Automated Actuator Lubing Station

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Final Report for 4600:471 Senior/Honor Design, Spring 2021

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Abstract

For our senior design project, we partnered with Swagelok to create a working prototype of an automatic lubrication system that would allow for consistent application of a lubricant dispersed on the inside of a Swagelok-manufactured part. This device needed to be simple enough in design and operation so that Swagelok operators could properly lubricate the specific area on the inside of an actuator on a routine basis. The device created has a cylindrical housing that, when loaded with an actuator, will stabilize the part as a pneumatic cylinder drives a lubricant-dispensing head up into the actuator. As the cylinder retracts, lubrication will excrete from the head, creating an even, consistent layer on the desired area within the actuator. We were able to design and assemble an operational prototype that Swagelok will fine tune and finalize using permanent materials and replicate throughout their facility.

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1. Introduction

By working with Swagelok on our senior design project, it was expected that through our engineering experience and their materials and available resources, we would be able to create a fully functional prototype lubrication system. In order to satisfy Swagelok's requirements, we needed to have a clear understanding of what the main objectives were and how we were expected to verify those objectives. Swagelok desired a fully-automated system that could provide a consistently even coat of lubricant on the inside of one of their actuators. Though a simple process, there were a great deal of areas that needed to be discussed with our Swagelok advisor to make sure all of their wants and needs were addressed. This communication allowed us to produce a working prototype that met the standards they had laid out for us.

1.1 Background

Swagelok is a manufacturing company known for its production of components that are utilized in fluid-based systems. They manufacture many different types of fittings, valves, hoses, and other equipment that are necessary parts for companies and operations around the world. The part focused on in this project is found within a BN and BK valve. In every one of these valves, there is either a normally open or normally closed air actuator. This actuator uses air as an intake fluid to drive mechanical motion within the BN or BK valve. Prior to the actuator being inserted into the valve during assembly, the actuator must be properly lubricated on its internal face. If the part is not properly lubricated, there is the risk of the valve malfunctioning For this project, we were tasked with creating a smooth, more consistent way of applying the specific lube used by Swagelok, on the inside of an actuator.

The current process of applying lubricant on the inside of the actuator is entirely manual. A technician uses a cotton swab to spread an even layer around the internal face. Though this process meets the requirements needed to have a properly lubricated actuator, Swagelok was looking for a more automated way of getting a thin, consistent film applied to help improve quality. Swagelok looked to our group to create a system that would be placed on a table of the manufacturing floor where the normal lubrication was applied onto the actuator. This device would need to provide a sturdy enclosure for the part to sit in as the lube is dispensed. The system also needs to be worker-friendly, avoiding any sharp edges, pinch points, or potential misfires that could cause injury to the part or the person operating it.

Before we were able to meet with our primary contact from Swagelok, it was required that we all sign a nondisclosure agreement (NDA). This NDA states that certain information, processes, and results that come from this project cannot be used or replicated to anyone outside of Swagelok. The list of acceptable material that could be published was given to us, as well as was to do with disclosed material once the project was completed. As soon as the NDAs were created, signed, and returned back to Swagelok, it was time to begin the project. There is certain information that will be withheld due to the NDA, but all necessary information can still be included.

1.2 Product Definition

Prior to beginning the design phase of this project, we first needed to have a clear understanding of what surface the lubricant was to be applied to, as well as any specific features the Swagelok team wanted implemented in the system. To gain more information in this area, we reached out to our industrial contact from Swagelok, Tony Caprez, who is an assembly engineer for the company. After a few meetings with Tony, we concluded that our design would need to be able to:

- Apply an even lubricant around the internal area of the actuator, at a specified range given by Swagelok
- Be applied in a specific area, as not to get onto any of the actuator's threading (see Diagram.1)
- Finish the lubing process in a 3 - 5 second time window
- Be a finished product that has shown success through adequate testing
- Be made out of materials that Swagelok could provide, or be provided by an approved Swagelok vendor
- Keep operator safety as the number one priority
- Be easily cleaned and maintained

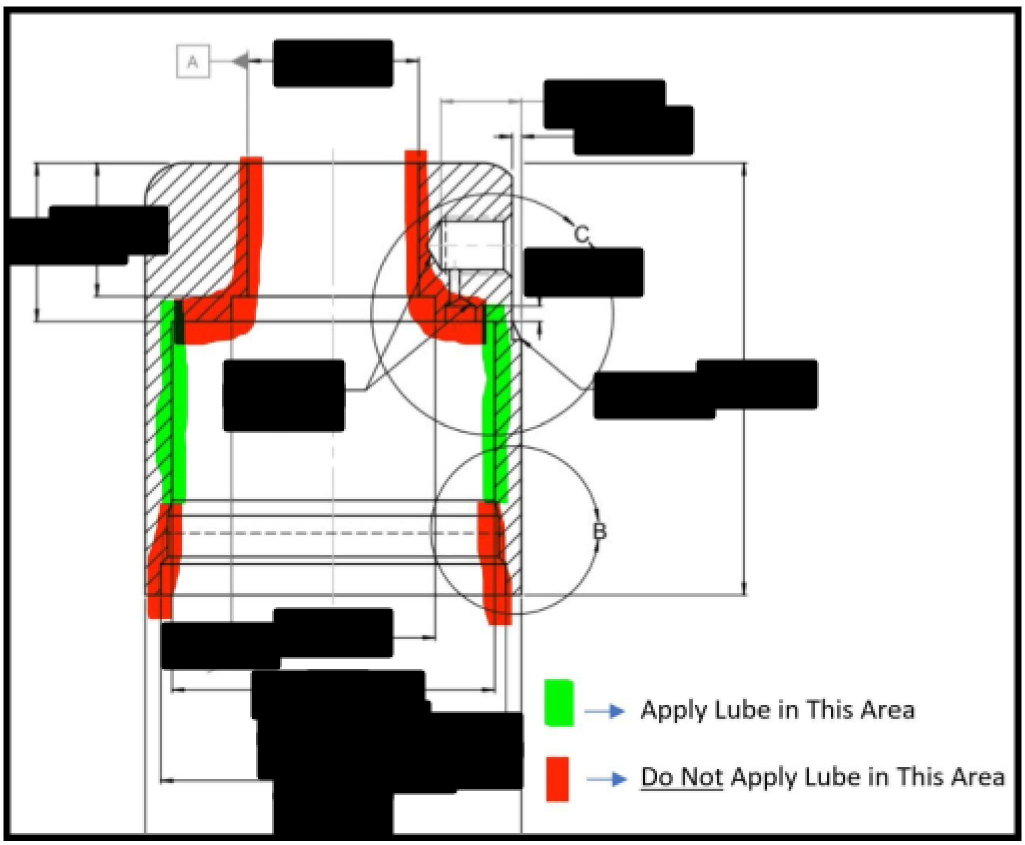


Image 1: Areas of lubing interest

Before starting any sort of design, we searched to see if there were any automated lubrication systems that were already being used in a similar environment. Though there were several different systems that we found, none were applicable to our project’s criteria, thus we knew it would be a design that was to start from scratch without worry of IP infringement This initial research was a good first step to see what exists in industry and what other concepts are used to deliver lubricant to a part.

2. Design

We began the design process by researching and moving into utilizing our conceptual design tools. With our new knowledge in this area, we were able to utilize these tools to get a good foundation for our design. We utilized pencil & paper, Google sheets & docs, and Solidworks to complete this step. We moved this foundational design into the embodiment design phase where we filled the design out by selecting suppliers and components that fit our design and budget. Lastly, there were a number of specialty components that we needed machined and required a more detailed analysis on their properties.

2.1 Design Procedure

The initial design was chosen soon after we started and was continually fine-tuned to fit all the needs of the operator keeping easy maintenance in mind. The flow of the design process, in any main step, went as shown in the Chart 1.

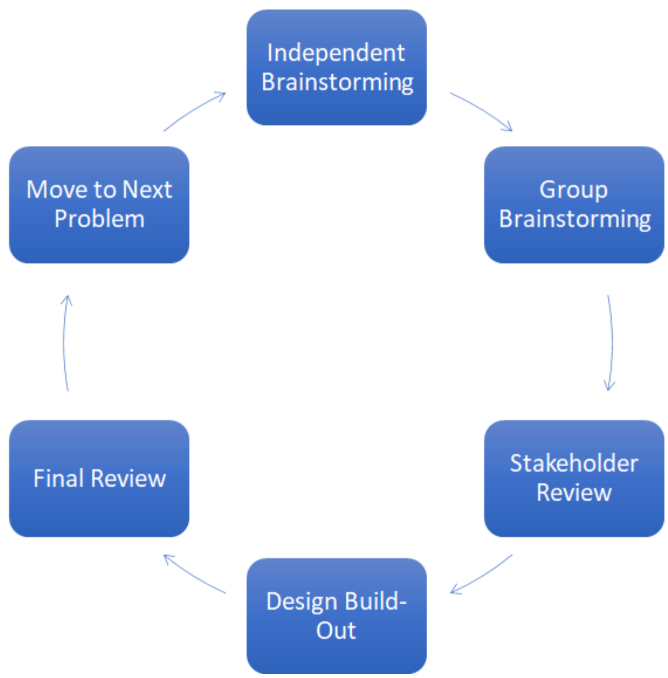


Chart 1: Specific Design Flow Chart

We cycled through the process a large number of times, as any time there was a problem, we fell back into this process. It was beneficial to brainstorm independently, then as a group, so we could bring different ideas to the table without influence of others' ideas, and then further refine the ones we like. Then these developed ideas were reviewed with our Swagelok representative. This flow happened during all the different steps of the design process, and at all different levels. Below, each design step was further detailed, and graphics were added to document our progress. In the embodiment and detail design stages, we had to utilize this flow to figure out what would work best.

2.2 Conceptual Design

To help narrow our scope of focus, we decided as a team to implement a series of commonly used conceptual design tools that we had learned and practiced through our education in our engineering program. These tools included using a function structure diagram to determine the main functions of our system, a morphological chart to create potential system layouts, an objective tree to determine areas of focus and assign weighted values to these areas, and a weighted decision matrix that would allow for a final decision on design to be made based on numerical ratings. After the conceptual design phase concluded we were left with a basic SolidWorks assembly that captured all of our ideas up to that point.

2.2.1 Function Structure Diagram

In order to move forward in the design process, it was key to take a step back and clearly define what were the main functions. We determined there were three individual functions of this process that we were trying to automate. The first function would include having some form of a fixture to hold our actuator. This fixture would need to be specific in shape so that the actuator would remain in its seated position as it was lubed, yet also rugged so that it would not fail after constant usage but soft enough to not scratch the part. The next function was applying the lubricant to the internal surface of the actuator. The constraints of this function were those discussed in the Product Definition section. As previously mentioned, our actuators are currently all being lubricated by having a worker use a cotton swab to apply a thin coating of lube on the inside of the device. Though this method has worked so far, Swagelok desired an approach that allowed for better consistency and efficiency. Our third function revolved around determining how the lubing process would start. There would need to be some sort of switch flipped to tell the system to begin lubing the part, whether it be manual or automatic. This step was key leading into the morphological chart, allowing us to brainstorm freely, yet within the loose bounds.

2.2.2 Morphological Chart

The morphological chart provided a method in which we could split our design criteria into separate identities and create varying solutions that would satisfy each identity's needs. For the first identity, the part was to be held in place. Looking into this, our group hypothesized several ideas which included; having a rigid fixture seated on or within the table that the part would sit in, creating some form of a turntable for the part, clamping the actuator down to the table, or having the part sit on top of a device that used magnets or some other feature to lock it in place.

With several options created for the first phase of the system's criteria, we then moved onto the next phase, where the part would have the specified lubrication applied to it's internal face. When brainstorming, we created several different ideas in which lube could be applied to our specific area of the device. First, we considered the idea of using a small, cylindrical-shaped tube, that could either be straight or contain a slight bend in shape, depending on the desired lubrication surface area. This tube would push out an even amount of lube over the necessary space, while rotating about the inside of the actuator. Our next idea was similar in design, except this time the lubricant would be dispensed from a thimble-shaped head. This would allow for the thimble to be inserted within the actuator and dispense lube out of it's many open pores. Another idea was using the lubrication device that Swagelok was providing us, and have the worker manually apply the lubricant. We also considered the potential of having a plunger-like device that would be inserted into the actuator and have the lubricant dispense from its sides, while retracting out of the part. This would allow for the lubricant to be controlled in terms of the area it was applied to and the time it was applied for.

Lastly we moved to the third function, starting the lubricating process. This feature not only allowed for a more automated system, but it also decreased the risk of any potential injury that might be caused by an accidental cycle of the system without the operator's knowledge. One thought was that we could use a sensor to read the part and tell the system that the part was in place and ready to be lubed. This would provide flexibility in terms of where the sensor was placed, as well as ensuring that the part was properly situated before the process began. Another thought was that we could have a foot pedal that would manually be pressed to cycle the lubing application. This would allow for the operator to begin that cycle once the part was properly seated in its fixture. Lastly and most simply, a safety button set that would start the process. This is a common start method for shop floor system automation at Swagelok. This safety button set requires two hands to begin, to ensure that one hand is not starting the system while the other is inside the operating area of the system.

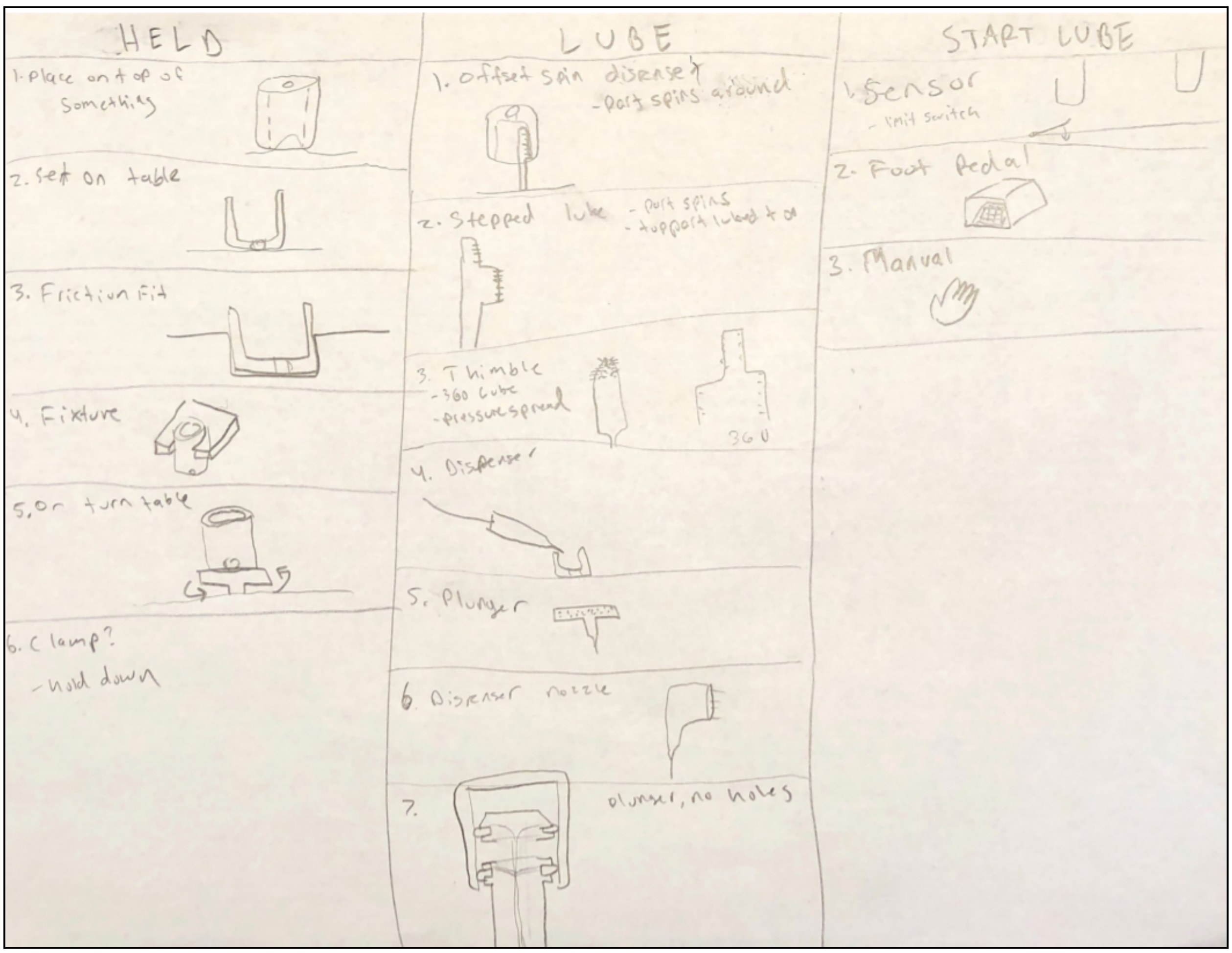


Image 2: Morphological Chart

2.2.3 Objective Tree

An objective tree is an apparatus that when used properly, can help a design team determine what characteristics of the system are the most important to ensure successful operation. By creating an objective tree, we were able to guide our focus to the areas where it is needed most, rather than wasting time trying to improve areas that matter far less.

To begin our objective tree, we first had to create several areas that would summarize our entire design. These categories should be able to describe all of the features, operations, and interactions with external sources, so that we could determine the importance of each. Our lubrication system is defined using the following categories: aesthetics, repeatability, durability, simplicity, short cycle time, low cost, high safety, and small footprint. Each of these criteria played a key role in decision making for our design, though not all were equally important. This is where the weighted value came into play. Using a weighted-decimal system, we assigned a level of importance to each category. Categories that were extremely valuable to our design would receive a high value, whereas areas that had far less of an impact on our design would receive a lower value. Based on the information we were able to gather so far in the project, we deemed repeatability to be the most vital area to ensure our system would be a success. For that reason, we assigned it a 0.24 weight, making it the 'heaviest' weight in our objective tree. Aesthetics, which had nearly no impact on the way our system would function, had the lowest possible weight to it at 0.01.

Now that we had our first set of criteria categories created, we could go into greater detail with subcategories. By taking several of our categories and dissecting them further, we were able to assign values to other important areas of our design, which might have been overlooked otherwise. For instance, referring to our repeatability category, we had three subcategories which consisted of the positioning or placement of the lubricant, the uniformity of the lubricant, and the positioning of the cylinder with the fixture. Each of these areas received an equal weighting that when summed together, equaled the weighting of the main repeatability category. By narrowing our focus to a smaller area of concern, we could ensure that we were providing enough time and value to the details that would allow for the system to function properly, on a consistent basis.

We went on to create subcategories for the simplicity of the design, as well as the level of safety that design would provide when in operation. With confidence that we had covered all the necessary details of our theoretical design, we could now take the weighted values assigned to each category and subcategories and use them to help finalize an actual design. To do this, we took our values and plugged them into our weighted decision matrix, allowing us to make a final decision based on the numerical feedback given by the spreadsheet.

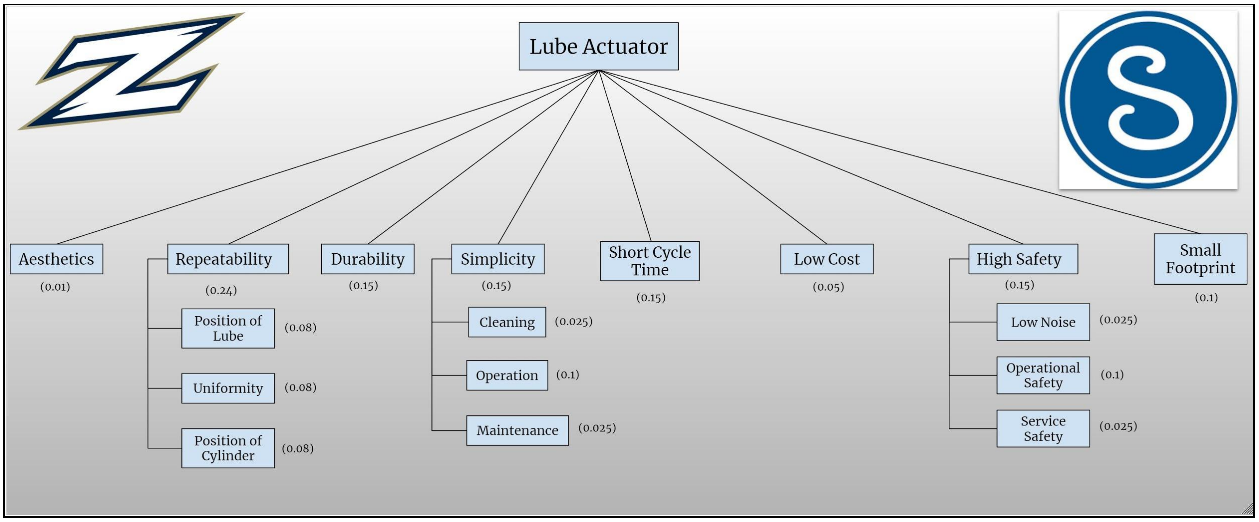


Image 3: Objective Tree Diagram

2.2.4 Concept Sketches

Two main concepts were created from our morphological chart and objective tree. These two concepts are combinations of designs from the morphological chart, specifically one design from each function grouping was used. We quickly realized the only loading and unloading design in-scope for our project was an operator doing it by hand. Both of the below designs have potential to be fully automated if that is a route Swagelok wishes to go down in the future. Both concept sketches focus on the middle function of the process- lubing.

The first concept consists of a nozzle which resembles a thimble, mounted to the table. To use this system the operator would flip the actuator upside down and push it down on the thimble, as this happens, a sensor would trigger the lubing and lube would come from the small holes. This design relies on the nozzle spraying the lube evenly, and then retracting from the actuator.

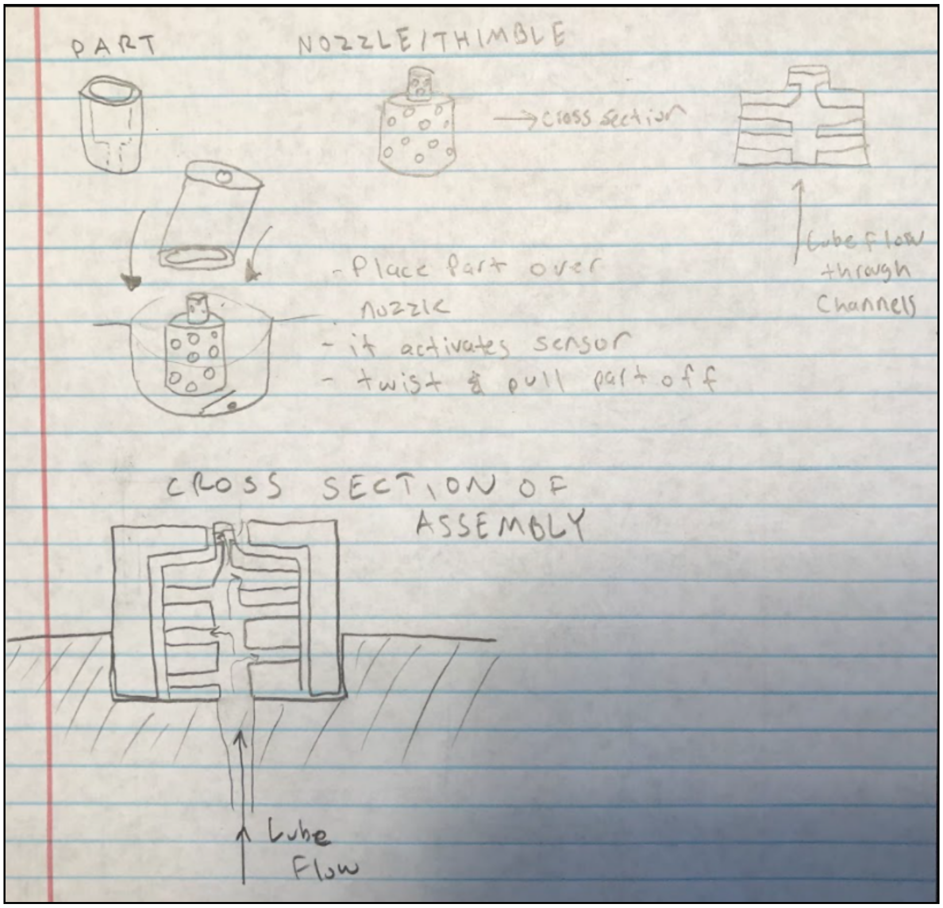


Image 4: Concept Sketch 1

Concept sketch 2 (Image 5) is similar to concept sketch 1 (Image 4), except the nozzle is a different shape. This nozzle is more of a disk with small holes along the radius. This will allow for lube to flow and then get spread over the inner diameter of the actuator. This design relies on the nozzle to evenly spread the lube as the actuator is pulled off.

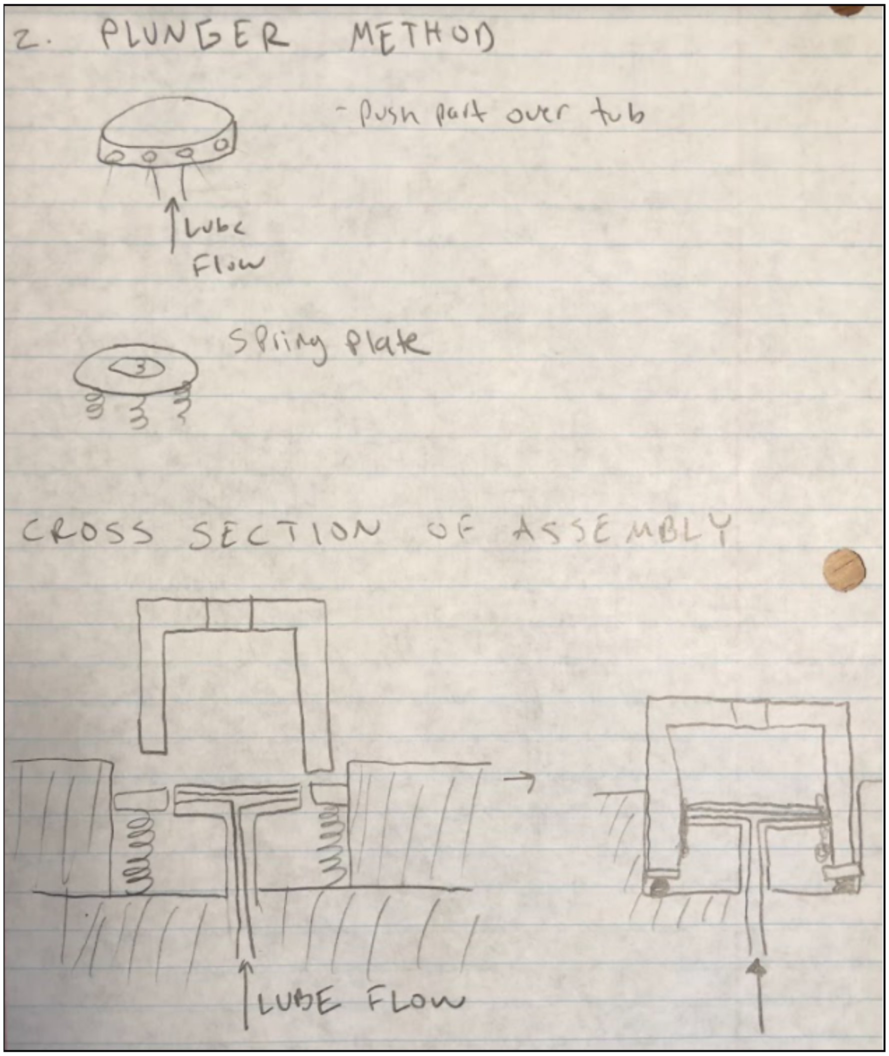


Image 5: Concept Sketch 2

The concept sketches served as a great starting point to continue our design, add safety features, and improve the systems overall efficiency. The next section goes into greater detail, explaining how we chose between these two concept sketches.

2.2.5 Weighted Decision Matrix

With our weighted values in place, we were able to analyze each of our defined categories and subcategories in the matrix. As seen below in Table 1, each of these categories was listed with their weight factor defined right next to them. From there, we had three separate columns, one for each of our potential methods for dispersing lubrication into the part. Within each of these columns, we had two sub columns, one of which allowed for a grade on a scale of 1 to 10 on how well said design would meet our category requirements. The second column was used to multiply the weight factor with the assigned grade, to receive a value that provided a numerical rating to each design's ability to meet our requirements. From there, these numerical values were summed together for each design to provide a final rating for each overall design. With our group going through the matrix together, we were able to come to an agreement on the grades that each design received. Following this process as seen below, the weighted decision matrix concluded that the best design was the spring plunger design, which had the highest overall rating with a value of 7.245. We had solidified the method that we would use to dispense lubricant within the actuator, which allowed us to move on to the next phase of the design process.

Weighted Decision Matrix for Lube Actuator			Hand Lubing		Thimble Nozzle		Spring Plunger	
#	Evaluation Criteria	Weight Factor						
1	Aesthetics	0.01	0	0	6	0.06	8	0.08
2	Repeatability- 0.24 total							
	a. Position of Lube	0.08	1	0.08	4	0.32	7	0.56
	b. Uniformity	0.08	1	0.08	5	0.4	8	0.64
	c. Position of Cylinder	0.08	5	0.4	8	0.64	8	0.64
3	Durability	0.15	10	1.5	6	0.9	6	0.9
4	Simplicity- 0.15 total							
	a. Cleaning	0.025	10	0.25	3	0.075	5	0.125
	b. Operation	0.1	6	0.6	7	0.7	8	0.8
	c. Maintenance	0.025	10	0.25	6	0.15	7	0.175
5	Short Cycle Time	0.15	3	0.45	8	1.2	8	1.2
6	Low cost	0.05	5	0.25	6	0.3	6	0.3
7	High Safety- 0.15 total							
	a. Operational Safety	0.025	6	0.15	7	0.175	7	0.175
	b. Service Safety	0.1	10	1	8	0.8	8	0.8
	c. Low Noise	0.025	10	0.25	10	0.25	10	0.25
8	Small Footprint	0.1	10	1	6	0.6	6	0.6
	Total Check	1	Score: 6.26		Score: 6.57		Score: 7.245	

Table 1: Weighted Decision Matrix

2.3 Embodiment Design

The embodiment design phase is where we took our theoretical concept and turned it into a properly functioning system. This is a very complex step for which a number of key components will need to be explained. Turning the conceptual design we discussed previously, into a fully functioning automated system required many more well-defined aspects.

2.3.1 Schematic

Below are three renders in SolidWorks. The first one is an overall view of the system to get a general idea of what it looks like and what each component is. The second is a view of the internals of the design showing some hidden switches and sensors. In this view the delrin insert is removed from the assembly. Lastly there is a render of the nozzle with two O-rings, as this is an important part of the system. See the list of components and a brief description for each piece below the renders. There are a number of smaller components not listed below, those are discussed in Section 2.3.5.

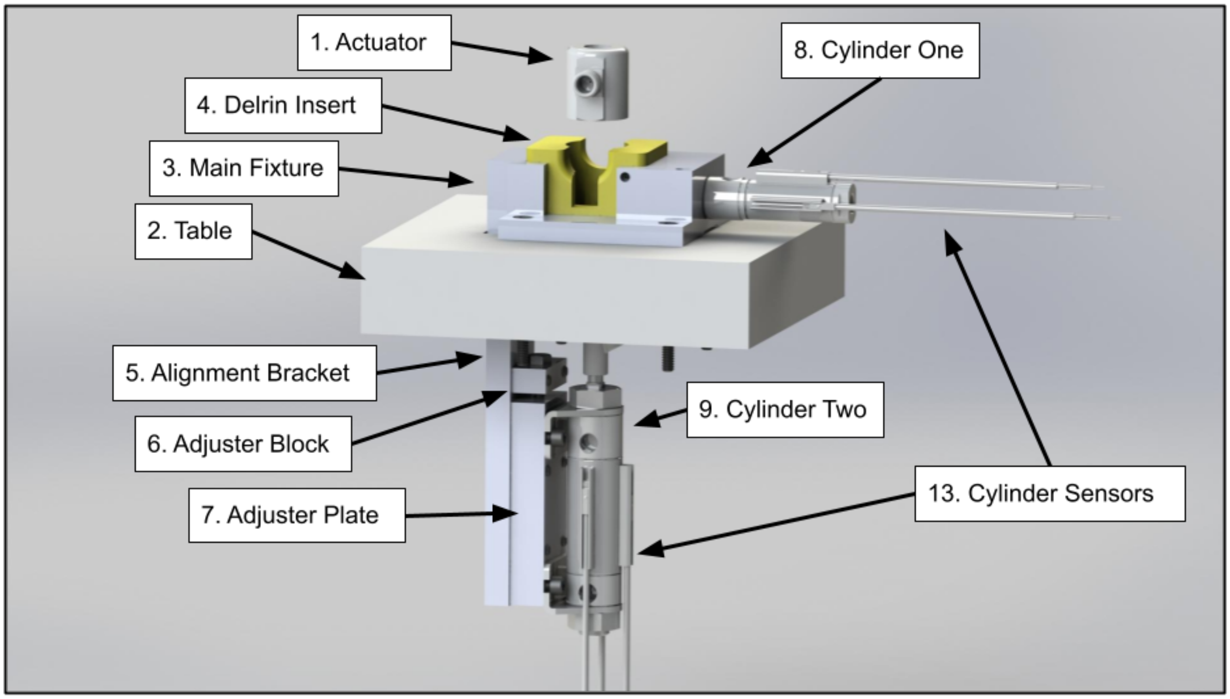


Image 6: Overall Schematic

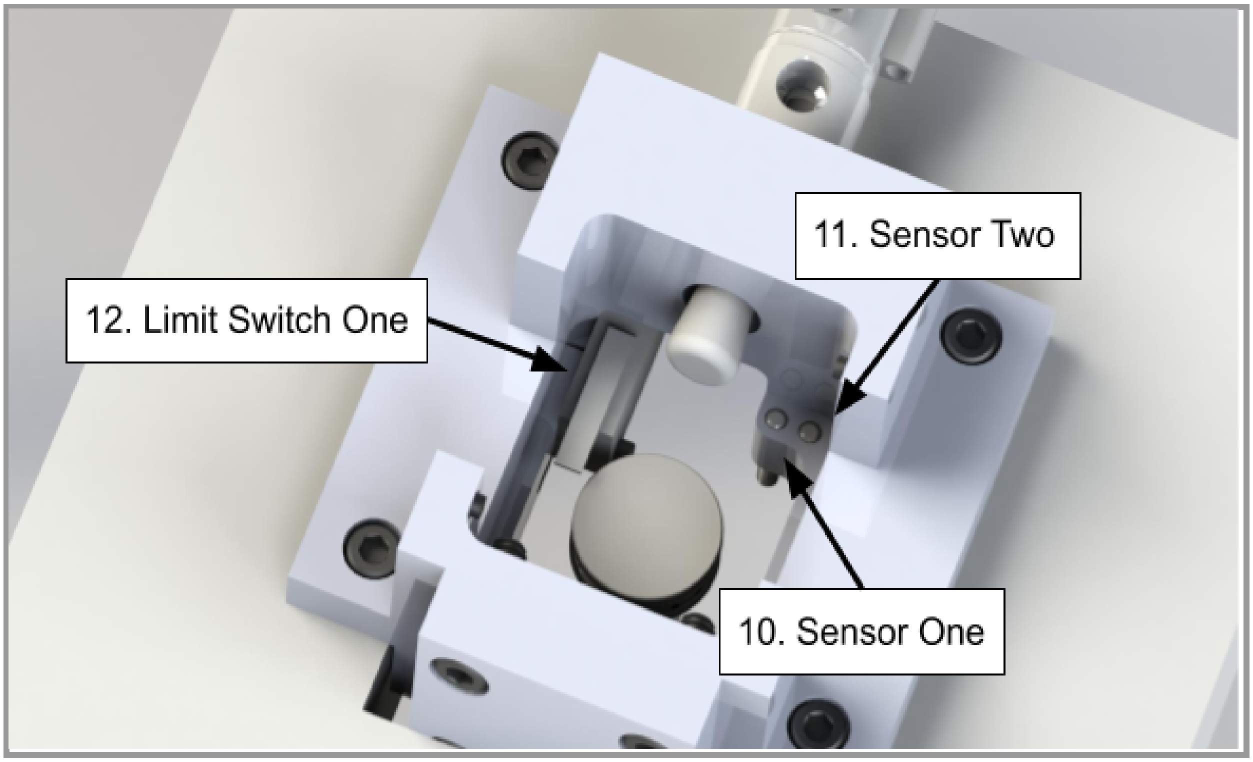


Image 7: Internal Schematic

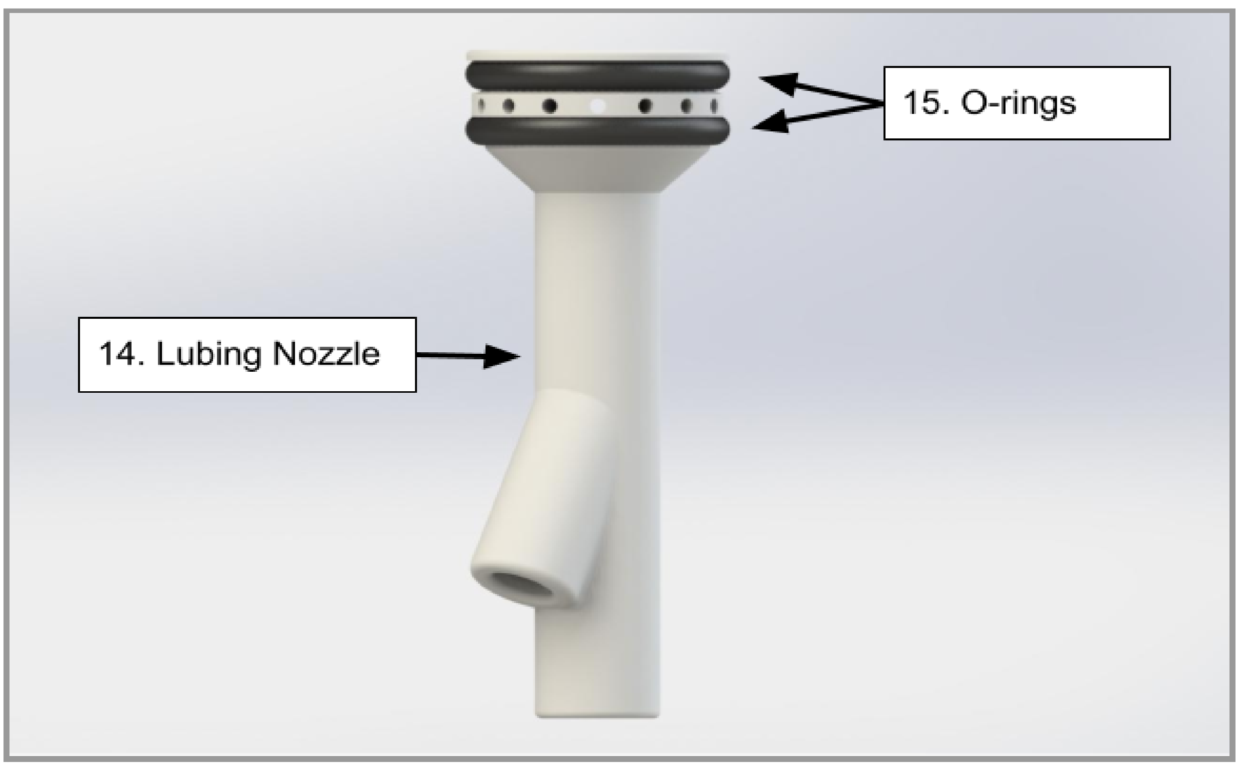


Image 8: Nozzle Assembly Schematic

1. **Actuator-** Swagelok actuator casing that needs internal lubrication prior to assembly.
2. **Table-** Where the system will be mounted
3. **Main Fixture-** Fixture base that affixes to the table and serves as the main alignment piece.
4. **Delrin Insert-** Piece that fits into the main fixture, that holds the actuators so they can be lubed.
5. **Alignment Bracket-** Long bracket that keeps the main fixture, adjuster block and adjuster plate all aligned so lubing can be completed successfully.
6. **Adjuster Block-** Small block that serves as the point of fine adjustment for cylinder one.
7. **Adjuster Plate- Plate** that goes between cylinder one and the alignment bracket. Serves as a mounting point for cylinder one while allowing for some height adjustment.
8. **Cylinder One-** Pneumatic cylinder that controls the position of the lubing nozzle.
9. **Cylinder Two-** Pneumatic cylinder that holds the part into the delrin insert during operation.
10. **Sensor One-** Inductive sensor that detects when the normal actuator delrin insert is being used.
11. **Sensor Two-** Inductive sensor that detects when the NPT actuator delrin insert is being used.
12. **Limit Switch One-** Limit switch that is mounted to the main fixture and detects when the actuator is fully inserted into the delrin insert.
13. **Cylinder Sensors-** Sensors mounted to the two cylinders that show the position of the piston within the cylinder.
14. **Lubing Nozzle-** 3D printed nozzle to dispense the lube evenly across the inner face of the actuator.
15. **O-rings-** Two standard O-rings fit onto the lubing nozzle to spread the lube to the desired thickness.
16. **Lube Dispenser-** Device used to distribute set amounts of lubrication. (not pictured)
17. **Tubing-** Transports lubricant from lube dispenser to the lubing nozzle. (not pictured)
18. **Electronics Box-** Mounted box containing electrical components. (not pictured)
19. **Pneumatics Box-** Mounted box containing pneumatic components. (not pictured)
20. **Light Indicator-** Light to tell the operator what the status of the system is. (not pictured)

2.3.1 Fixturing

In order to complete the project objective with the lubing method we designed during the conceptual design phase, our actuator needed to be fixed in a location. While the actuator was fixed, a lubing nozzle would be inserted into the part and the lubrication step would be performed. The requirements for this fixture were as follows:

- Part easily inserted and removed
- Interchangeable for different size actuators
- Must hold the actuator steady
- As safe as possible
- Inexpensive
- Simple, with readily available components
- Easily cleaned/maintained

The fixture consists of a number of different pieces. There is a main aluminum fixture that mounts to the table and serves as the main alignment piece. In this design, the alignment of the cylinder and the fixture is important, as that part ensures the even distribution of lube. Held within the main aluminum fixture is a delrin insert. This insert is specific to each sized actuator but fits into the main fixture so these inserts are interchangeable. It fits into the main aluminum fixture and is fastened in with two set screws. This insert holds the actuator at the right height for the lubrication nozzle to work correctly. Also featured in the delrin insert are two finger cut-outs to more easily insert and remove the actuator from the fixture. There are a number of cutouts, and both the delrin insert and main fixture have very unique features. The reason for this was to allow certain things to be mounted in them, mainly for safety, but also for automation. These things will be further discussed in the pneumatics, electronics and safety subsections.

2.3.2 Pneumatics

After a brief overview to acquaint ourselves with the different possibilities with pneumatic application, it was determined that pneumatics suited our needs well [1]. Pneumatic elements were utilized within the design to accomplish two separate tasks. The large main actuator (1 1/16" bore) was added to the design to translate the lubing nozzle up and down. An additional actuator was added to the design to hold down the part while the system is lubing it. This actuator is slightly smaller at a bore size of ¾". Both cylinders are required to remain concentric at all times and thus be non-rotating. The actuators have square piston rods to prevent rotation.

Certain specifications of the actuator were not needed thus calculations were also not needed. The force that the actuator fires with was not needed due to the applications of the actuators. The only specification other than the length of travel that was important was the bore sizes that are listed above. The bore size plays a big role in the ability to control the speed of the piston. The bigger the bore size the easier it is to control. For the smaller actuator the speed of the piston does not need to be controlled thus the ¾" bore size is adequate. The large actuator (1 1/16" bore size) is controlled by a regulator. The regulator controls the airflow into the actuator which in turn controls the speed the piston is fired at.

The large actuator must also be tied-in to the PLC. This is done by magnetic sensors that are attached to the actuator sides. The sensors will indicate when the actuator is all the way extended and compressed as well as when the actuator has travelled far enough where the nozzle has exited the part.

2.3.3 Electronics

In order to turn our lubricating nozzle into a more automatic system, we had to begin integrating more sensors and switches. Our conceptual design helped us understand what we needed to accomplish, and in this stage, we found the sensors and switches we wanted to use, and designed them into our system. There are two Turck inductive sensors mounted in the main fixture, they are sensors to determine if the correct delrin insert is set up properly. This is important because there are different programs for each different delrin fixture, as some actuators need more lube than others.

There is a Honeywell, lever-arm, limit switch also mounted on the main fixture. The limit switch's purpose is to detect when the actuator is fully positioned in the delrin insert. This is a key signal as it tells the PLC to begin the lubrication cycle. A key feature is that the actuator will only trip the switch when it is fully in the fixture. This is important because if the part is not fully bottomed-out in the fixture, it will not be fully lubricated.

A visual light indicator will also be tied into the system. This electronic component will be utilized to visually communicate the system status to the operator. Different light colors will signify different things to the operator. For example, green means the system is ready to operate, orange means automation in process, and red means there is an error. There will streamline production and keep an uninformed or new operator in the loop much better than risking a potential injury or system malfunction. This is a common tool used through the production floor at Swagelok.

Lastly, there are magnetic cylinder MSC sensors attached to both of the cylinders. They are mounted in tracks along the direction of the piston's movement and tied back into our main system PLC. The purpose of these sensors is to track the piston inside of each cylinder. This will tell us the location of each cylinder arm, allowing the start and stop of the lube at precise times.

As previously mentioned, all of these sensors and switches tie back in to a main PLC that controls our system. Many of these electronic components do more than their direct physical use. These can all be used as safety tools as well. To ensure the system isn't run when a hand is in the fixture, or it isn't run when the wrong delrin insert is in. This keeps safety at the heart of our lubrication system design.

2.3.4 Programs

The programming for the machine utilizes a PLC and ladder logic. To input information into this logic different sensors are utilized. The program is written in such a way that the machine will not start until the part is sensed to be in the proper position via an inductive sensor. Position sensors placed on the Bimba cylinders allow us to communicate with the PLC and have the correct positioning.

The ladder logic works as follows: the delrin insert is sensed to be inserted correctly into the aluminum fixture via an inductive sensor. The actuator is put into the fixture which is sensed when in place via a limit switch. When the switch is triggered, the horizontal trigger fires and holds the actuator in place. The sensor on the horizontal trigger confirms the actuator is being held in place. Then the vertical lubing cylinder fires. When the cylinder hits the top, a cylinder sensor is triggered. The lube dispensing until then dispenses lube based on the time set and a delay is put on the cylinder for that amount of time before it fires down into its initial position and the horizontal cylinder releases the actuator and the final sensor on the cylinder confirms that it's safe to remove the actuator.

2.3.5 Other Components

There are a number of other components utilized in our system. Smaller, off-the-shelf items such as socket head screws, nuts, washers and various fittings for the pneumatic system. These components are featured in our system in order to plumb the pneumatic line, route the lube, hold our other parts together and in some cases, allow for fine adjustments to tune the system. These components are generally from Swagelok or Grainger, so they can be easily replaced in the future.

2.3.6 Safety Considerations

The last highlight of the embodiment design phase is for the safety considerations designed into our system. At Swagelok, safety is the most important thing, more important than cost savings or shipping things on time. This ideology was reflected in our design. One feature in our system to keep the user safe is our programming. There are numerous checks through the sequence to ensure everything is running as operated. To make sure there is a part in the fixture, to make sure the part is secured and to make sure the *right* part is in the *right* fixture. Also, we ensured general safety operations by specifying that there are no sharp edges on the design and no pinch points to catch a finger, sleeve, or glove. This was achieved by covering or protecting any area that had a moving part.

In order to start the process, the group considered using dual-hand safety switches. These are essentially a two button system you press to start the system. The special part of these switches is that they require two hands to activate, to ensure that an operator doesn't have one hand inside of the fixture and one pushing the button. Although we moved away from this option when we were able to ensure safety with sensors and switches and allow the operator to retain full use of their hands.

2.3.7 FMEA

In order to ensure the reliability and have a full understanding of potential failures of our system we created a Failure Mode and Effect Analysis table [2]. Many considerations were taken during the design phase to limit the failures and ensure our system was reliable for production. We completed the FMEA chart after the design was finalized, and the only actions to come of it were non-design related.

Failure Mode and Effects Analysis (FMEA)														
System, Product, or Process:	Automated Actuator Lubing Device			Owner:				Josh Cummings		Date:	1/30/2021			
Background				Rating				Countermeasure			Results			
Description	Potential Failure Mode	Potential Effect of Failure	Root Causes	SEV	OCC	DET	RPN	Owner	Due/Done	Action	SEV	OCC	DET	RPN
Limit Switch that senses when part is placed into fixture	Doesn't open when part is removed	Always shows there is a part in the fixture. May erroneously run once.	Switch broken	7	3	1	21	Logan	Done	Ensure there is a check in the program to stop the process if it never shows that the switch is open.	6	3	1	18
	Doesn't close when part is inserted	System never starts the process	Switch broken	6	3	1	18	-	-	No action	6	3	1	18
Vertical Pneumatic Cylinder that controls lubing	Failure to fire	Part never gets lubed	Cylinder or pneumatic malfunction	1	3	2	6	-	-	No action	1	3	2	6

nozzle	Untimely firing	Hits something that is in the way, finger pinch point	Program or pneumatic error	10	1	1	10	-	-	No action	10	1	1	10
	No Retraction	Lubing process takes longer	Cylinder or pneumatic malfunction	5	3	1	15	-	-	No action	5	3	1	15
Horizontal Pnuematic Cylinder that holds actuator into fixture	Failure to fire	Part never gets held in	Cylinder, program or pneumatic malfunction	1	3	6	18	-	-	No action	1	3	6	18
	Untimely firing	Hits something that is in the way, blocks part from entering fixture	Cylinder, program or pneumatic malfunction	2	1	1	2	-	-	No action	2	1	1	2
	No Retraction	Part not released	Cylinder, program or pneumatic malfunction	4	3	1	12	-	-	No action	4	3	1	12
Delrin Insert that holds actuator in place	Wears out and allows the actuator to wiggle around	Part has uneven lube coating	Excessive cycles	5	2	7	70	Josh	Done	Create procedures to check lubing quality of the first piece of every order	5	2	1	10
Alignment bracket	Bends out of shape	Part has uneven lube coating	Operator deforms it with foot	5	2	7	70	Logan	Done	Create procedures to check lubing quality of the first piece of every order	5	2	1	10
	Bolts loosen and vert cylinder slides out of position	Part not fully lubed	Vibration over time	4	1	2	8	-	-	Regular Maintenance	4	1	2	8

Table 2: FMEA Table

2.4 Detail Design

For a design used in a scenario like ours, many factors had to be weighed and analyzed before making a decision. These components have to be certified to a heightened level of cleanliness, they have to withstand hundreds of thousands of cycles, they have to last through everyday wear and tear, be user friendly, and lastly, be easily replaceable.

2.4.1 Specific Component Selection

First, there were a number of screws, nuts and washers that were all selected because they were readily available at Swagelok. These components were from Grainger and the black oxide alloy components fit all of our needs. These were the simplest to select.

The cylinders are Bimba, original line, non-rotating, magnetic cylinders. The only cylinder property that was of importance was the stroke length. We were able to design our fixturing around these cylinders to ensure they fit. The importance of the non-rotating property is that the end of the vertical cylinder is connected to the lube nozzle. The lube feed line is connected to the lube nozzle, and if this part twists, the lube feed line will become tangled and possibly malfunction. These cylinders are magnetic so that they can be sensed from the exterior of the cylinder. We are using MSC switches from Bimba, these fit right into tracks on the exterior of the cylinder. They show an ON/OFF state depending on if they currently sense the magnetic piston at their exact location. These switches are made to be paired with this style of cylinder.

The inductive sensors from Turck and the limit switch from Honeywell (from Grainger) were chosen because they were approved suppliers for Swagelok, and they fit our application. These components had less specifications than the cylinder, they just had to perform the sensing task desired and fit into our tight-quarters design. These were two of the hardest components to find based on our constraints, and we had to make some design changes to fit the components we found.

2.4.2 Material Selection

The materials chosen for the manufactured portions of the system each have a reason to why they were chosen. The insertable fixture that holds and directly contacts the actuator casing each time was chosen to be made out of delrin. Delrin has properties that combine the strength of commonly used metals and hardness of Nylon. The delrin is strong enough to hold the casing accurately every time while not scratching the casing to maintain the parts surface finish. The machining of the delrin insert will be completely using a CNC mill through Swagelok's Machining Services.

While the other components of this system do not specifically undergo high loads or impacts the rest of the manufactured part will be machined out of aluminum. Aluminum has been chosen mainly because of its light weight and its ability to be corrosive resistant. The lightweight of the aluminum will help keep the overall system light enough that it can be supported by the table. The assembly area for the actuator casing is designated as a clean environment. The aluminum will ensure the brackets and fixtures do not rust over time and introduce contaminants into the clean environment. We also needed something that was capable of being threaded and was cost effective.

2.4.3 Components Drawings

These drawings are for our custom components only. Off the shelf items did not have drawings made. The components included are the nozzle, the delrin insert, the main aluminum fixture, the adjuster block and plate, the alignment bracket, and the special pins for the NPT version of the system. These drawings were utilized to machine the components. They can be found in the appendix, DWG 1 through DWG 6.

2.4.4 Assembly Drawings

The assembly drawings for our design include the overall assembly, and the nozzle assembly. These can be found in the appendix as DWG 7 and DWG 8. The nozzle assembly includes the specially designed nozzle piece paired with a set of O-rings. This assembly process is easy as the O-rings are just slid onto the nozzle. The assembly drawing for the overall design is more complex. This assembly includes upwards of 75 components, a bit over half being a variety of off-the-shelf hardware. The assembly process just requires light assembly work, but the important part is that everything is assembled as shown. Certain screws only fit into certain places, and if used in the wrong location, they may mess up the system.

2.4.5 Bill of Materials

The bill of materials is found in the appendix, Table 3. When working through our design phase, we had to take into account the necessary materials and how readily available they were for us to obtain. Some materials were special ordered, with a lead time of 5-6 weeks, whereas some parts Swagelok had available and ready to use at our discretion. Listed in the bill of materials (BOM) were the following: a brief description of the component, the supplier, the quantity, how each part was to be acquired, and the costs associated with that part. This allowed for our group to clearly track and communicate to Swagelok what parts we already had, what parts we needed from Swagelok, and what parts we needed ordered. Those parts that were listed as 'Have' were given zero cost as we were strictly looking at the cost of this project for our group, not the cost that Swagelok would accumulate having purchased these materials in the past. A great deal of research was done to find the parts needed, as Swagelok had specific suppliers that they required we work with. For that reason, we often had to review with our Swagelok advisor that the site we were ordering our supplies from satisfied Swagelok's requirement. The BOM also allowed for the ordering process to flow smoothly, as it was structured in such a way that once given to Swagelok, they were able to quickly send the list up the chain of management to get the parts approved and ordered.

2.4.6 Prototype Testing Results

Our group was able to meet on several occasions to create a testing plan and run tests based on our prototype design. The testing was done in person to allow for the entire support of the team. Several key tasks needed to be done before we were able to confidently test our prototype with the idea that it would produce results that were accurate to our specifications. Since we decided that our part was going to be seated within a cut-out of a table, we had to design a part on SolidWorks and 3D print a fixture that could hold the test piece. This fixture (Images 9 & 10) allowed us to place the actuator in a stable position, similar to the position it would be in when seated in a table and apply lubricant inside of it by manually moving our lube-dispensing nozzle up and down.

Image 9 & 10: Prototype Testing Fixture

Swagelok also provided materials for us to make the testing process much more accurate to what the final product would be put through. We were able to use one of Swagelok's lube dispensing machines, known as the Nordson *Performus X100 Series Dispenser.* This machine allows the lubricant to be dispensed inside of our actuator. The dispenser was connected to a portable compressed air source, as well as to a local electrical outlet, so that it had all the necessary utilities needed to function for testing. A water separator was also required to ensure that the compressed air we were getting from the air compressor was clean and dry. If not, we risked potentially damaging our lube dispensing unit.

2.5 Standards

Throughout the design phase as well as the final embodied design multiple ASME standards were used. The Y14.5 standard of dimensioning and tolerancing was used when designing the fixture and creating the drawings for manufacturing. This standard is more commonly referred to as GD&T (Geometric Dimensioning and Tolerancing) and is the authoritative guidelines for the industry. Due to this the parts were able to be machined accurately. The knowledge of this standard spreads throughout the industry so each reader knows what the part is and what features it has.

3. Design Verification

Though our group did a relatively good job at staying on schedule with this project since Fall 2020, we still had times where time was lost due to waiting to be properly initiated with Swagelok, finding an applicable time to run tests, or longer than normal lead time on needed products. With all that being said, it was decided with Swagelok that we would not be producing a final product, but rather the final prototype. This means that since we would not have necessary time to create the final product, we would design and build a step below the final product and test it. With the results from testing, we could pass this information onto Swagelok so that they would have a clear plan of action to create and implement the final product.

Once the majority of parts listed in our BOM had been ordered and delivered, we were ready to go into Swagelok to begin the assembly of our final prototype for testing. Though the assembly could have taken place elsewhere, handling it in Swagelok's building provided us with any and all necessary tooling, support, and realistic testing locations that we required. It also allowed us to work with the engineers that have been guiding us through the entire process, in the event that any issues would arise, so that we could have their support in finding a solution.

The final design will be a station within the Swagelok workcell and thus will need additional design verification. The majority of the design verification will include qualitative tests as our project description gave reference images to the end goal, rather than an exact measurement. Through the testing of the prototype design the lubed parts were compared to a standard completed part. The verification of the final assembled design will include the same comparisons. The first standard in the verification process is the location of the lube. The lube must only be applied to certain surfaces of the casing, as shown early in the report. The final design will be verified in this aspect of lubing if it can keep the surfaces that must be lube free clear of lube.

The thickness of the lube will also need to be verified in order to verify the whole design. The specification that we are trying to meet is qualitative. The thickness is either the correct thickness or not. Currently the thickness of the lube is unable to be measured. This is due to how miniscule the amount is, and how it is positioned within the casing. Another part of the design parameter is to cut the cycle time down. This must be met as it was a main parameter and the cost justification of the project. The cycle time of this process when done by hand is already relatively short, so any slight increase to this may throw off the timing of the rest of the assembly process, so it was key our design was a more efficient process. The overall cleanliness of the nozzle is an important aspect to the design that must also be verified. If the nozzle gets lube built up frequently then the design will not be overall effective, and lube will be left on surfaces that cannot be lubed.

These parameters will be verified once the whole assembly is together. The verification process will act just as if the design is being used in the assembly work cell. The process will include lubing of 30 parts. This will allow the design to go through work conditions and allow for the design to be verified. In Table 4 in the Appendix, we summarized all of our accomplishments and verifications.

4. Costs

There are two main portions of cost that go into this design. The main portion is the cost of parts and the labor cost. Both are further discussed in the following subsections. This system was designed for a shop floor environment and would have to be replicated to scale the effectiveness. With this in consideration, it was key that the design was cost effective.

4.1 Parts

The details for this system's cost can be found in Table 3 in the Appendix. There are several items here, either bought, made internally, or had on hand. The total cost for the system built was $933.75. We expect this cost may be around $1,000 when it is duplicated, because of less components on hand to use, somewhat offset by possible discounts when buying more than one component, like we had to do with our initial prototype. Even with this price tag, the design has a return on investment (ROI) of around a year. In similar industrial applications, it's desired that purchases have a ROI of less than three years. This design is determined to be cost effective.

4.2 Labor

The other proponent to the cost of our project is the labor cost, seen in Table 5 below. Firstly, there were two other associates involved in the production, one manufacturing some of the pieces, and another to 3D print other pieces. These two played a small part in the labor cost. Our team put in extensive hours to research, brainstorm, design and test this system. This cost cannot be included in the cost of the system, as systems from here on out won't include this large chunk of cost. Most of the time recorded for the team members is for the research and design (R&D) phase of the project. There was very little info to begin with, so the R&D phase really started from the ground, a big reason so many hours went into this system. The cost per hour of our labor is a desired cost, no compensation was given so the cost to Swagelok was low.

Category	Name	Cost per Hour	Total Number of Hours	Total Cost
Team Member Labor:	Logan Haid	$40	400	$16,000
	Heather Sommer	$40	400	$16,000
	John Maly	$40	400	$16,000
	Josh Cummings	$40	400	$16,000
Manufacturing Labor:	Associate 1	$30	8	$240
	Associate 2	$40	5	$200
			Total	$48,440

Table 5: Team Labor Cost

5. Conclusion

Our design group was able to fully construct an operational prototype that, with further involvement of our group and Swagelok's representatives, will be able to be fully implemented into the company's assembly process. We will continue to work with Swagelok for the remainder of the semester with plans of creating a final product that can be used on their production floor.

5.1 Accomplishments

This project can be broken down into three major goals: 1) improve throughput by automating the lubing process, 2) create a reliable, consistent layer of lube in the desired location and, 3) design a system where maintenance can be done with ease and operators are kept safe. The finished product has cut the lubing time by 3 seconds at a minimum, with potential to save even more time per piece. The results of the testing have shown a consistent layer of lube applied to the ID of the actuators. The design does not currently control the lube well enough to fulfill the requirement. With more time spent on testing and tweaking this goal is reasonable. The Automatic Actuator Lubing System has been able to accomplish some of these goals and has shown a clear path forward to accomplishing the rest. Once these requirements are hit, it also has a future of expanding the design into the facility on different product lines. The accomplishments are summarized in the System Requirements and Verifications table in the Appendix.

5.2 Uncertainties

While the design is robust there are a few uncertainties of the system. These uncertainties are all based on the machine running for extended periods of time. The buildup of lube of the nozzle is a concern for the system. While the nozzle is designed to minimize this it could occur while the system is operating in long part runs. The O-rings bring another uncertainty with them relating to the life of the O-ring. At a certain point in time the O-ring may become worn and result in a thicker layer of lube. The exact point in which the O-ring should be replaced is an uncertainty of the system. This is true for all components in the system though. Eventually, things will wear out and the lubing process may change a bit. Some of these possibilities were reviewed in the FMEA table. We do not expect this to be an issue.

5.3 Ethical considerations

The ethical concern that the project primarily dealt with was that of safety. During the design process, the safety of the operator was of utmost importance. The design is constructed in such a way to minimize pinch points, encourage ergonomics for the process through automation, and with ease and safety of maintenance in mind. Sensors were added to ensure that the machine could not run without the part being loaded. Parts of the design were adapted to accommodate safety regulations during maintenance to make the regular maintenance as easy as possible. Pinch points were reduced by utilizing a design that holds the part from within the design instead of externally.

5.4 Future work

After months of focused work and testing different design methods, we were finally successful in creating a fixture that could bring automation and moderate consistency to the lubrication of the inside of Swagelok's actuator. Though both parties were thrilled with the results, there is still more work to be done moving forward. Our group's final product was not what Swagelok was ready to implement throughout their facility. More work will be needed to fine-tune the lubrication dispensing and to ensure the system will be able to function properly over a long period of time. This could be guaranteed by improving the materials in which the entire fixture was made out of. Due to a series of time constraints, we were not able to make each custom piece out of a stronger metal alloy, but rather used plastic 3D printing as a prototype design for the time being. These plastic pieces are much more fragile and susceptible to scratches, so ideally they will be upgraded.

The design of this system follows the dimensions of a particular actuator. The system has the capabilities to be expanded to other part numbers within Swagelok's inventory. To accomplish this task certain variables of the design will indeed to be changed. The insert in which the part sits will need to be changed to one that is sized to the new actuator's dimensions. The insert also selects the height of the actuator in respect to the nozzle. This height effectively influences the location of the lube. Following these hardware changes, the program on the Nordson will need to be adjusted to achieve the correct properties of the lube such as location and thickness. These properties are not easily determined, so a table to help clarify this was created. Table 5 in the appendix shows what factors affect the lubing placement and how to control them.

This information will be passed to other engineers in the department to finish the final design and allow it to have future implementation to other product lines. Our team gathered all of our pertinent documents and information and passed it onto the aforementioned engineers. There are a number of things still need to happen in tandem with full implementation. Extensive validation will need to be completed, associates will need trained on use and maintenance, the maintenance team will need training on the upkeep and preventative maintenance, standard work for the system will need written and approved, and many more things that go into systems on a production line. The accomplishments our team managed to hit, starting from scratch and designing and prototyping this complex system, will allow for robust improvement and implementation throughout the company.

References

[1] Woodford, Chris. “Pneumatics: a Simple Introduction.” *Explain That Stuff*, 7 May 2020, www.explainthatstuff.com/pneumatics.html.

[2] Forrest, George. “FMEA (Failure Mode and Effects Analysis) Quick Guide.” *ISixSigma*, 26 Mar. 2020, www.isixsigma.com/tools-templates/fmea/fmea-quick-guide/.

Appendix A

Table 3 BOM With Costing Information

Component	Part Number	Supplier	QTY	How to Acquire	Cost Each	Total Cost
Lube Nozzle	-	Team	1	3D Print	$0.00	$0.00
Original line, non-rotating actuator, magnetic rod, ITEM: NRM-091-DXPT1T3T4, 1 1/16 bore, 1" stroke	NRM-091-DXPT1T3T4	Bimba	1	Buy	$98.00	$98.00
Cylinder Sensors for Lubing cylinder (3 wire, 1 1/16 bore)	MSC	Fluidraulics (Bimba)	5	Buy	$40.53	$202.65
Rubber Tip for Hold down Actuator (Round Slip-On Furniture Protective Leg Tips, Black Rubber, 1/4 in Leg Outside Dia., 10PK)	16ZD80	Grainger	1	Buy	$5.01	$5.01
Original line, non-rotating actuator, magnetic rod ITEM: NRM-040.5-DXPT1T2 , 0.5" stroke and 3/4" bore	NRM-040.5-DXPT1T2	Bimba	1	Buy	$66.50	$66.50
Inductive Sensor	1619327	Turck	2	Buy	$26.00	$52.00
Limit Switch	V7-2B17D8-022	Grainger (Honeywell Product)	1	Buy	$2.83	$2.83
Metering Valves Part # 5RTJ6 SMC Elbow Flow Control Valve	5RTJ6	Grainger	4	Buy	$6.81	$27.24
5-Port Solenoid Valve (Grainger part # 6JJ44 ARO 4-way solenoid valve – 24 VDC $103.42 Qty: 2)	6JJ44	Grainger	2	Buy	$103.42	$206.84
Non-Metallic Enclosure – 8H x 6W x 5D	52XD34	Grainger	1	Buy	$57.22	$57.22
Aluminum Plate – 12H x 12W x 1/16	3DRZ2	Grainger	1	Buy	$12.55	$12.55
Metallic Enclosure – 12H x 12W x 8D	6HXZ2	Grainger	1	Buy	$125.60	$125.60
Interior Panel	2W822	Grainger	1	Buy	$14.31	$14.31
Power Supply Part # 55JA29 Omron DC Power Supply – 4.5 amps	55JA29	Grainger	1	Buy	$115.00	$115.00
Fittings	-	Swagelok	1	Have	0	$0.00
Green LED	-	Swagelok	1	Have	0	$0.00
Small PLC	-	Swagelok	1	Have	0	$0.00
Lube Control Box	-	Nordstrom	1	Have	0	$0.00

Adjustment Bolt (1/4-20 2" hex head bolt)	-	Swagelok	1	Have	0	$0.00
Bolts & Screws	-	Swagelok	-	Have	0	$0.00
Tubing	-	Swagelok	-	Have	0	$0.00
Main Fixture	-	Swagelok	1	Machine	0	$0.00
O-Ring (#208, CS .139, ID .609, OD .887	41UK84	Grainger	2	Have	0.0744	$0.15
Delrin Insert	-	Swagelok	1	Machine	0	$0.00
Bracket	-	Swagelok	1	Machine	0	$0.00
					Total Cost:	$985.90

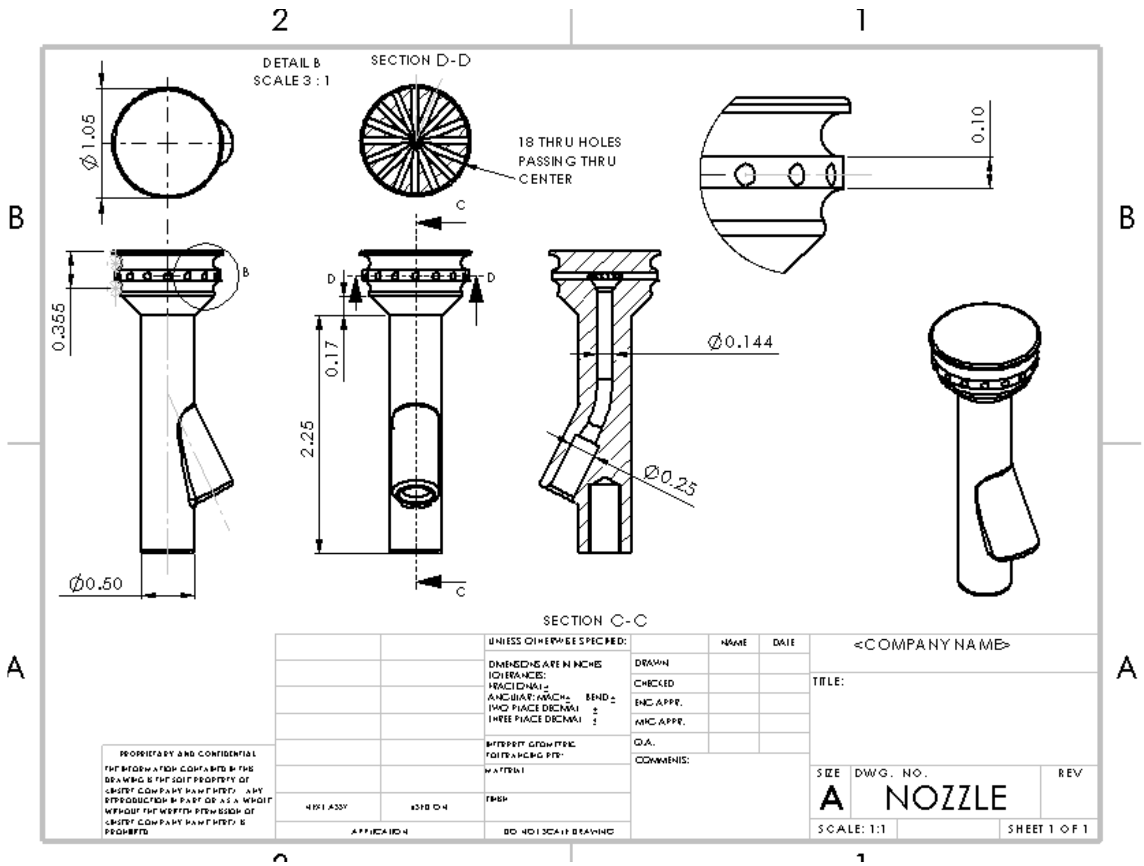
Table 4 System Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. Lubrication applied to part correctly a. Applied to correct location b. Even coating of lubricant	1. a. Further verification needed- inability to control lube from being applied to threading b. Further verification needed- more fine tuning necessary	
2. Prioritize operator safety a. No pinch points b. Completed FMEA c. Ergonomically efficient	2. Acceptable under Swagelok's safety standards	Y
3. Process cycles in 3-5 seconds	3. The prototype cycles in 7 seconds, with much room for improvement. 3-5 Second cycle time is attainable.	N
4. Easily cleaned and maintained	4. Considered during design phase	Y
5. Be replicable to other workcells	5. BOM and part drawings created and shared	Y
6. Seamless hand-off to next team a. Documentation on project history b. Part drawings for custom components c. Test results d. Guide on optimizing lubrication	6. Created these files and passed on to Swagelok	Y

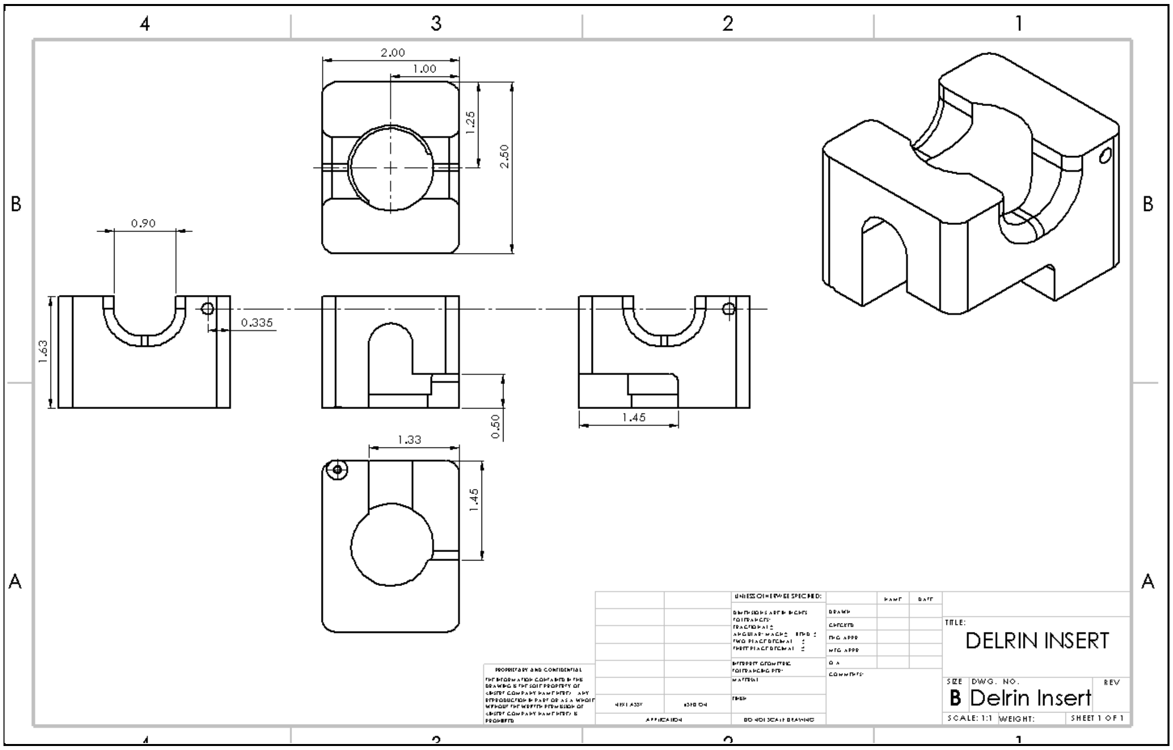
Table 5: Lube Parameter Adjustments

			Factor Affected:			
			Thickness	**Uniformity**	**Lube Build-Up**	**Lube On Threads**
Variable:	**O-Ring**	OD	Increasing the O-Ring OD would decrease lube thickness	-	-	If too big OD, will scrape all the lube off into the threads
		Thickness	Increasing the O-Ring thickness would decrease the lube thickness	-	-	If too big OD, will scrape all the lube off into the threads
	Nozzle	OD	Increasing the nozzle OD would decrease lube thickness	-	-	If too big OD, will scrape all the lube off into the threads
	Pressure	Dispensing Pressure	-	Too little dispensed leads to partial coverage	Too much dispensed leads to excess build up	Too much dispensed leads to excess build up which gets into threads
	Time	Dispensing Time	-	To little dispensed leads to partial coverage	Too much dispensed leads to excess build up	Too much dispensed leads to excess build up which gets into threads
	Movement Speed	Cylinder	-	Moving too soon leaves the top unlubed	No movement until it is all dispensed may lead to slight build up	Moving too soon leaves lube on the threads
	Concentricity	Fixture/Cylinder/ Actuator	-	The better the concentricity, the better lube uniformity	-	Poor concentricity leads to lube getting pushed into threads

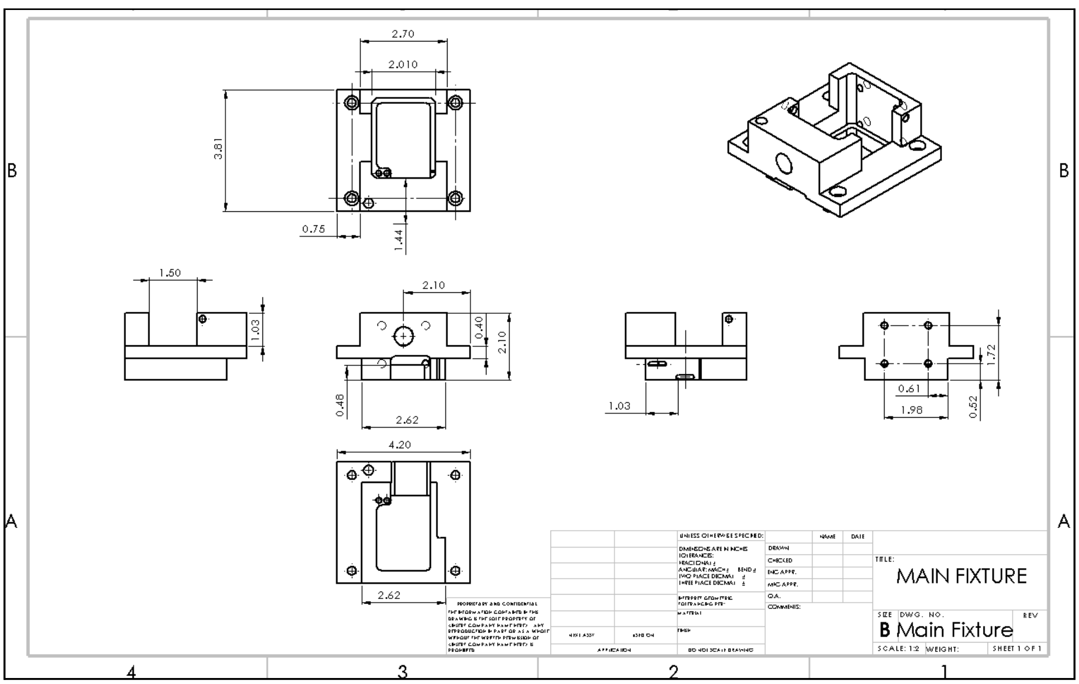
DWG 1: Nozzle Drawing



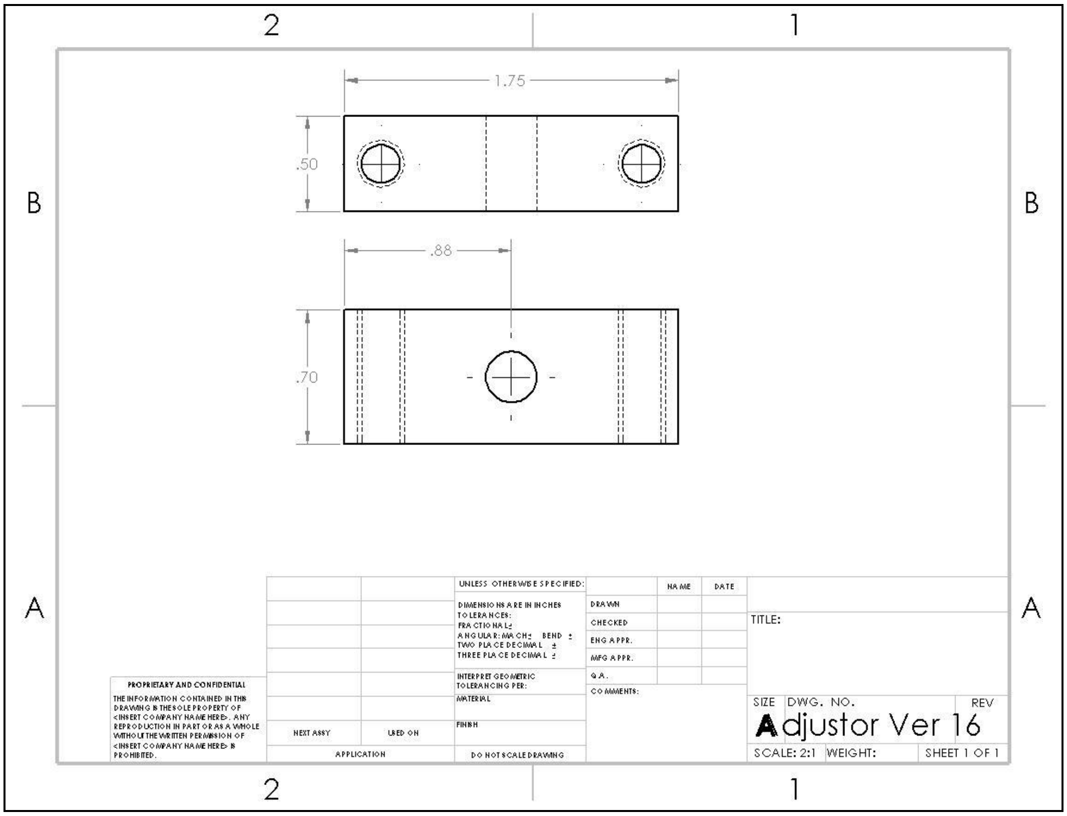
DWG 2: Delrin Insert Drawing



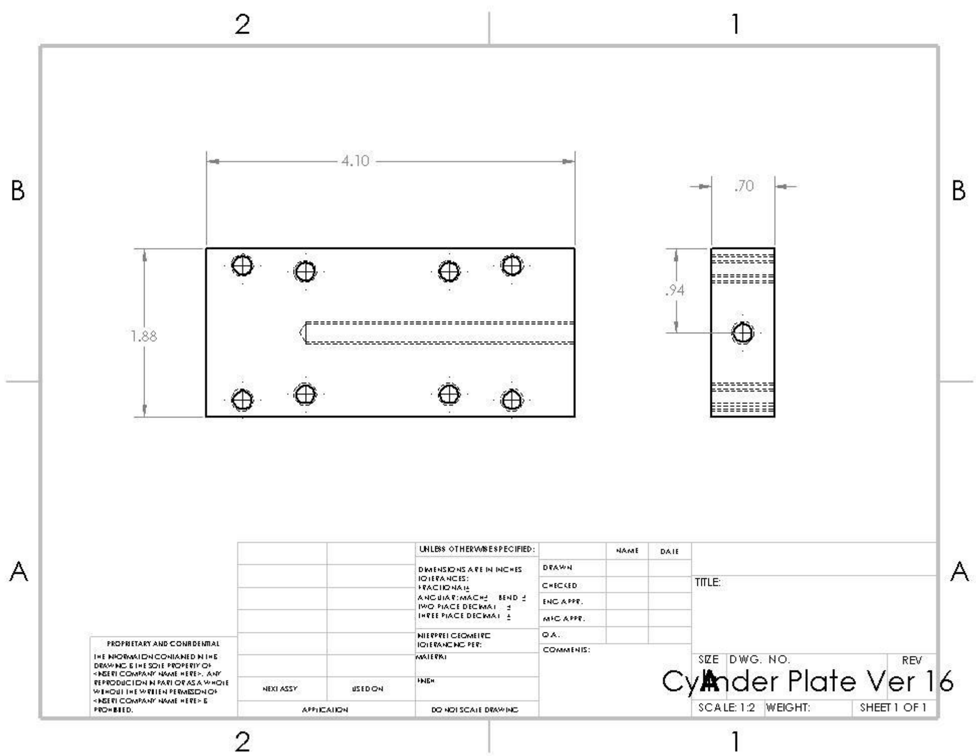
DWG 3: Main Fixture Drawing



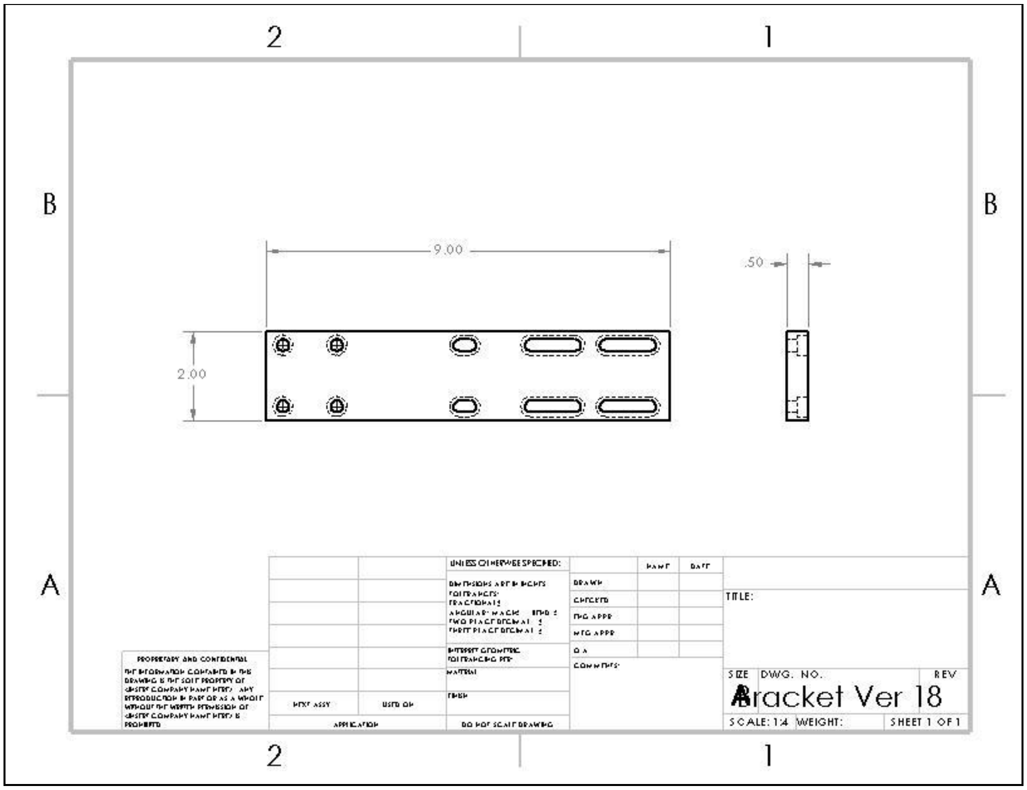
DWG 4: Adjuster Block Drawing



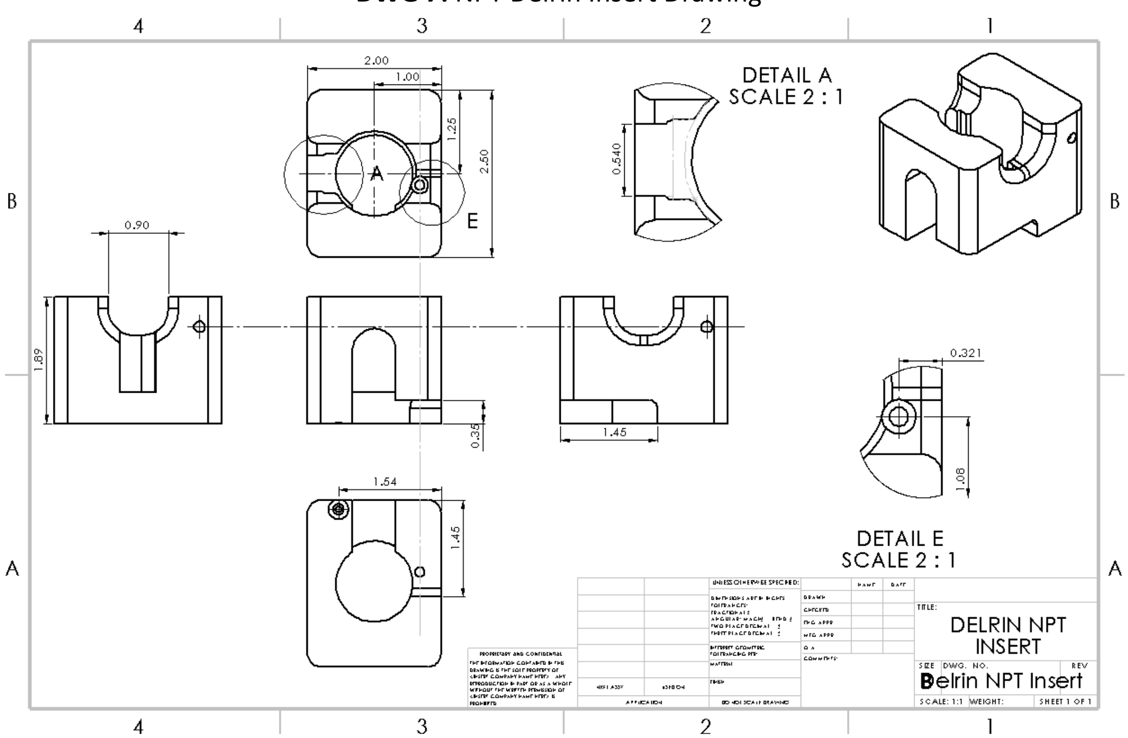
DWG 5: Adjuster Plate Drawing



DWG 6: Alignment Bracket Drawing

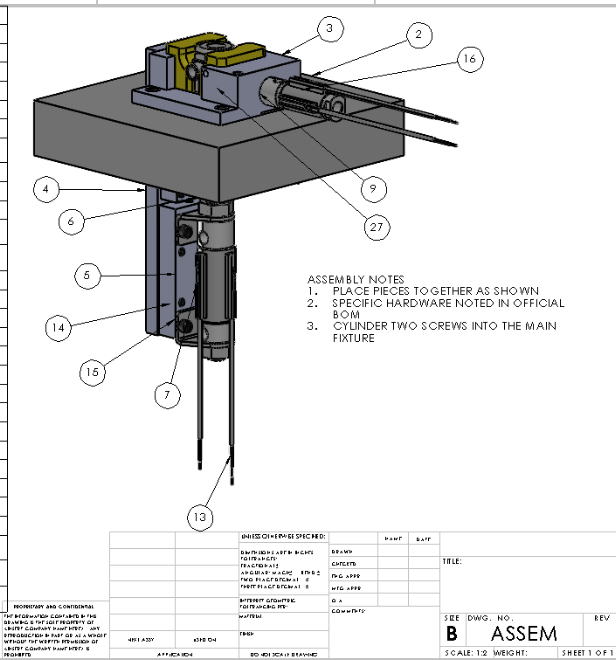


DWG 7: NPT Delrin Insert Drawing

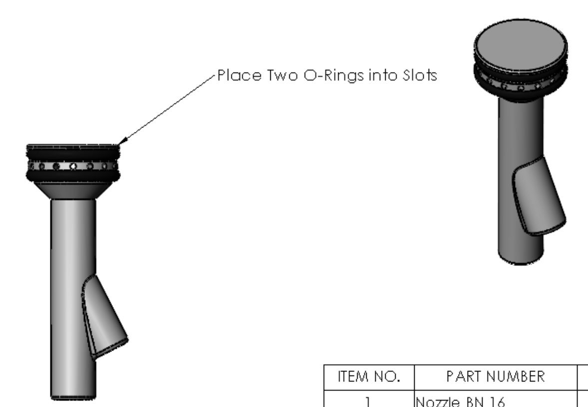


DWG 8: Full Assembly Drawing

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
ALL VERSIONS			
2	Table Top Ver17	TABLE TOP	1
3	Fixture Ver16	MAIN FIXTURE	1
4	Bracket Ver18	ALIGNMENT BRACKET	1
5	Cylinder Plate Ver16	ADJUSTER PLATE	1
6	Adjustor Ver16	ADJUSTER BLOCK	1
7	NRM_091_DXPT1T3T4_2x_D_129_	CYLINDER ONE	1
8	Nozz Assem BN Ver17	NOZZLE ASSEMBLY	1
9	NRM_040_5_DT1T2	CYLINDER TWO	1
10	91292A806	HARDWARE	2
11	Lim Switch V7-2B17D8-022 Ver16	LIMIT SWITCH	1
12	Rubber Tip 16ZD80 Ver16	RUBBER TIP	1
13	Mini Sensor V2	CYLINDER SENSOR	5
14	91251A542	HARDWARE	6
15	91251A540	HARDWARE	8
16	90044A128	HARDWARE	4
17	95479A111	HARDWARE	4
18	92620A554	HARDWARE	1
19	91251A113	HARDWARE	2
20	92845A736	HARDWARE	2
21	91253A143	HARDWARE	2
ACTUATOR VERSION			
23	Delrin Base Ver16	DELRIN INSERT	1
24	(BN ACTUATOR) 5c-bn	ACTUATOR	1
NPT ACTUATOR VERSION			
26	a-5c-bn-npt[27785]	ACTUATOR NPT	1
27	Delrin Base BNPT Ver18	DELRIN NPT INSERT	1
28	BNPT Actuating Pin Ver18	NPT PIN 1	1
29	BNPT Actuating Pin Cap Ver18	NPT PIN 2	1



DWG 9: Nozzle Assembly Drawing



ITEM NO.	PART NUMBER	QTY.
1	Nozzle BN 16	1
2	O-ring .902 Ver 17	2