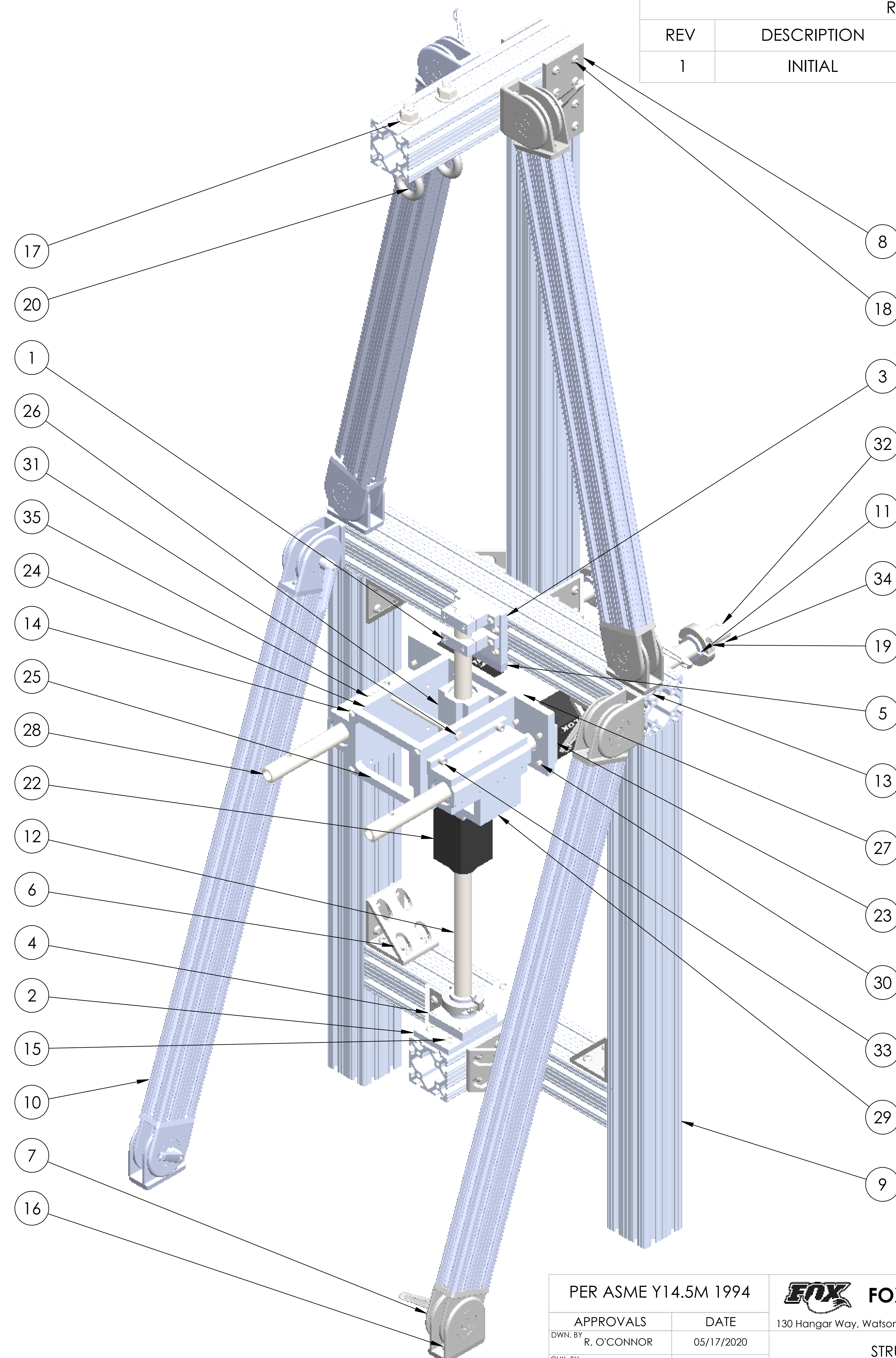
ITEM NO.	PART NUMBER	DESCRIPTION	QUANTITY
1	1865K6	EASY-ACCESS BASE-MOUNTED SHAFT SUPPORT FOR 1" DIAMETER SHAFTS	2
2	399-50-925-039	FOOT PLATE	1
3	399-50-925-040	HEAD PLATE	1
4	57745K23	FLANGE-MOUNTED SHAFT SUPPORT, FOR 1" SHAFT DIAMETER	1
5	399-50-925-043	TOP WEAR PAD	1
6	47065T906 WITH 47065T215	3" Quad Gusset Bracket with 8x 5/16-18 T-Slot Nuts and Screws	9
7	47065T227	T-Slotted Framing Locking Inline/Perpendicular Pivot for 3" Double/Quad	8
8	47065T264	T-SLOT FRAMING, SLIVER SURFACE BRACKET, 6" LONG FOR 3" HIGH DOUBLE/QUAD RAIL	2
9	399-50-925-045-XXX	QUAD 8020	1
10	399-50-925-057-XXX	DOUBLE 8020	1
11	399-50-925-042	SHAFT WEAR COLLAR	6
12	399-50-925-049	VERTICAL SHAFT	1
13	47065T907	T-SLOT FRAMING, END FEED SINGLE NUT, 5/16-18" THREAD	20
14	91255A540	BUTTON HEAD HEX DRIVE SCEW, BLAX OXIDE ALLOY STEEL, 1/4"-20 THREAD 3/4" LONG	26
15	91255A582	BUTTON HEAD HEX DRIVE SCREW, BLACK-OXIDE ALLOY STEEL, 5/16"-18 THREAD, 7/8" LONG	8
16	91251A580	BLACK OXIDE ALLOY STEEL SOCKEH HEAD CAP SCREW, 5/16"-18 THREAD SIZE, 5/8" LONG	32
17	92018A650	HIGH STRENGTH STEEL NYLON-INSERT FLANGE LOCKNUT, GRADE G, ZINC YELLOW CHROMATE PLATED, 5/8"-11 THREAD SIZE	2
18	47065T215	T-SLOT FRAMING, END FEED SINGLE NUT WITH BUTTON HEAD 5/16"-18 THREAD	16
19	6436K23	Clamping Two-Piece Shaft Collar for 1-1/2" Diameter, Black-Oxide 1215 Carbon Steel	3
20	3018T18	Galvanized Steel Eyebolt with Nut and with Shoulder for Lifting, 5/8"-11 Thread Size, 2" Thread Length, 4" Shank	2
21	91251A242	10-24x1/2" SHCS	2
22	RLN-100200MXO	Amlock RLN Pneumatic RodLock	3
23	399-50-925-041	Rodlock Mount	3
24	399-50-925-035	Side Plate	2
25	399-50-925-036	Front Plate	1
26	399-50-925-056	Mounted Linear Ball Bearing Fixed Alignment, for 1" Shaft Diameter	3
27	399-50-925-034	Back Plate	1
28	399-50-925-050	Horizontal Motion Shaft	2
29	399-50-925-037	Bottom Plate	1
30	91251A600	Black-Oxide Alloy Steel Socket Head Screw 5/16"-18 Thread Size, 4" Long	12
31	98306A310	1004-1045 Carbon Steel Clevis Pin 3/8" Diameter, 5-7/8" Usable Length	1
32	98306A161	1004-1045 Carbon Steel Clevis Pin 1/4" Diameter, 1-1/16" Usable Length	2
33	91251A581	5/16"-18x0.75" SHCS	12
34	98335A044	Cotter Pin	2
35	98335A069	Cotter Pin	1
36	5779K108	Push-to-Connect Tube Fitting for Air Straight Adapter, for 1/4" Tube OD x 1/8 NPT Male	3

REVISIONS

REV	DESCRIPTION	DATE	APPROVED
1	INITIAL	05/17/2020	R. O'CONNOR



PER ASME Y14.5M 1994

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CAL POLY College of Engineering

APPROVALS	DATE
DWN. BY R. O'CONNOR	05/17/2020
CHK. BY D. DALEY	05/17/2020
ENG. T. MULROONEY W. CRAWFORD	
MFG.	

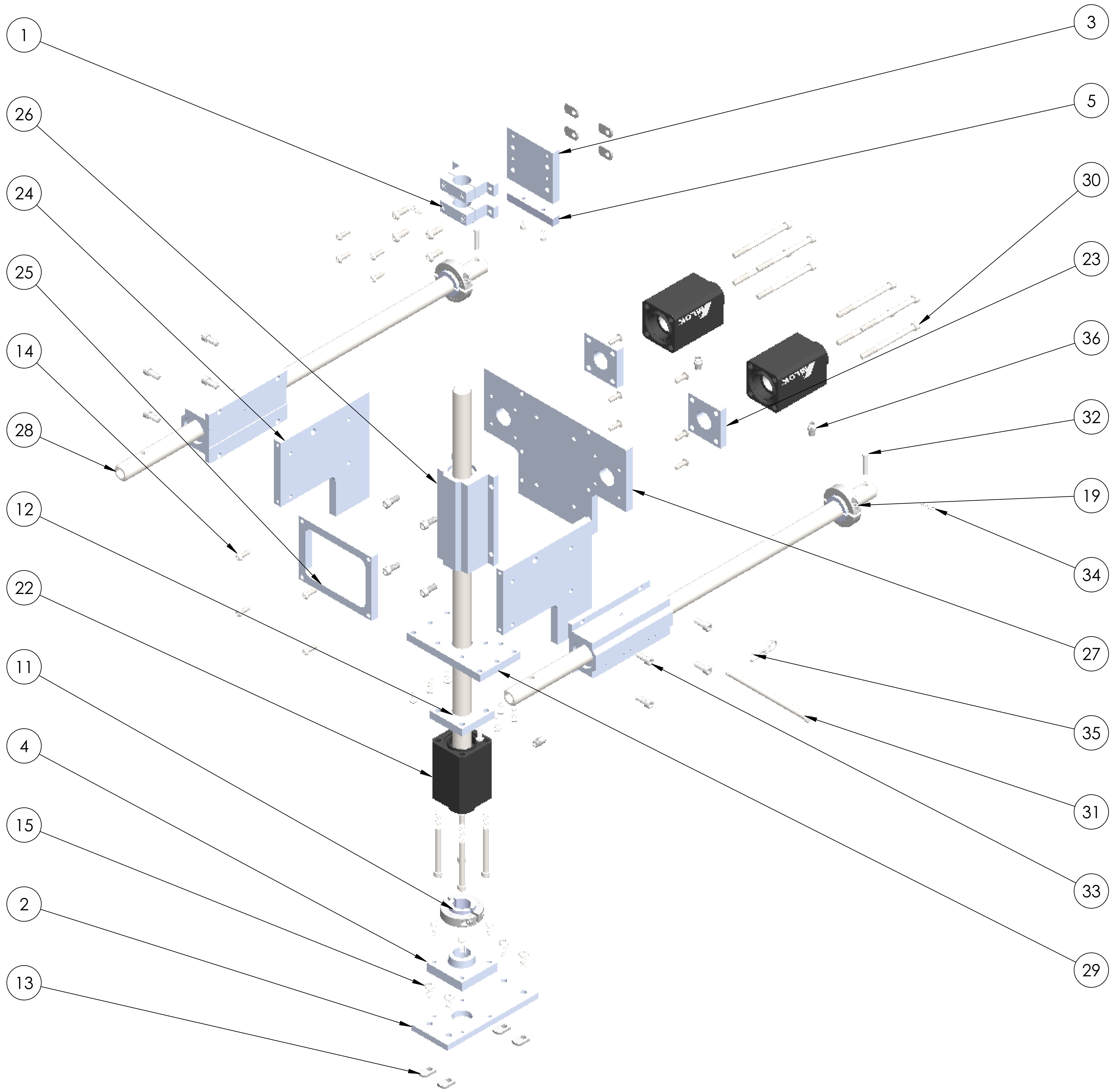
STRUCTURES ASSEMBLY

SIZE C | ASSEM. NO. 399-50-925-03

PLOT SCALE: 1:5 | SHEET 1 OF 2

REVISIONS			
REV	DESCRIPTION	DATE	APPROVED
1	INITIAL	05/17/2020	R. O'CONNOR

NOTES:
1. APPLY 80PSI AIR MINIMUM TO RAIL BRAKES DURING ASSEMBLY
2. RELEASE AIR ONCE RAIL BRAKES ARE ON SHAFT



SIZE	ASSEM. NO.	REV.
C	399-50-925-03	1
PLOT SCALE: 1:5		SHEET 2 OF 2

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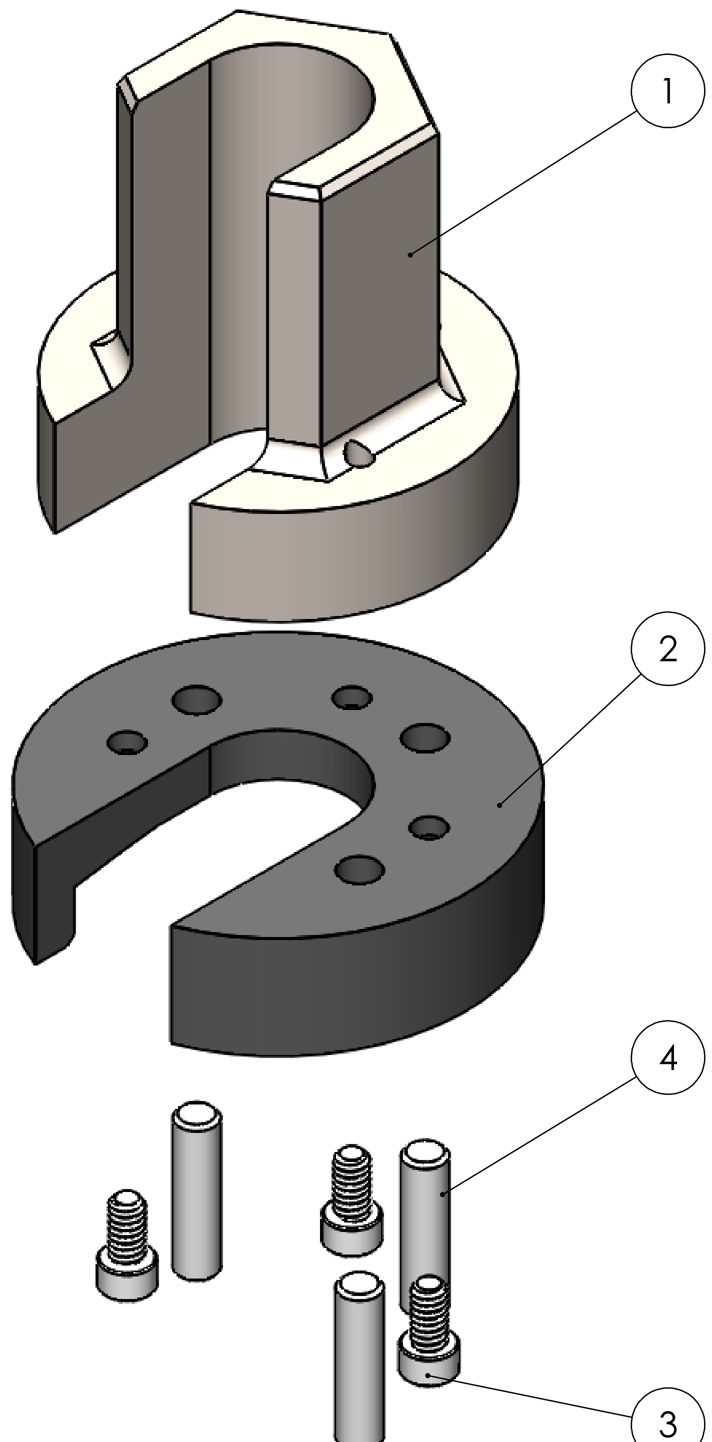
REV	DESCRIPTION	DATE	APPROVED
1	INITIAL	05/17/2020	C. HANSEN



NOTES:
1. DOWEL PINS (4) NEED TO BE PRESS FIT INTO THE ADAPTER BODY (1) UNTIL THEY MAKE CONTACT WITH THE BOTTOM OF THE HOLE
2. DOWEL PINS SHOULD BE PRESS FIT INTO THE ADAPTER BODY BEFORE DELRIN PIECE (2) IS FASTENED

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	399-50-925-005	Adapter Body	1
2	399-50-925-006	Adapter Delrin	1
3	91251A240	10-24 x3/8" Socket Head Cap Screw	3
4	98381A542	Steel Dowel Pin	3

PER ASME Y14.5M 1994

FOX Factory, Inc.

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APPROVALS	DATE
DWN. BY C. HANSEN	05/17/2020
CHK. BY D. DALEY	05/18/2020
ENG. T. MULROONEY W. CRAWFORD	
MFG.	

ADAPTER ASSEMBLY
ADAPTER ASSEMBLY PACKET

SIZE B | ASSEM. NO. 399-50-925-04

PLOT SCALE: 1:1 | SHEET 1 OF 1

4 3 2 1

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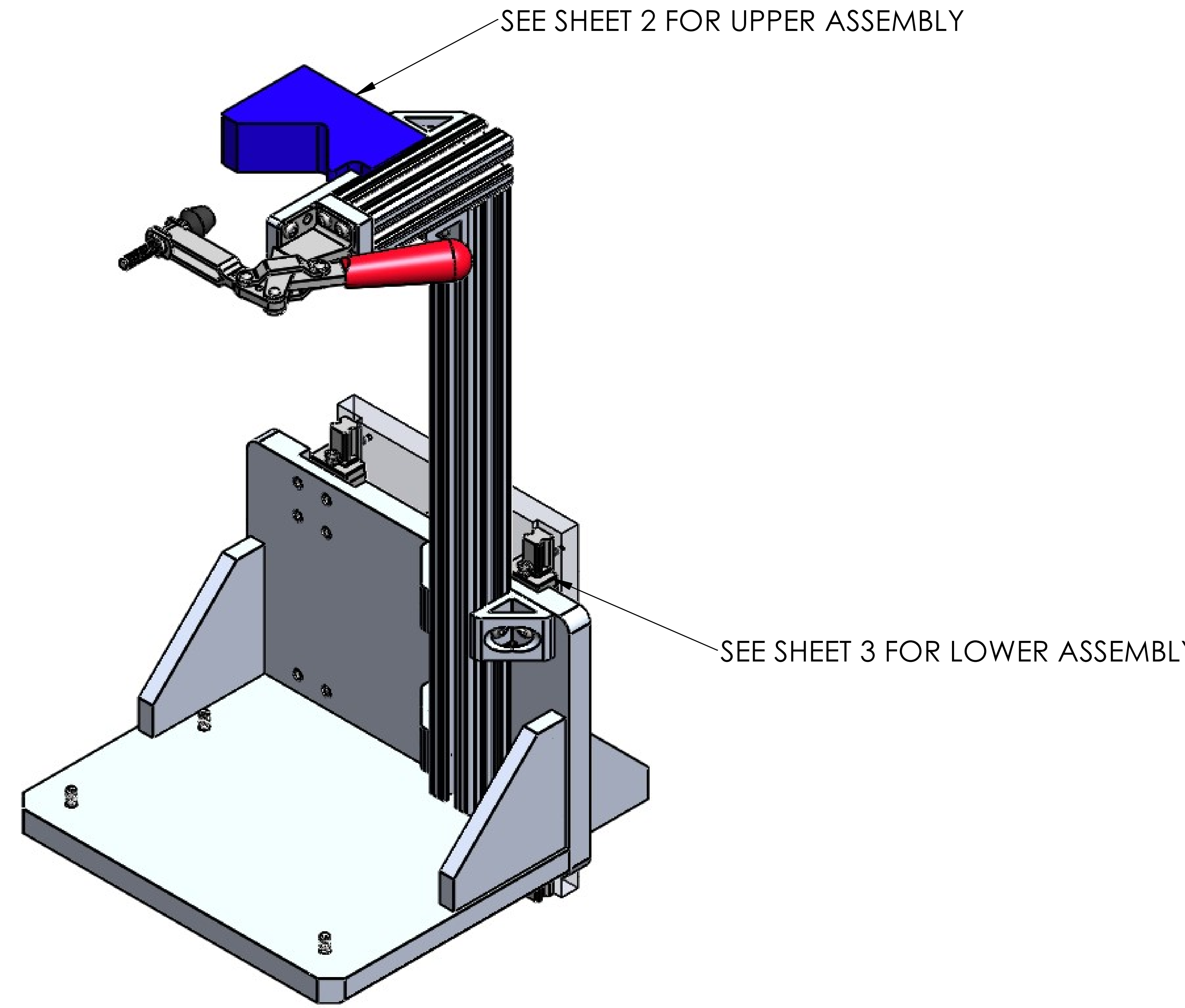
REVISIONS			
REV	DESCRIPTION	DATE	APPROVED
1	INITIAL	05/16/2020	D. DALEY

B

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	6709K12	MCMASTER BALL-BEARING CARRIAGE FOR 15MM LINEAR RAIL	4
2	6709K302	MCMASTER 15MM LINEAR RAIL	2
3	399-50-925-011	CARRIAGE PLATE	1
4	399-50-925-015	BODY CAP PALLET PLATE	1
5	399-50-925-012	RAIL BACKING PLATE	1
6	399-50-925-007	GUSSET PLATE	4
7	399-50-925-023-001	8020 VERTICAL COLUMN	1
8	399-50-925-023-002	8020 HORIZONTAL COLUMN	1
9	47065T679	MCMASTER 1.5" SINGLE 8020 BRACKET	5
10	50225A120	MCMASTER TOGGLE CLAMP	1
11	399-50-925-027	8020 END TOGGLE CLAMP MOUNT	1
12	399-50-925-028	8020 SIDE TOGGLE CLAMP MOUNT	1
13	399-50-925-029	DELRIN V-BLOCK	1
14	47065T229	8020 DROP-IN NUT WITH SPRING TAB, 5/16"-18	7
15	91255A537	1/4"-20x0.5" BHCS	4
16	91255A535	1/4"-20x3/8" BHCS	2
17	91251A581	5/16"-18x0.75" SHCS	1
18	91290A140	M4x0.7x8mm SHCS	16
19	91290A168	M4x0.7x20mm SHCS	10
20	91251A541	1/4"-20x.875" SHCS	8
21	92395A030	BRASS PRESS-FIT EXPANSION INSERT, 3/8" DRILL HOLE, 5/16"-18 THREAD	1
22	91255A582	BUTTON HEAD HEX DRIVE SCREW, BLACK-OXIDE ALLOY STEEL, 5/16"-18 THREAD, 7/8" LONG	4
23	91251A542	1/4-20x1" SHCS	8



A

PER ASME Y14.5M 1994		FOX Factory, Inc.		CAL POLY College of Engineering
APPROVALS	DATE	130 Hangar Way, Watsonville, CA 95076 USA, Ph 831-768-1100, Fax 831-768-9312		
DWN. BY D. DALEY	05/16/2020	BEARING RUNDOWN & TORQUE MACHINE SHOCK FIXTURING ASSEMBLY		
CHK. BY E. FORRESTER	05/16/2020			
ENG. T. MULROONEY W. CRAWFORD		SIZE B	ASSEM. NO. 399-50-925-06	
MFG.		PLOT SCALE: 1:4	SHEET 1 OF 3	

3 2 1

4 | 3 | 2 | 1

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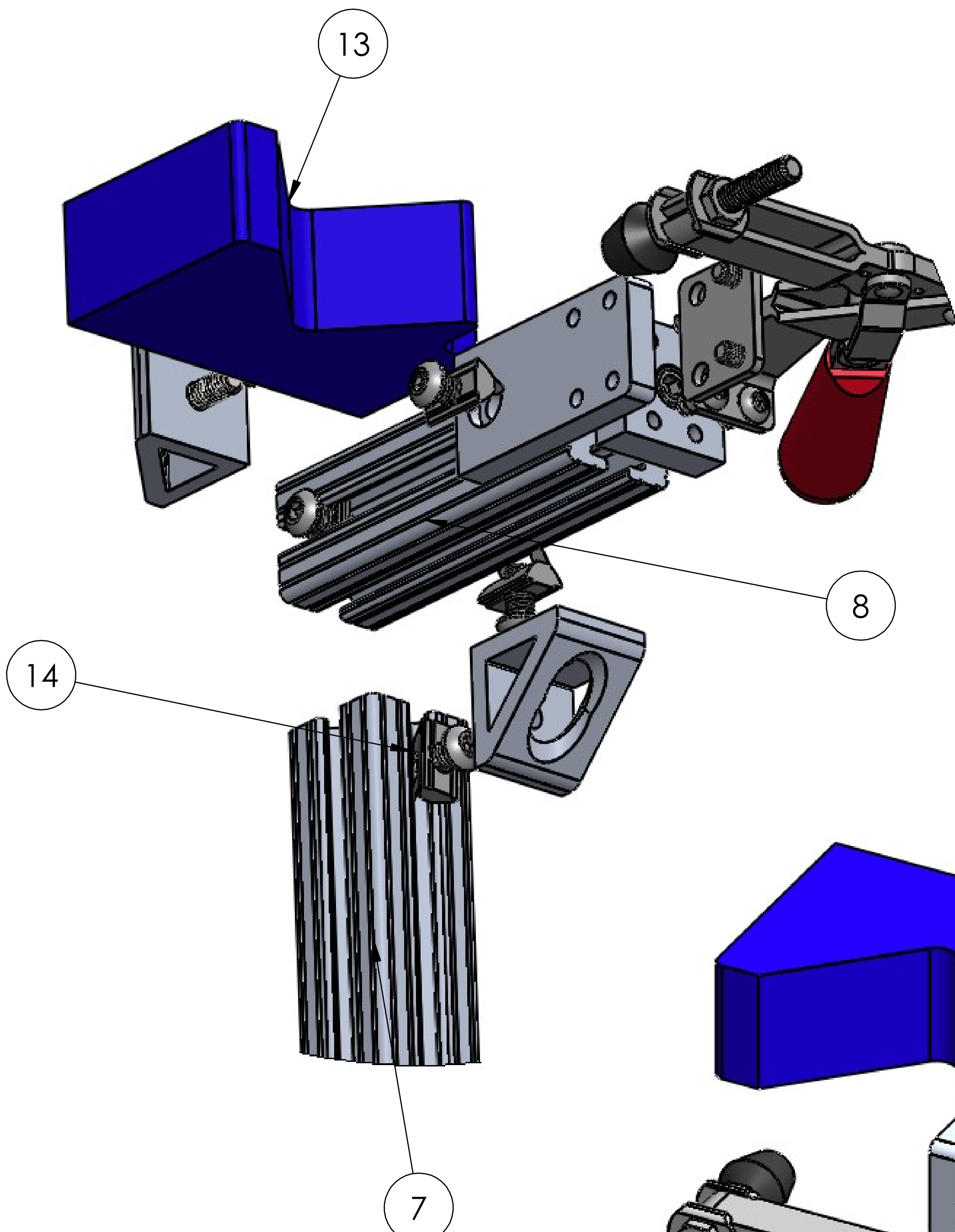
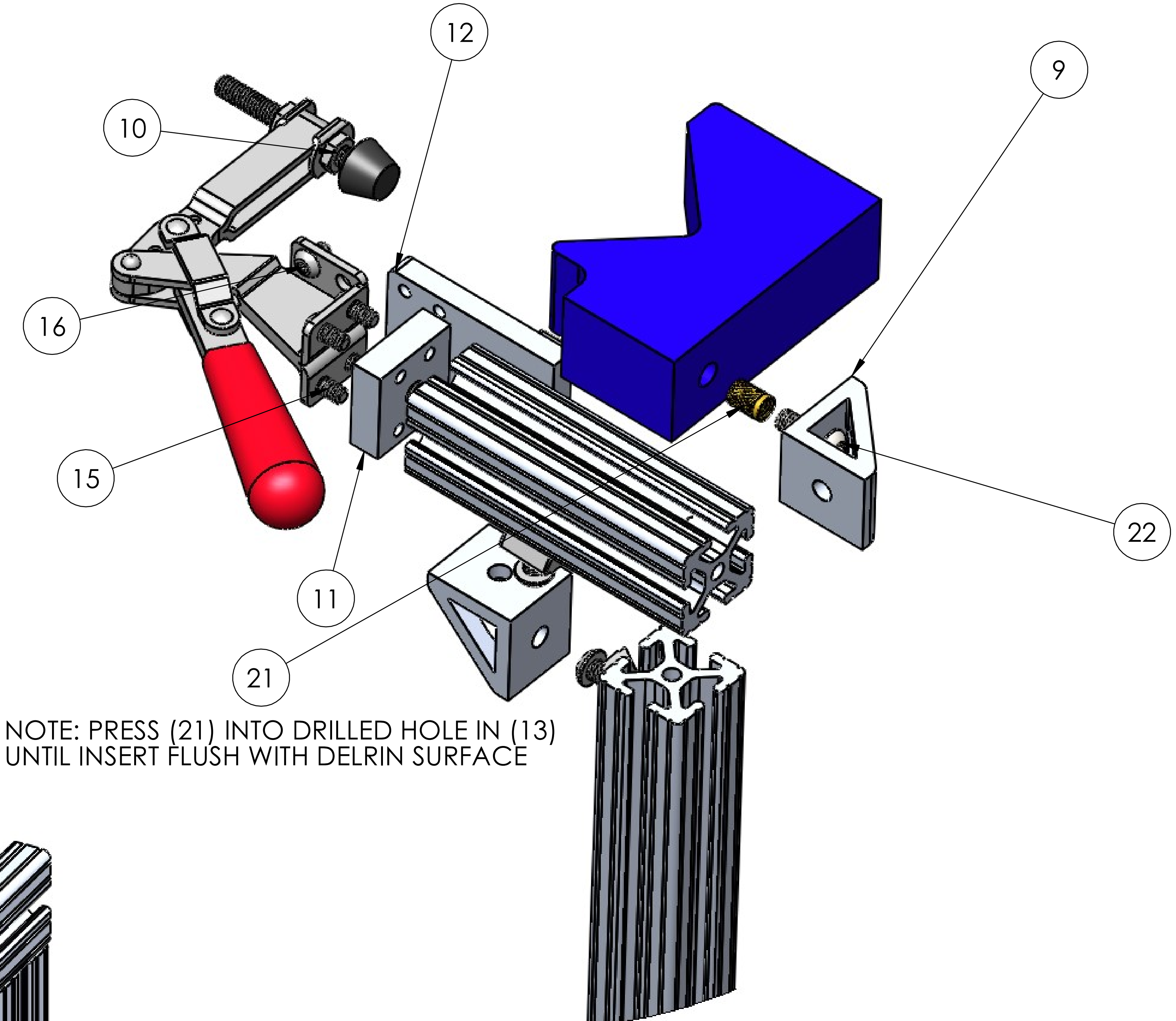
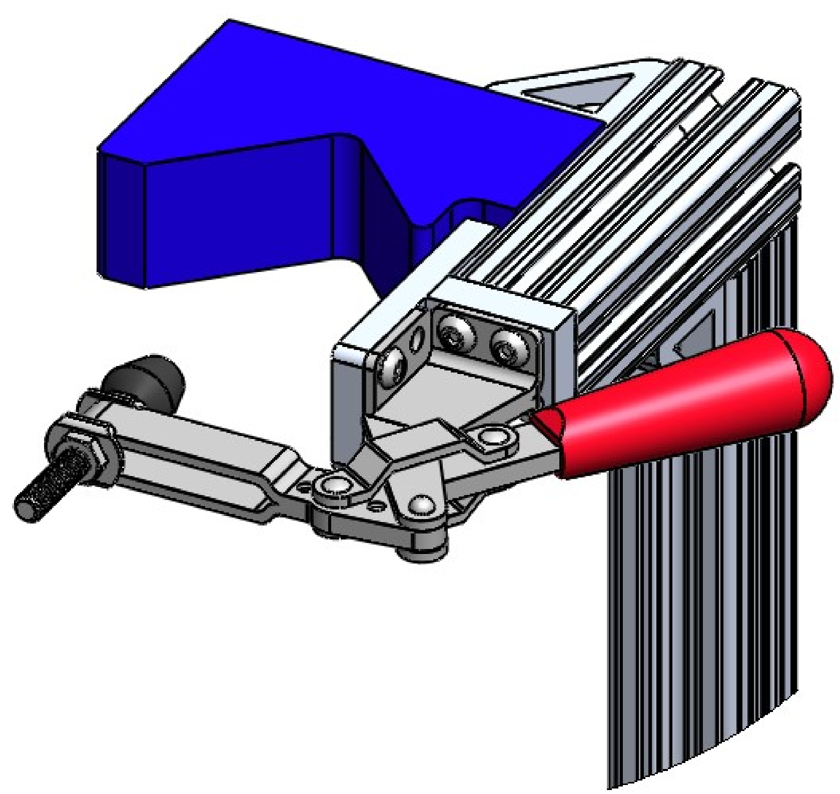




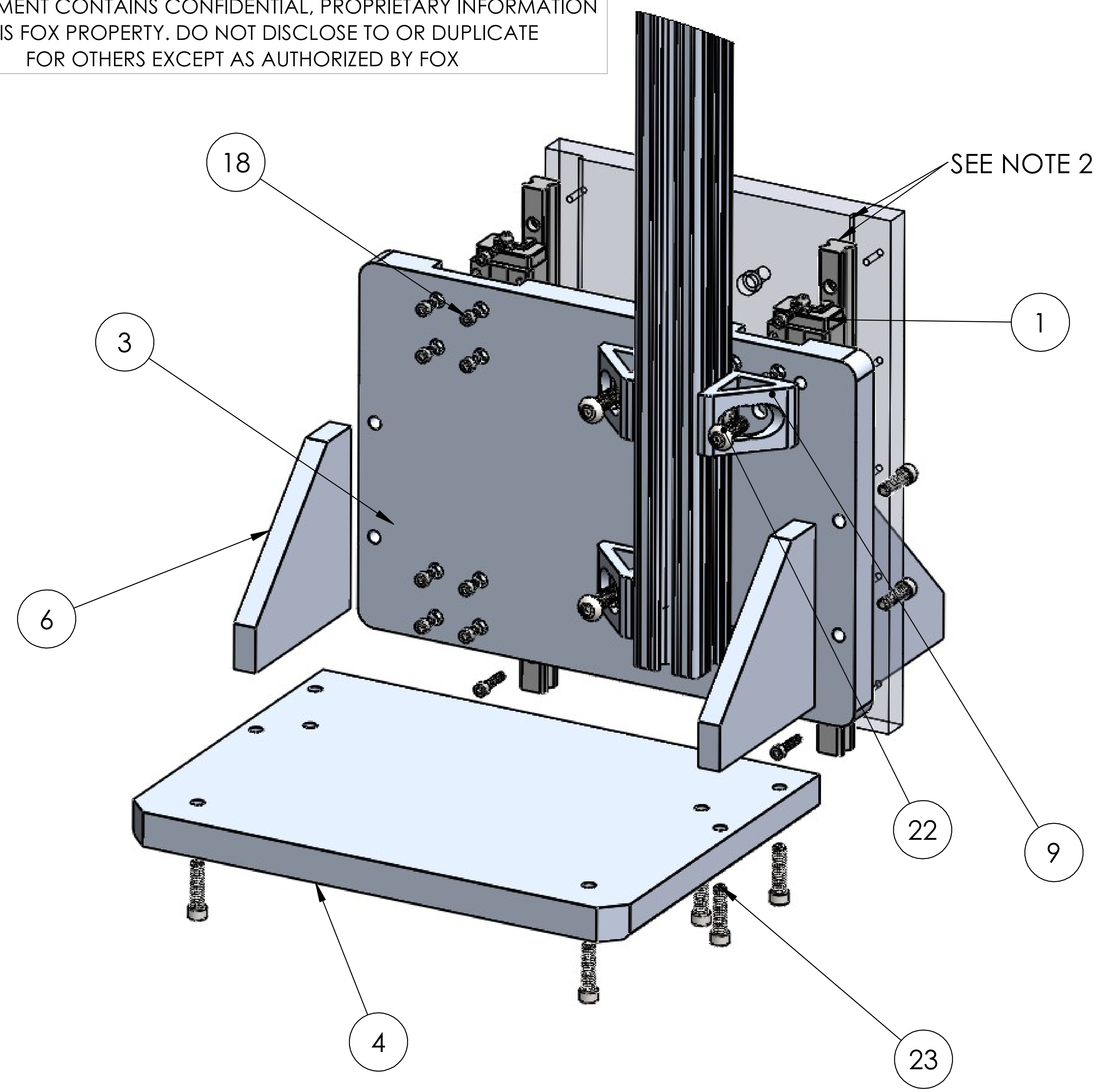
NOTE: PRESS (21) INTO DRILLED HOLE IN (13)
UNTIL INSERT FLUSH WITH DELRIN SURFACE

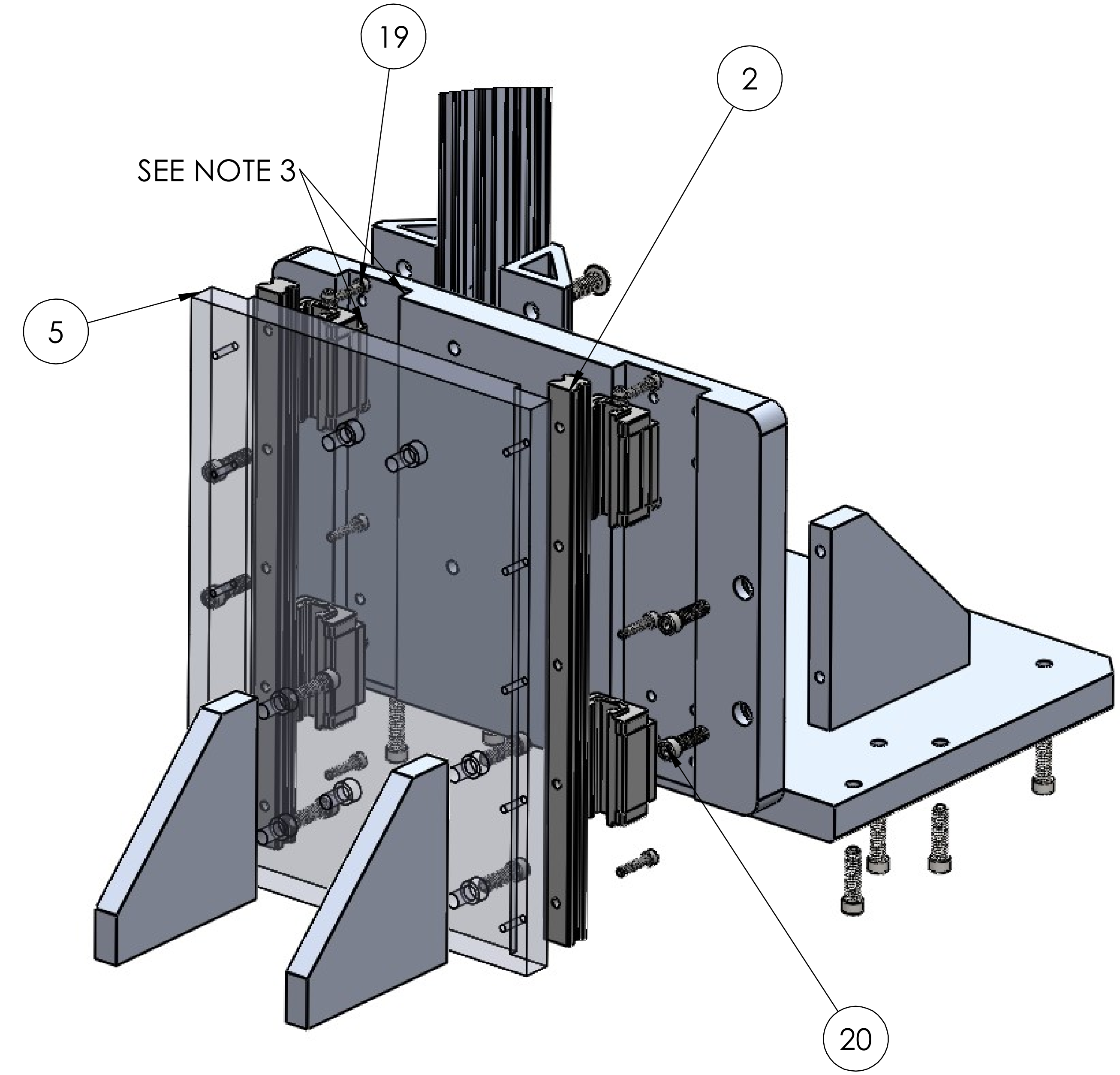


A

SIZE	ASSEM. NO.	REV.
B	399-50-925-06	1
	PLOT SCALE: 1:2	SHEET 2 OF 3

3 | 2 | 1





NOTES / CARRIAGE & RAIL ASSEMBLY INSTRUCTIONS:
1) ASSEMBLE 2 CARRIAGES TO EACH LINEAR RAIL & APPLY GREASE TO INCLUDED ZERK FITTINGS
2) FASTEN LINEAR RAILS (2) TO BACKING PLATE (5), WITH RAILS HELD AGAINST PLATE SHOULDERS
3) FASTEN 2 BEARING CARRIAGES (1) TO NARROW SLOT IN FRONT PLATE (3), WITH CARRIAGES
HELD AGAINST INNER SIDE OF SLOT
4) FASTEN REMAINING CARRIAGES TO FRONT PLATE & ENSURE SMOOTH SLIDING / NO BINDING
5) ADJUST CARRIAGE FASTENERS AS NEEDED UNTIL SMOOTH MOTION ACHEIVED

SIZE	ASSEM. NO.	REV.
B	399-50-925-06	1
	PLOT SCALE: 1:3	SHEET 3 OF 3

4 3 2 1

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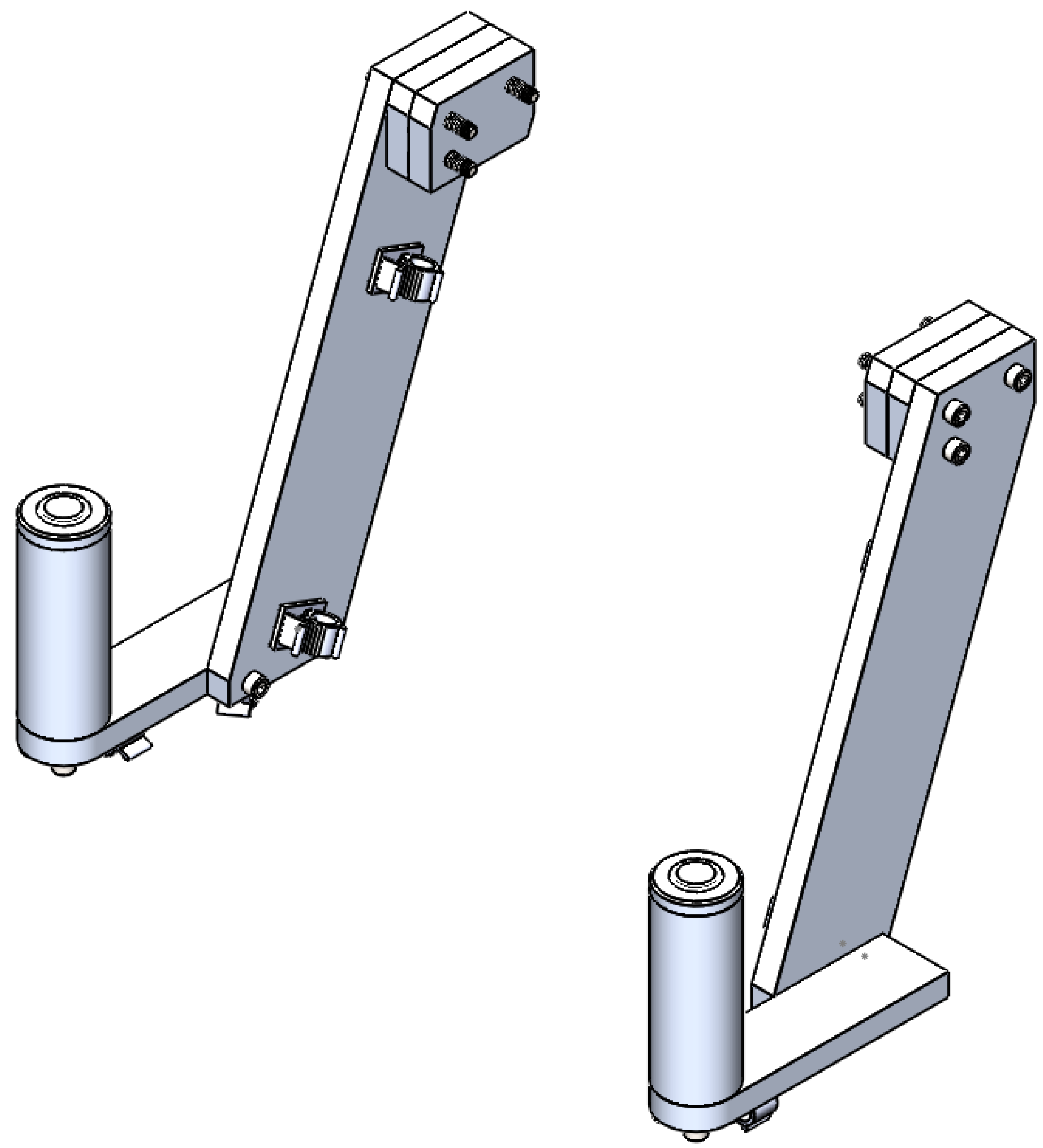
1	INITIAL	05/17/2020	C. HANSEN

B



Handles Assembly Packet

A

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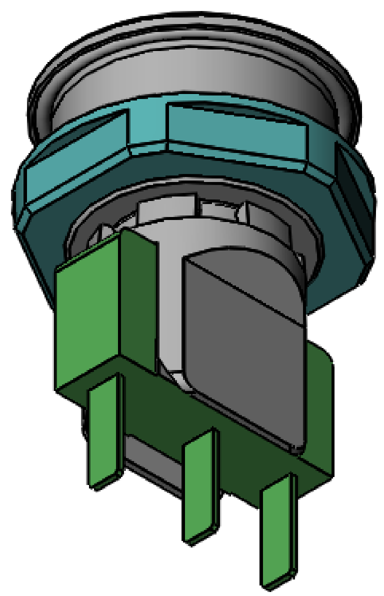
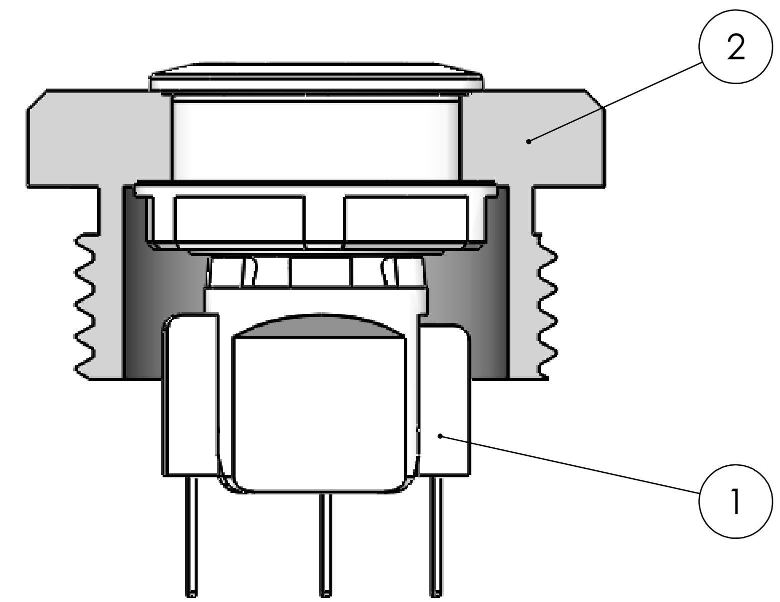
APPROVALS	DATE	130 Hangar Way, Watsonville, CA 95076 USA, Ph 831-768-1100, Fax 831-768-9312		
DWN. BY C. HANSEN	05/17/2020	HANDLE ASSEMBLY HANDLE ASSEMBLY PACKET		
CHK. BY D. DALEY	05/18/2020			
ENG. T. MULROONEY W. CRAWFORD		SIZE B	ASSEM. NO. 399-50-925-09	
MFG.		PLOT SCALE: 1:3	SHEET 1 OF 3	

4 3 2 1

REVISIONS			
REV	DESCRIPTION	DATE	APPROVED
1	INITIAL	05/17/2020	C. HANSEN



PUSH BUTTON WITH COMPONENTS COLORED



BUTTON AND HANDLE CAP ASSEMBLED WITH CUT AWAY VIEW OF THE HANDLE CAP

TO ASSEMBLE THE BUTTON WITH THE HANDLE CAP, THE GREEN AND BLUE PIECES MUST BE REMOVED FROM THE BODY OF THE BUTTON. THEN THE BUTTON CAN BE INSERTED INTO THE HANDLE CAP FROM THE TOP.
ONCE INSERTED, THE BLUE AND GREEN PIECES ARE PUT BACK ONTO THE BUTTON. THE BLUE PIECE PROVIDIGN COMPRESSIVE FORCE TO HOLD THE BUTTON IN PLACE

BOM FOR REFERENCE ONLY. TOTAL QTY SHOWN ON PG 3

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	6023T130_FLUSH-MOUNT PANEL-MOUNT PUSH-BUTTON SWITCH	Panel Mount Push Button Switch	1
2	399-50-925-020	Handle Cap	1

NOTE:
TWO BUTTON ASSEMBLIES REQUIRED FOR THE TOTAL HANDLE ASSEMBLY.
INSTRUCTIONS AND QUANTITIES ARE SHOWN FOR ONE BUTTON ASSEMBLY
INSTRUCTIONS DO NOT DIFFER BETWEEN THE TWO BUTTON ASSEMBLIES

PER ASME Y14.5M 1994

FOX Factory, Inc.

CAL POLY College of Engineering

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APPROVALS		DATE
DWN. BY	C. HANSEN	05/17/2020
CHK. BY	D. DALEY	05/18/2020
ENG.	T. MULROONEY W. CRAWFORD	
MFG.		

BUTTON ASSEMBLY
HANDLE ASSEMBLY PACKET

SIZE B | ASSEM. NO. 399-50-925-09

PLOT SCALE: 2:1 | SHEET 2 OF 3

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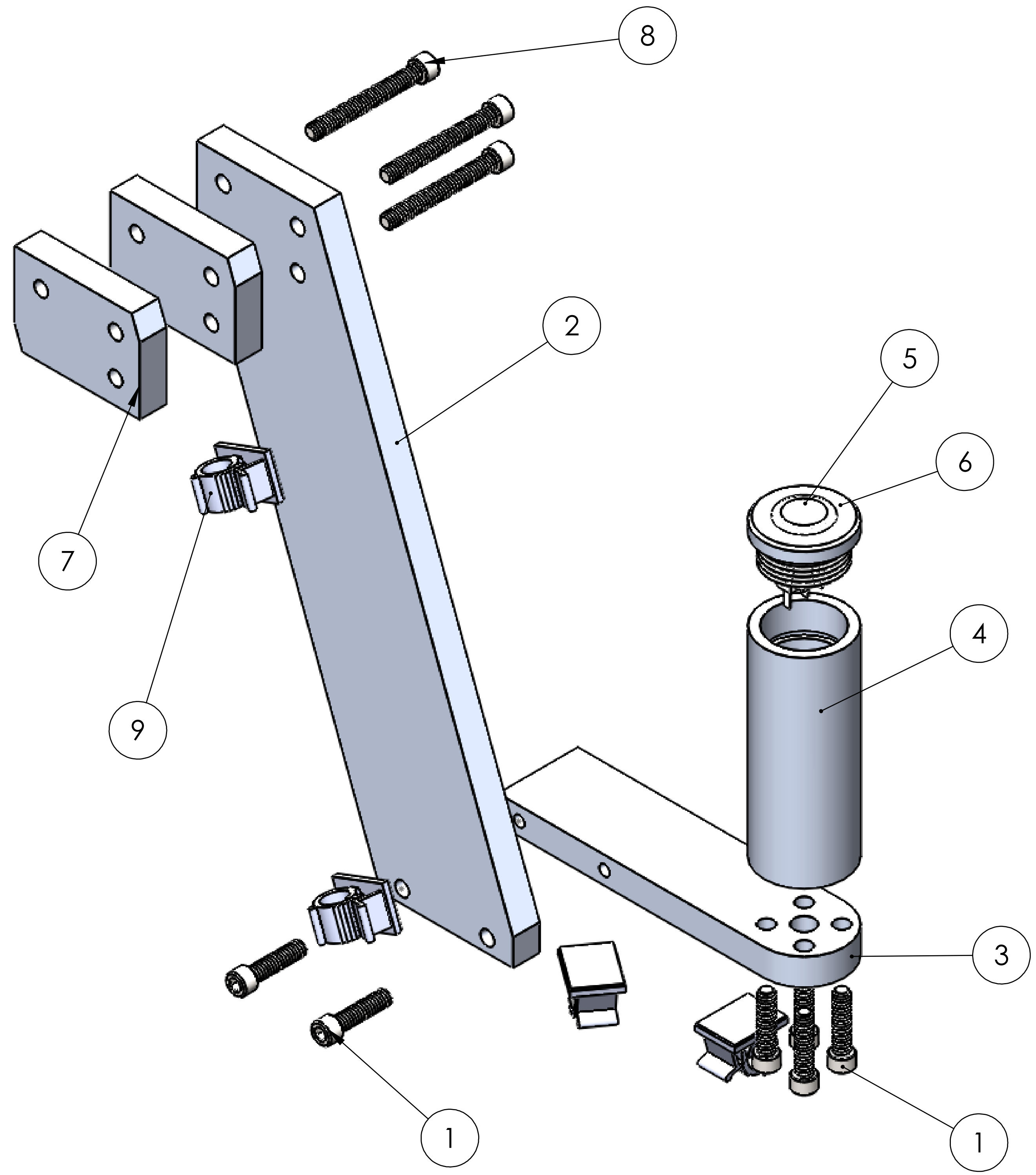
REV	DESCRIPTION	DATE	APPROVED
1	INITIAL	05/17/2020	C. HANSEN



ASSEMBLE AS SHOWN

NOTES:
1. FULL HANDLE ASSEMBLY COMPRISED OF 2 OF THE SHOWN ASSEMBLIES, THE SECOND A MIRROR OF THE FIRST
2. ADDITIONAL INSTRUCTIONS FOR ASSEMBLING (5) AND (6) ON PAGE 2
3. ADHESIVE CABLE HOLDERS (9) CAN BE PLACED AS NEEDED

ITEM NO.	PART NUMBER	DESCRIPTION	QUANTITY	/FULL ASSEMBLY QUANTITY
1	91251A542	1/4-20 x1" Socket Head Cap Screw	6	12
2	399-50-925-022		1	2
3	399-50-925-021	Handle Bottom Plate	1	2
4	399-50-925-051	Handle	1	2
5	6023T130_FLUSH-MOUNT PANEL-MOUNT PUSH-BUTTON SWITCH	Panel Mount Push Button Switch	1	2
6	399-50-925-020	Handle Cap	1	2
7	399-50-925-047	Handle Connector Plate	2	4
8	90044A125		3	6
9	7565K46	Adhesive Cable Holder	4	8

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CAL POLY College of Engineering
130 Hangar Way, Watsonville, CA 95076 USA, Ph 831-768-1100, Fax 831-768-9312

APPROVALS	DATE
DWN. BY C. HANSEN	05/17/2020
CHK. BY D. DALEY	05/18/2020
ENG. T. MULROONEY W. CRAWFORD	
MFG.	

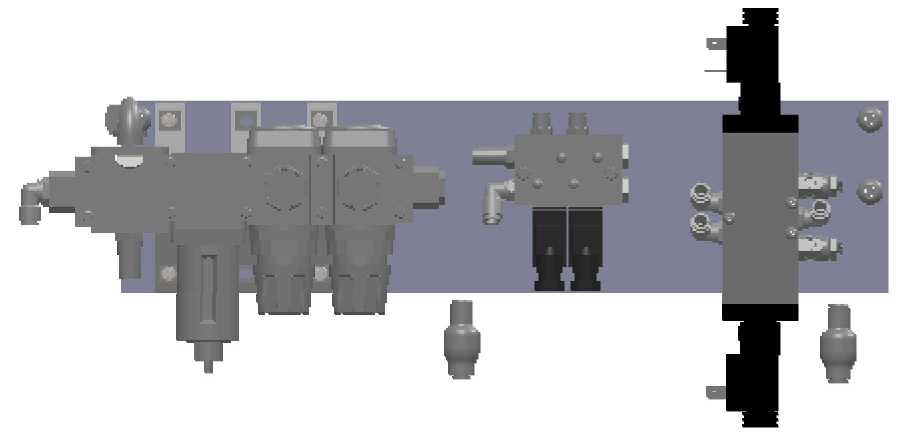
HANDLE EXPLODED VIEW
HANDLE ASSEMBLY PACKET

SIZE B | ASSEM. NO. 399-50-925-09

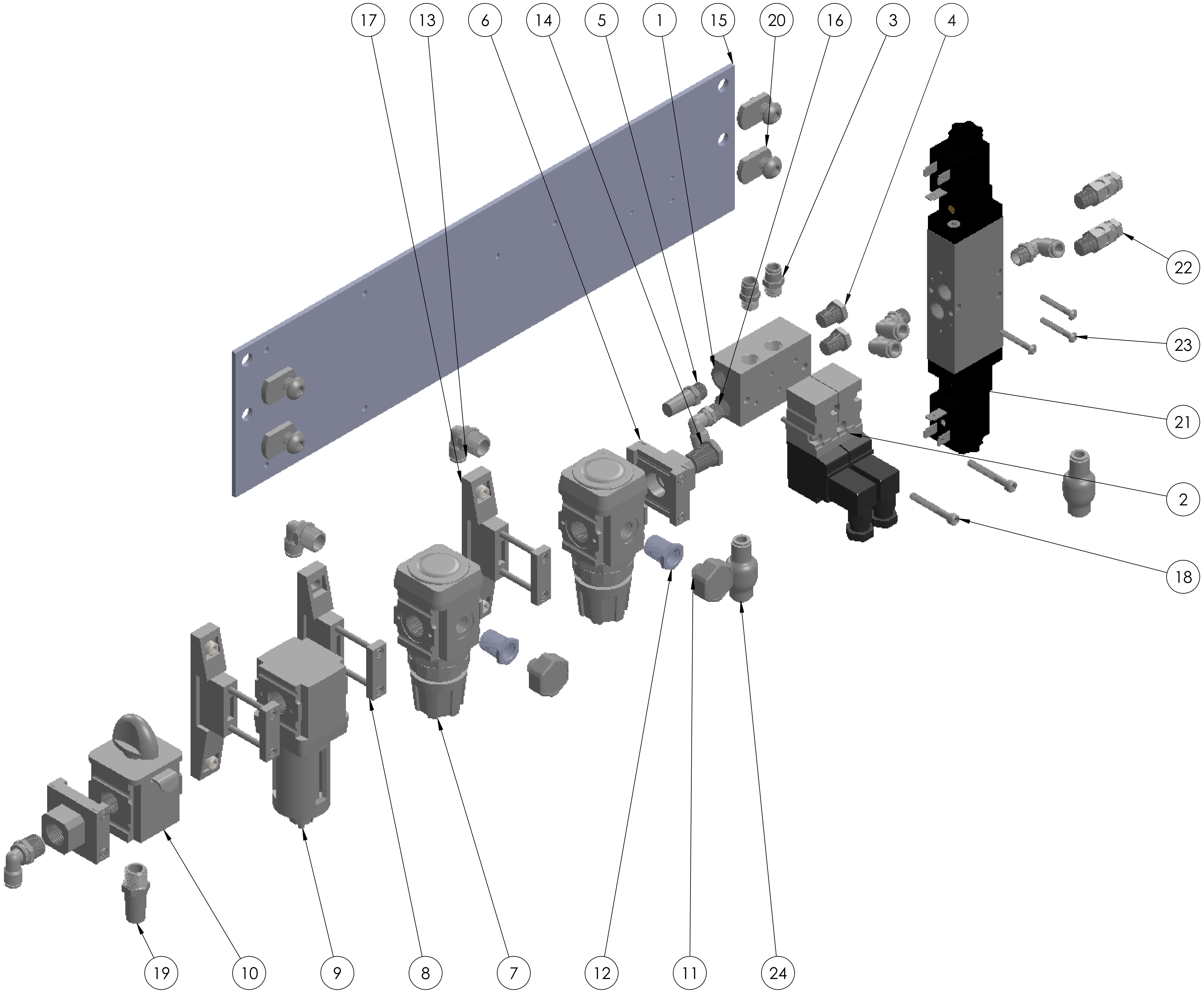
PLOT SCALE: 1:2 | SHEET 3 OF 3

4 3 2 1

NOTE:
HOSES NOT SHOWN



REVISIONS			
REV	DESCRIPTION	DATE	APPROVED
1	INITIAL	05/19/2020	R. O'CONNOR



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	61975K31	2 Station 1/8 NPTF Manifold for Modular Air Directional Control Valve	1
2	61975K55	Air Directional Control Valve 3-Way Single Solenoid with Spring, 7.9 scfm	2
3	5779K108	Push-to-Connect Tube Fitting for Air Straight Adapter, for 1/4" Tube OD x 1/8 NPT Male	2
4	4452K141	316 Stainless Steel Threaded Pipe Fitting Low-Pressure, Plug with External Hex Drive, 1/8 NPT	2
5	4450K1	Muffler 1/8 NPT Male, Steel, 11 scfm at 100 PSI Maximum Flow Rate	1
6	60115K250	End Block Set for Modular Compressed 1/4 NPT Wilkerson Modular Compressed Air FRL	2
7	4927K26	Wilkerson Compressed Air Regulator Manifold Modular, Series Number R09, 1/4 NPT Female	2
8	60115K210	Joiner Clamp for 1/8 and 1/4 NPT Lubricator	3
9	60115K720	Wilkerson Air Filter, Series F08, 1/4 NPT Female	1
10	6148K320	Safety Lockout Valve for Compressed Air FRL Wilkerson V40 Series, Modular, 1/4 NPT Female	1
11	9767T211	Miniature Pressure Gauge with Nickel-Plated Brass Case 1/8 NPT Male Center Back Connection	2
12	4452K161	316 Stainless Steel Threaded Pipe Fitting Low-Pressure, Bushing Adapter, 1/4 Male x 1/8 Female	2
13	5779K152	Push-to-Connect Tube Fitting for Air 90 Degree Swivel Elbow, for 1/4" Tube OD x 1/4 NPT Male	3
14	4452K142	316 Stainless Steel Threaded Pipe Fitting Low-Pressure, Plug with External Hex Drive, 1/4 NPT	1
15	399-50-925-033	PNEUMATICS BACK PLATE	1
16	5779K151	Push-to-Connect Tube Fitting for Air 90 Degree Swivel Elbow, for 1/4" Tube OD x 1/8 NPT Male	4
17	91251A242	10-24x1/2" SHCS	4
18	91251A201	Black-Oxide Alloy Steel Socket Head Screw 8-32 Thread Size, 1-1/4" Long	2
19	4450K2	Muffler 1/4 NPT Male, Steel, 21 scfm at 100 PSI Maximum Flow Rate	1
20	47065T215	T-SLOT FRAMING, END FEED SINGLE NUT WITH BUTTON HEAD 5/16"-18 THREAD	4
21	2945N21	5/3 Pressure Center 24V Solendoid Valve	1
22	9834K31	Flow-Control Muffler 1/8 NPT Male, 20 scfm at 100 PSI Maximum Flow Rate	2
23	91255A153	Button Head Hex Drive Screw Black-Oxide Alloy Steel, 6-32 Thread, 1" Long	3
24	1096T2	Air Flow Check Valve 1/4" Push-to-Connect Female Inlet x Outlet	2

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APPROVALS		DATE
DWN. BY	R. O'CONNOR	05/19/2020
CHK. BY	D. DALEY	05/23/2020
ENG.	T. MULROONEY W. CRAWFORD	
MFG.		

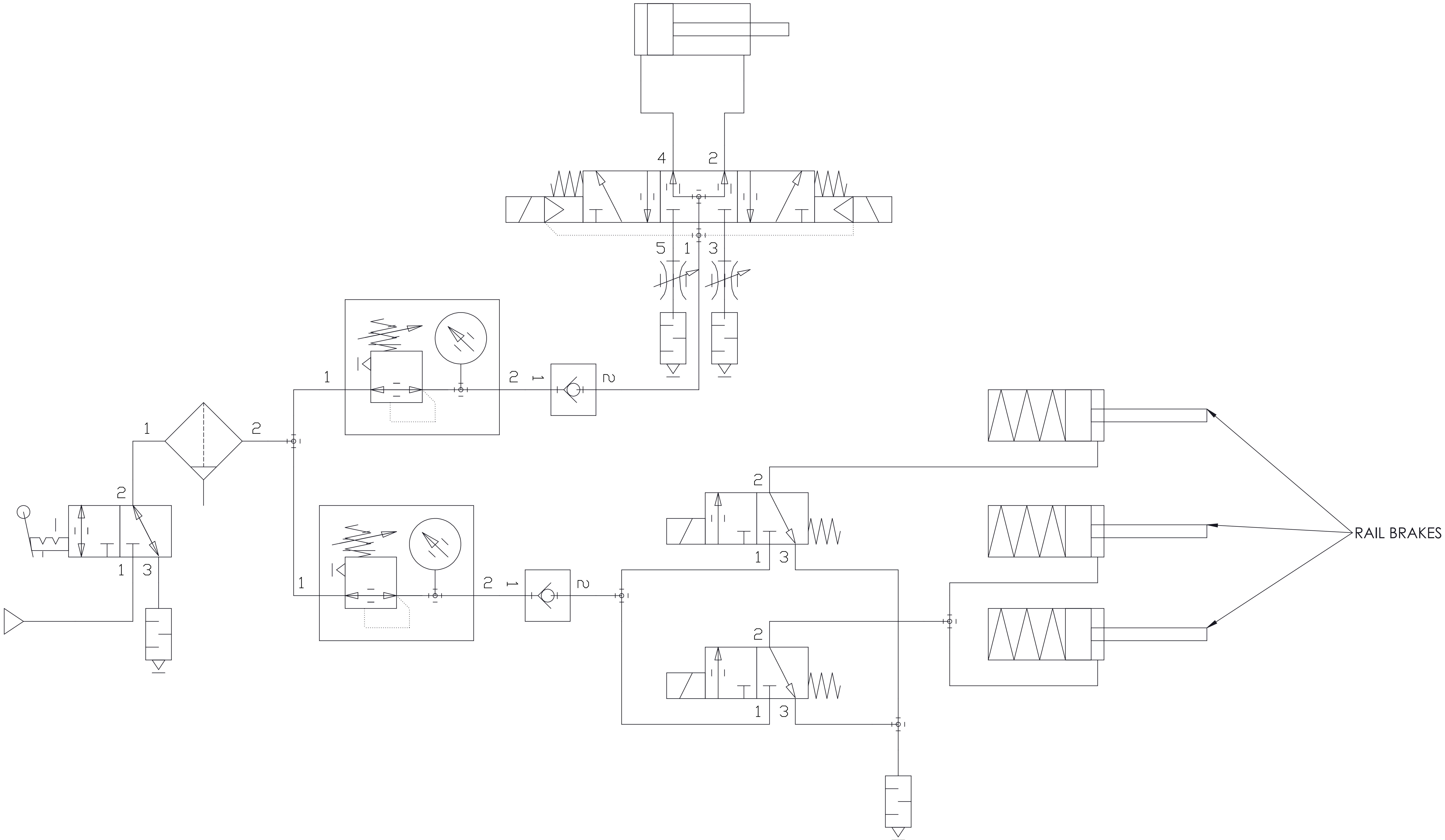
PNEUMATICS

SIZE C — ASSEM. NO. 399-50-925-10

PLOT SCALE: 1:2 — SHEET 1 OF 2

4 3 2 1

REVISIONS			
REV	DESCRIPTION	DATE	APPROVED
1	INITIAL	05/19/2020	R. O'CONNOR



SIZE	ASSEM. NO.	REV.
C	399-50-925-10	1
PLOT SCALE: 1:2	SHEET 2 OF 2	

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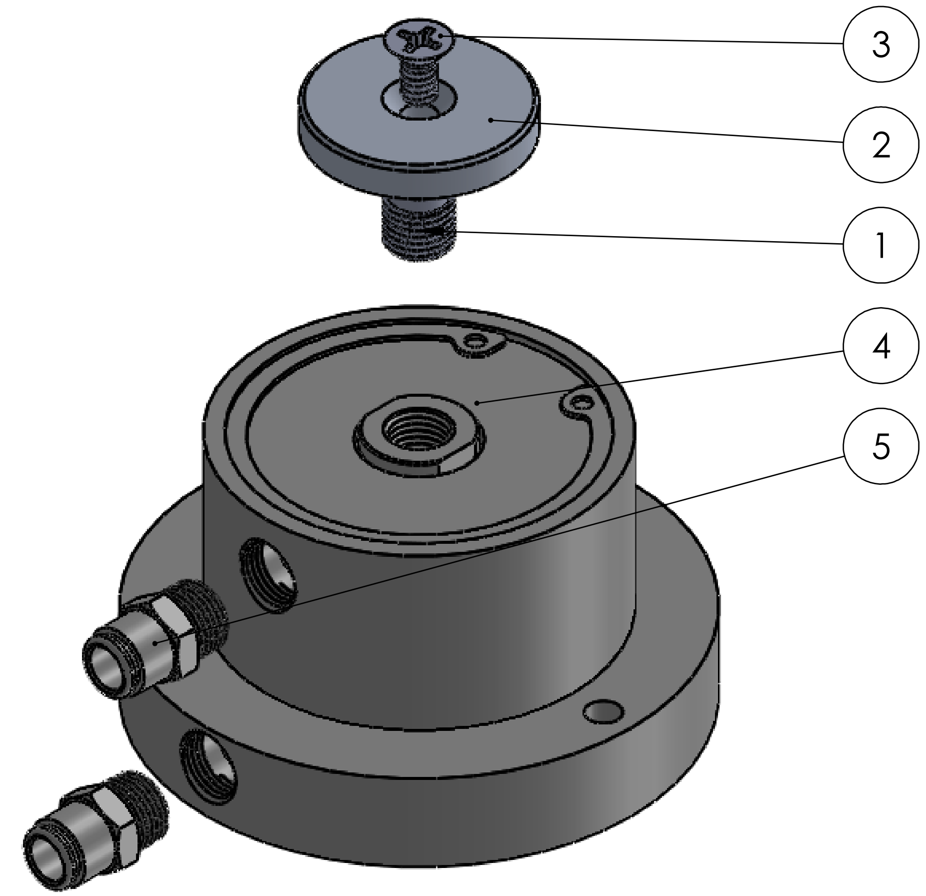

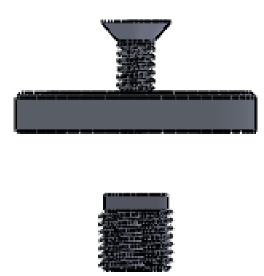

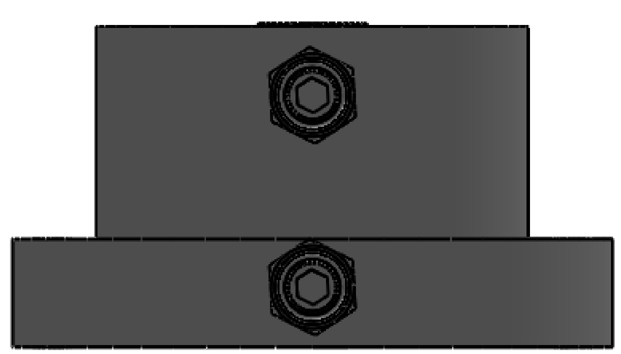

REVISIONS			
REV	DESCRIPTION	DATE	APPROVED
1	INITIAL	05/18/2020	E. FORRESTER
2	ADDED PUSH FITTINGS	05/23/2020	R. O'CONNOR

BEGIN BY ASSEMBLING PARTS 1,2, AND 3. UTLIZE BLUE LOCTITE ON THE PHILLIPS HEAD SCREW THREAD AND TIGHTEN INTO THE MACHINED 3/8-24 SCREW

SCREW PARTS 1,2, AND 3 AS AN ASSEMBLY INTO THE PANCAKE CYLINDER

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	399-50-925-025_92196A363_3_8-24 screw	Machined 3/8-24 screw	1
2	399-50-925-026	Ram mount wear piece	1
3	96640A132	910-32x3/8 Philiips Machine Screw	1
4	6212K222	344lbs at 100PSI Round Pancake Cylinder	1
5	5779K108	Push-to-Connect Tube Fitting for Air Straight Adapter, for 1/4" Tube OD x 1/8 NPT Male	2

PER ASME Y14.5M 1994		FOX Factory, Inc. 130 Hangar Way, Watsonville, CA 95076 USA, Ph 831-768-1100, Fax 831-768-9312	CAL POLY College of Engineering
APPROVALS	DATE		
DWN. BY E. FORRESTER	05/18/2020	AIR CYLINDER RAM ASSEMBLY	
CHK. BY D. DALEY	05/18/2020		
ENG. T. MULROONEY W. CRAWFORD		SIZE B	ASSEM. NO. 399-50-925-11
MFG.		PLOT SCALE: 1:1	SHEET 1 OF 1

4	3	2	1

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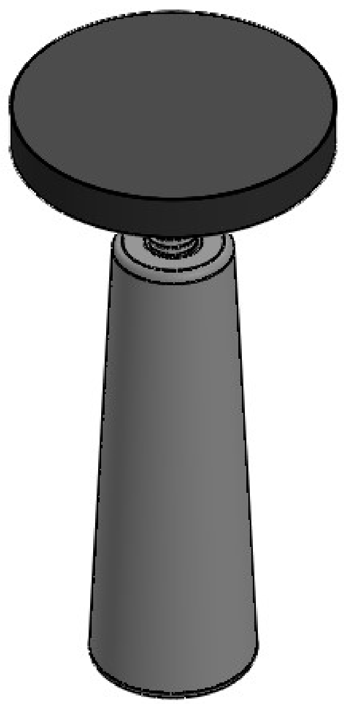
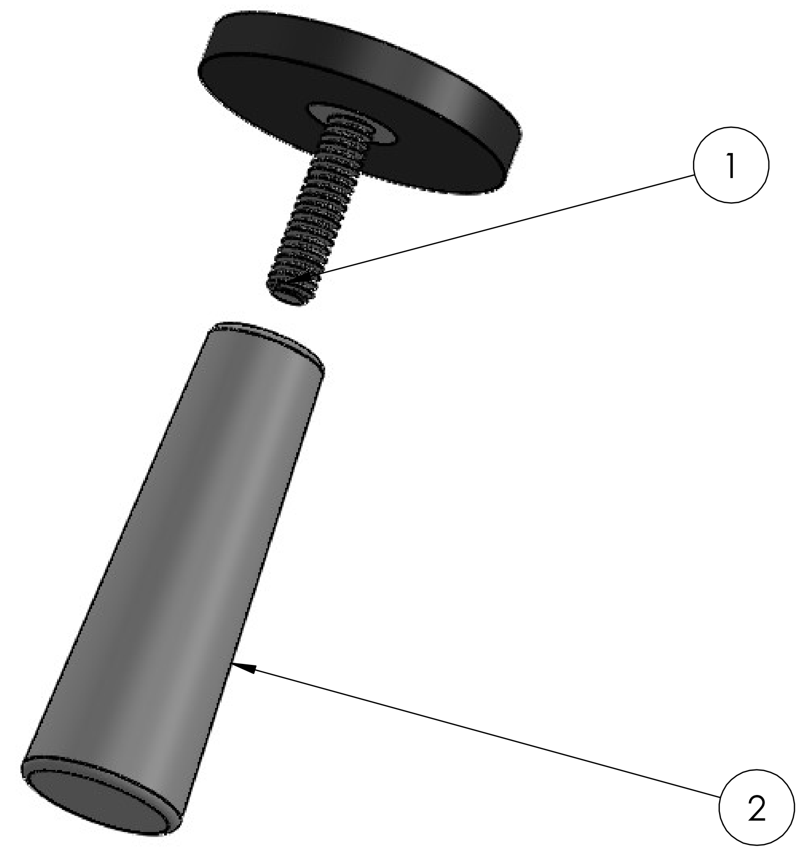
REV	DESCRIPTION	DATE	APPROVED
1	INITIAL	05/18/2020	D. DALEY

B





B

A

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	7132T24	MCMASTER NEODYMIUM MAGNET, 1/4"-20 THREAD	1
2	57455K51	MCMASTER PLASTIC TAPERED HANDLE, 1/4"-20 THREAD	1

A

PER ASME Y14.5M 1994

APPROVALS	DATE
DWN. BY D. DALEY	05/18/2020
CHK. BY R. O'CONNOR	05/18/2020
ENG. T. MULROONEY W. CRAWFORD	
MFG.	

FOX Factory, Inc.

CAL POLY
College of Engineering

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BEARING RUNDOWN & TORQUE MACHINE MAGNET CLIP FOR BOOT & CAP

SIZE	ASSEM. NO.
B	399-50-925-14

PLOT SCALE: 1:1 SHEET 1 OF 1

3	2	1