Design of Sensor Deployment Mechanism for Wall-Climbing Robot for Dry-Cask Storage Container Inspection

Submitted to:

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Austin, Texas

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Mechanical Engineering Design Projects Program
The University of Texas at Austin
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Spring 2022

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ACKNOWLEDGEMENTS

Our team has taken efforts in this project; however, it would not have been possible without the kind support and help of many individuals and organizations. We would like to extend our sincere thanks to all of them.

We would like to express our gratitude to Dr. Mitchell Pryor and Dr. Blake Anderson for their guidance and supervision as well as for providing necessary information regarding the project. We would also like to thank Dr. Salvatore Salamone, Dr. Stylianos Livadiotis, and Tony Lee for their assistance and the information they provided regarding the project. We would like to express gratitude to Jane He, Sven Bader, and Ernesto Villaflores of Orano USA for their time and kind support during the completion of this project.

We would like to express our gratitude to members of the wall-climbing robot design team which includes the team lead Ethan Elgavish, Kartik Mohan, Riley Sanders, and Andrew Waldschmidt for their cooperation and reliable communication during the completion of this project. Thanks and appreciation also go to the team members Ryan Lee, Lainey Scott, Trent Walker, and Victor Winston in developing this project and being such a pleasure to work with throughout the duration of this semester. They demonstrated their passion for engineering and their enthusiasm for finding solutions to difficult engineering problems was integral to the success of this project.

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EXECUTIVE SUMMARY

The University of Texas Nuclear & Robotics Group's (UTNRG) efforts have been put forth working towards deploying robotics in hazardous environments to reduce human personnel exposure and minimize costs allocated to training, execution, and inspection time. The main objective of this report is to summarize the information gathered from our background research, showcase our project solution and evaluation of its design, and provide recommendations that we have for further development and testing.

The sponsor for this project is Dr. Mitchell Pryor who is a senior research scientist with the Nuclear & Applied Robotics Group. There are a few other interested parties including Dr. Blake Anderson, Ethan Elgavish's team who is designing the wall-climbing robot, and Orano who owns 40% of the DSC market share. The deliverables of this project to be given to our sponsor at the conclusion of the project include a detailed design, Bill of Materials, and Concept of Operations. Throughout completion of the project, restraints including temperature, radiation, and size of opening into the cask were heavily considered in all aspects of design and material selection. The budget was approximately $500 dollars for experimentation and prototyping.

The project group, Team UTNRG Deployment, was tasked with creating a sensor deployment mechanism for a wall-climbing robot. The sensors to be deployed are a new development which once in place can determine corrosion sizing and localization as well as witness stress corrosion cracking on dry cask storage containers. Dry cask storage containers are used to store spent nuclear fuel rods. The internal components of a Dry cask storage container are under harsh conditions of heat and radiation.

Through conceptual generation and optimization of design, the sensor deployment mechanism exhibits all mechanical components and ease of use by the potential operator. The design requires minimal training upon use and instructions for deployment preparation as well as HGUW sensor deployment are provided in the a Concept of Operations (ConOps) document.

With knowledge of Orano's equipment specifications and environmental conditions such as temperature and radiation levels within their DSCs, the team determined the optimal materials and adhesives to be utilized for sensor deployment and adhesion of HGUW sensors to a DSC canister surface. The adhesive, Epoxy, Loctite® M-121hp, was selected after thorough testing given its desirable properties such as two-hour hardening time, thick fluid viscosity, and high temperature rating. Steel and aluminum alloys, such as 4140 and 6061, and thermoplastics, such as PEEK and PEI, were selected for the design of the deployment mechanism based on minimum weight requirements, resistance to degradation, and overall strength.

1 INTRODUCTION

The goal of the proposed project is to design a sensor deployment mechanism that will be attached to a wall-climbing robot and will deploy multiple piezoelectric sensors that use helical guided ultrasonic waves (HGUW) to detect stress corrosion cracks and corrosion inside dry cask storage containers. Dry cask storage containers, also known as DSCs, are used to store spent nuclear fuel after it has been removed from a spent fuel pool and continue the cooling of this spent fuel through natural convection using air vents. Due to the dangerous nature of spent nuclear fuel and the harsh internal conditions of these DSC's, it is imperative that interested parties have a safe way to inspect the inside of these containers to prevent injury and leakage of radioactive material. Our sensor deployment mechanism will attach the necessary number of HGUW sensors with the fewest number of trips inside a DSC to reduce the frequency of inspections and thus inspection costs. The project will be conducted under the supervision of, Dr. Richard Crawford (Professor - Mechanical Engineering), Dr. Mitchell Pryor (Senior Research Scientist - Nuclear & Applied Robotics Group), and Dr. Blake Anderson (Research Associate - Nuclear & Applied Robotics Group). The Nuclear & Applied Robotics Group is sponsoring this project and is collaborating with Orano U.S., a nuclear fuel cycle company.

1.1 Sponsor

Our sponsor is Dr. Mitchell Pryor and he is a senior Research Scientist and Lecturer for the Cockrell School of Engineering at the University of Texas at Austin. Dr. Pryor completed his Masters (1999) and PhD (2002) at UT Austin with an emphasis on the modeling, simulation, and operation of redundant manipulators. Since earning his PhD, Dr. Pryor has taught graduate and undergraduate courses in the mechanical and electrical engineering departments as well as led and conducted research in the area of robotics and automation in Mechanical Engineering, Petroleum Engineering and the Nuclear Engineering Teaching Laboratory. He is a co-founder of the University of Texas Nuclear Robotics Group (UTNRG) which is an interdisciplinary research effort to deploy robotics in hazardous, uncertain environments to minimize the risks undertaken by human personnel. UTNRG efforts are going towards reducing exposure of human operators to hazards while minimizing the overall costs (training, execution, time and money) allocated with the use of remote systems.

2 PROBLEM STATEMENT

2.1 Problem Background

The development of “cutting-edge robot technology is making it easier to inspect [the] inside [of] spent fuel dry cask storage systems” (Dunn, 2016). Nondestructive examination (NDE) techniques have been used for decades; however, the introduction of robots have now provided a delivery system for these techniques. The NDE techniques include a variety of methods, such as visual, ultrasonic, eddy current and guided wave examinations. Although these inspection tools have existed for decades, there is no deployment mechanism that attaches these tools inside the DSC’s in a “drop it and forget it” manner. The inspection tools are built into the robot performing the inspection, meaning that the robot must enter the DSC every time it needs to be inspected.

In order to remove the need for a robot to enter the DSC every time an inspection needs to be performed, our deployment mechanism will allow the Nuclear Regulatory Commission

(NRC) and Orano U.S. to perform inspections without a robot once the sensors have been installed inside.

2.1.1 Dry Cask Storage Containers

Dry cask storage containers are used to store spent nuclear fuel "that has already been cooled in the spent fuel pool for at least one year to be surrounded by inert gas inside a container called a cask" (U.S.NRC, 2021). The DSCs increase spent fuel storage capacity and prevent the exposure of radioactive materials to the environment as well as continue the cooling of the spent fuel. Natural convection is used to cool the spent nuclear fuel through air vents that are located on the concrete overpack that surrounds the cask. The concrete overpack is protected by a heat shield that is located between the cask and concrete to protect it from the heat coming from the cask. The space between the heat shield and cask is approximately 4-6 inches wide. The cask, also known as the canister, is typically made of stainless steel grades 304, 304L, and 316L. The stainless steel is shaped into ½ inch thick curved sheets that are then welded together and sealed with radiation shielding material (National Academy of Sciences, 2006, p. 62).

Dry cask storage containers come in two different orientations: vertical and horizontal. The images and information provided to us by Orano that are being used in this report are available to the public. Orano U.S. is the leader in used fuel dry storage and owns 41% of the United States' dry fuel storage systems. Orano has built 190 vertical DSC's and 1,075 horizontal DSC's. Since nearly 90% of Orano's are horizontally oriented, both senior design team's projects will be designed to be implemented in horizontal DSCs, which can be seen in Figure 1. The air inlet is approximately 4-6 inches in height. The air inlets act as an entrance for robots used to inspect the inside of DSC's.

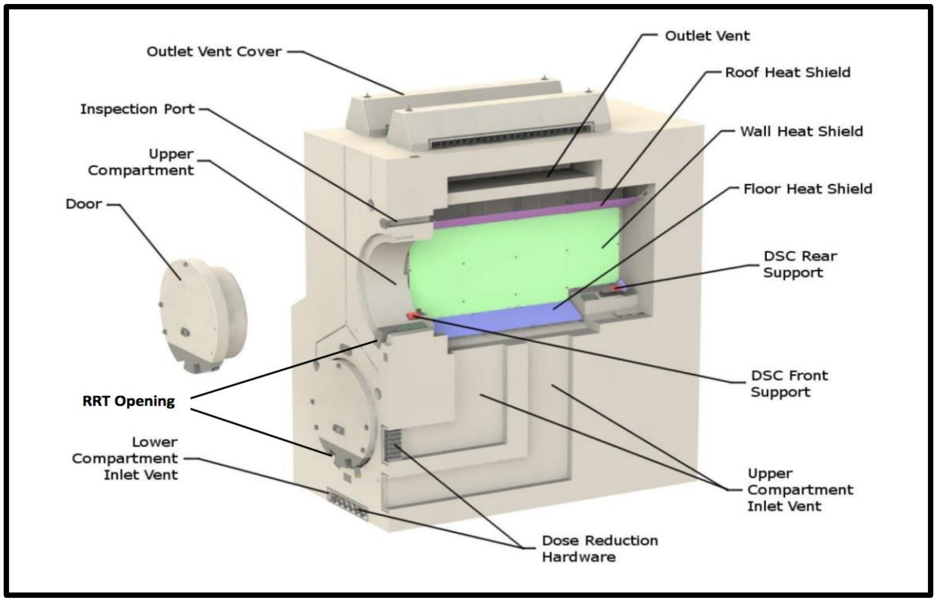

Figure 1. Horizontal Storage Module (Narayanan, Shih, et al., n.d.)

2.1.2 Internal Conditions of Dry Cask Storage Containers

The internal conditions within DSCs are harsh. With low levels of gamma radiation and high temperatures, it is unsafe for any human personnel to enter an in-service DSC. Rough estimates were provided during our meeting with Orano representatives for temperature and radiation intensity inside DSCs and these values can be seen in Table 1.

Table 1. Temperature and Radiation Intensity Estimates (J. He, personal communication, February 4, 2022)

	Heat Load: 40.8 kW	
Temperature	Ambient (°F)	Canister Surface (°F)
	106	422
Radiation	Gamma Intensity (gamma/sec)	Neutron Intensity (neutrons/sec)
	$1 * 10^{17}$	$1 * 10^{10}$

*Conservative estimate for temperature

The values provided in Table 1 were given assuming that the heat load of the spent fuel within the canister was 40.8 kW. According to Banerjee and Scaglione (2017), the current capacity for storage is a 50-kW heat load meaning that temperatures and radiation intensity will be higher when the spent fuel is first loaded into the canister of the dry cask storage container. The ambient temperature range inside DSCs that have been in service from 5 to 55 years is 114.8 °F - 174.2 °F, where the ambient temperature is hottest when the spent nuclear fuel is first removed from the spent fuel pool.

2.2 Problem Statement

Due to the dangerous nature of spent nuclear fuel and the harsh internal conditions of these DSC’s, it is imperative that interested parties have a safe way to inspect the inside of these containers to prevent injury and leakage of radioactive material. Our sensor deployment mechanism will attach the necessary number of HGUW sensors with the fewest number of trips inside a DSC to reduce the frequency of inspections and thus inspection costs.

3 REQUIREMENTS AND CONSTRAINTS

The requirements and constraints for this project were discussed during our initial sponsor meeting on January 28, 2022 as well as the meeting with Orano representatives, led by Jane He, on February 4, 2022. After meeting with Dr. Livadiotis, representative of the sensor team, on March 9, 2022, we were given further information regarding specific requirements and limitations when handling the HGUW sensors.

3.1 Quantified Requirements

The primary requirement of our sensor deployment mechanism is to successfully deploy between 24-30 HGUW sensors in the fewest number of trips within the DSC. All decisions our team makes regarding our design and when selecting materials will need to consider how to adhere these sensors to the surface of the DSC in a high temperature and radioactive environment. Our deployment mechanism will need a rigid attachment vehicle to ensure the mechanism does not become detached during deployment. The mechanism will also need to be reloadable to ensure multiple sensors can be deployed. Various adhesives will need to be extensively researched and tested under extreme temperature conditions to ensure no degradation of the adhesive during and after deployment. Additionally, materials used in our mechanism cannot be degradable when exposed to elevated temperatures and low-energy gamma and neutron radiation.

There are two thin wires soldered to each sensor that attach to a coaxial cable which will lead to the outside of the DSC. This enables data and signals from the sensors to be transported to monitoring software. Our mechanism will need to ensure prevention of wire entanglement and relief on solders to reduce the risk of damaging wires and the sensors. We will be required to maintain a connection between the sensors and coaxial cables throughout deployment. The sensor team plans for us to be able to deploy 5-6 sensors along each ring around the diameter of the DSC which would optimally be done in a single run (Livadiotis, 2022).

After discussing each of our concepts during our sponsor meetings, our sponsor noted our initial concepts included too many electronic components and to consider mechanical components. We updated our requirements to prioritize designing a mechanically powered deployment mechanism that could be actuated by personnel from outside of the DSC. By the end of the semester, the deliverables that will need to be given to our sponsor include a detailed CAD design, bill of materials, and concept of operations. Our sponsor, Mitchell Pryor, is not requiring a final prototype, but recommended it since it would be useful in designing and testing the functionality of our mechanism (Anderson & Pryor, 2022).

3.2 Quantified Constraints

Considering the sensor deployment mechanism will be attached to a wall-climbing vehicle in an environment containing spent nuclear fuel, there will be constraints regarding size, temperature, and radiation. Ethan Elgavish’s team is designing the vehicle that will be deployed into the DSC and our sensor deployment mechanism will be directly attached to the back end of their vehicle.

Due to the size limitations when entering and egressing the DSC vent inlet, our mechanism will need to be less than six inches in width and less than four inches in height and length. The vehicle team plans to utilize suction cups to adhere to the DSC wall and depending on the strength of these suction cups, this will limit the weight of their robot as well as our design. Our design will need to be less than five pounds which includes the weight of the components of our mechanism, sensors, adhesive, and coaxial cables. Coaxial cables, weighing approximately 0.070 kg/m, will be attached to each sensor (Livadiotis, 2022). To prevent wire entanglement and accommodate for the weight of these cables, our group will be limited to the number of sensors we are able to deploy at a time.

The HGUW sensors themselves are ceramic and 12 mm in diameter and 0.6 mm in thickness. Two thin wires are soldered onto each sensor and on the other end of the wire, the coaxial cable is attached. Since these sensors and the solders are extremely fragile, our team will need a method of providing strain relief to this connection point and reduce the risk of failure in this location.

Temperatures may reach a conservative maximum of 422 *℉* and there will be low amounts of low-energy gamma and neutron radiation present in the DSC (He, 2022). To ensure no degradation or loss of functionality during deployment, our team will be limited when selecting materials and adhesives that can withstand these environmental conditions. Given our team's current plan to apply adhesive to the bottom of each sensor before deploying the vehicle into the DSC, we will also be limited to certain adhesives that exhibit a higher viscosity, longer hardening times, and are non-corrosive. To satisfy weight and manufacturability constraints, the materials selected will need to be lightweight, durable, cost effective, and preferably off-the-shelf available for easy purchase to avoid the need for machining.

Our starting budget is approximately $500 for experimentation and prototyping. If our team requests more, the amount will need to be approved by our sponsor. For functional prototyping, our group will select cheaper and off-the-shelf materials to reduce costs and ease of replication. For our final bill of materials, our sponsor has requested we select as many products as possible that are widely available to purchase and to avoid extensive machining. This limits the complexity and detail of components within our design in order to avoid expensive manufacturing costs.

3.3 Specifications Sheet

A list of the specifications discussed in the previous two sections is compiled in Table 2 below.

Table 2. Specifications Sheet

Demand/Wish	Functional Requirements	Required Values / Targets	Units / Scale	Test / Verification Method
D	Robot attachment options	>= 1	Options	Mechanism is mounted onto wall-climbing robot
W	Common tools used for attachment	Yes		Off the shelf tools, does not require additional training to assemble
W	Store multiple HGUW sensors	> 5	# of stored sensors	
D	Mechanism controlled using mechanical components	< 1	# of electrical components	
D	Reloadable	Yes		
W	Deploy multiple HGUW sensors in a single trip	> 5	# of deployed sensors / trip	
D	Prevent wire entanglement	Yes		Deployment method testing with user deployment instructions
D	Number of sensors deployed before mechanism is replaced	>= 24		
D	Operate in high ambient temperature environment	> 114	°F	Radiation / temperature testing at NETL
D	Withstand low-energy gamma radiation	> 1E17	gamma / second	Radiation / temperature testing at NETL
D	Withstand neutron radiation	> 1E10	neutrons / second	Radiation / temperature testing at NETL
W	Number of trips to deploy needed number of sensors	< 15	# of trips / DSC	Sensor load testing
D	Ability to clean surface of sensor deployment location before adhering sensor	< 1	sensor detaches / DSC	
W	Quick sensor deployment	< 30	seconds / sensor	Timer
D	Maintain connection between coaxial cable and sensor during deployment	< 1	disconnections / DSC	
Demand/Wish	**Constraints**	**Required Values / Targets**	**Units / Scale**	**Test / Verification Method**
		Geometry		
D	Height	< 4-6	inches	
D	Length	< 4-6	inches	
D	Mass	< 2	lbs	
		Operations		
D	Human input only for deployment actuation	1	human personnel	Bowden cable actuation testing
W	Single input deployment	1	actuation	Bowden cable actuation testing
W	Adhesive covers sensor surface	<= 0.7	in^2	Deployment testing
W	Quick to reload	< 2	min	Deployment testing
W	Common tools used for reloading sensors	Yes		Off the shelf tools, require no special training
		Material		
D	Non-degradable	Survive > 10^17	gamma rays / sec	Radiation / temperature testing at NETL
D	Non-corrosive adhesive	> 7.52	pH	Radiation / temperature testing at NETL
D	Durable	Survive 5 ft drop test		Drop test
		Cost		
W	Project Cost	<= 500	$	Budget management
W	Manufacturing Cost	< 250	$	Bill of materials
		Reliability		
D	Full sensor deployment (Sensor does not get stuck)	< 1	sensor stuck / deployment	CAD simulation and extensive physical testing

4 ADHESIVE TESTING

Our group thoroughly researched different methods of adhering HGUW sensors to the wall of spent nuclear fuel DSCs. Our original design concept was to attach a bottle or tube of adhesive to our mechanism and a nozzle would be connected directly below the sensor. Once a mechanism was actuated, a small amount of adhesive would be applied to the bottom surface of the sensor. We first considered a peristaltic pump powered by a DC motor that moves fluid through tubing with forward displacement using rollers within the pump. It would have been relatively difficult to actuate our mechanism mechanically and perfect the timing of the peristaltic pump to apply adhesive before the sensor is pushed forward. After this concept was dismissed, we considered a mechanism similar to a toothpaste tube squeezer. The advantage to this concept is it could be mechanically actuated, but a major disadvantage is that we would have to purchase specific adhesives that come in tubing or transfer adhesive into tubing which poses the risk of the adhesive hardening too quickly. Due the complexity of our design and difficulty of incorporating several Bowden cables to actuate other subsystems along with the adhesive applicator makes executing this method less ideal.

To reduce the number of components needed for adhesive application, our team ultimately decided to apply the adhesive to the bottom of the sensors and load them into the sensor storage of the mechanism before the inspection vehicle is deployed into the DSC. This lowers the overall weight of our design and decreases the chances of failed deployment if there were to be application malfunctions while in the DSC. Since the adhesive will be applied by personnel outside of the DSC, precise application is easily achievable.

4.1 Adhesive Selection

From our first meeting with Dr. Salamone's sensor team, we were able to learn more regarding the HGUW sensors our mechanism will be deploying, and their team's current methods used for sensor adhesion to tube surfaces. The sensor team has primarily conducted tests using two-part epoxy and hot glue. During actual deployment, neither of these adhesives would be probable or effective for sensor adhesion. The two-part epoxy they have experimented with hardens within minutes and which would be far too quick and would not enable enough time for vehicle deployment into the DSC and sensor deployment. Hot glue is a thermoplastic that hardens relatively quickly and has a softening range of approximately 200 °F to 240 °F (*Hot-melt adhesive,* n.d.*)*.

Our group began researching other adhesives that would be relatively easy to apply, have longer hardening times, withstand elevated temperatures, and are non-corrosive. We also took into account the consistency of the adhesives and opted for more viscous adhesives that would not easily flow or spread extensively after application. The two adhesives we selected for testing were epoxies made by J-B Weld and Loctite®.

4.2 Adhesive Specifications

The J-B Weld epoxy is rated from -20 °F to 450 °F, is a one-part epoxy, and has a putty-like consistency. This adhesive begins hardening in 60 minutes and fully cures within eight hours (J.B. Weld, 2020). The Loctite® epoxy is rated from -65 °F to 300 °F, has a 2:1 mix ratio, and is a thicker fluid. This adhesive begins hardening in two hours and fully cures within 24 hours (Loctite EA M-121HP Technical Data Sheet, 2020). Both adhesives are chemically resistant and easily accessible to purchase online. Additionally, these adhesives have optimal hardening times and consistencies for our proposed idea to apply adhesive to the sensors before vehicle deployment.

4.3 Wall-Climbing Robot Capability Assumptions

The senior design team developing the wall-climbing robot provided an estimate for the speed at which their robot could travel along the canister surface, which was approximately two inches per second. The wall-climbing robot must also be transported into the dry-cask storage container using another robot so that it can be deployed onto the canister surface. The robot design team provided an approximation for the time needed to enter the dry-cask storage container and deploy the wall-climbing robot onto the canister surface which is ten minutes. We were also told to assume that the robot delivering the wall-climbing robot would travel at a speed of 2 inches per second as well. Our team used these values and the geometry of the cask to calculate the length in time between when the adhesive is applied to the sensor and when the sensor is deployed onto the canister surface. “Casks are typically about 19 feet (6 meters) in height [and] 8 feet (2.5 meters) in diameter (National Academy of Sciences, 2006).”

Another assumption our team made was that the ring of sensors on the ends of the cask would be 6 inches away from the edge of the cask. The circumference of the cask is 301.6 inches and the distance between the ring of sensors closest to the entrance and furthest from the entrance of the dry-cask storage container is 216 inches. Using these assumptions and values, the times we used to guide our adhesive experiments can be found in Table 3 below.

Table 3. Adhesive Test 2 Timetable

<table>
<tr><th></th><th>Sensor Number</th><th>Sensor Carriage Loading Time (min)</th><th>Robot Deploymen t Time (min)</th><th>Travel Time to Deployment Position (min)</th><th>Sensor Holding Time (min)</th><th>Total Time Until Deployment (min)</th></tr>
<tr><td rowspan="6">1st Ring</td><td>1</td><td rowspan="6">10</td><td rowspan="6">10</td><td>0</td><td>5</td><td>25</td></tr>
<tr><td>2</td><td>0.5</td><td>5</td><td>30.5</td></tr>
<tr><td>3</td><td>0.5</td><td>5</td><td>36</td></tr>
<tr><td>4</td><td>0.5</td><td>5</td><td>41.5</td></tr>
<tr><td>5</td><td>0.5</td><td>5</td><td>47</td></tr>
<tr><td>6</td><td>0.5</td><td>5</td><td>52.5</td></tr>
<tr><td rowspan="6">4th Ring</td><td>1</td><td rowspan="6">10</td><td rowspan="6">12</td><td>0</td><td>5</td><td>27</td></tr>
<tr><td>2</td><td>0.5</td><td>5</td><td>32.5</td></tr>
<tr><td>3</td><td>0.5</td><td>5</td><td>38</td></tr>
<tr><td>4</td><td>0.5</td><td>5</td><td>43.5</td></tr>
<tr><td>5</td><td>0.5</td><td>5</td><td>49</td></tr>
<tr><td>6</td><td>0.5</td><td>5</td><td>54.5</td></tr>
</table>

The first sensor in each ring would be deployed as soon as the wall-climbing robot was attached to the canister surface and each sensor would be held onto the canister surface for five minutes to allow the adhesive to cure. The time that is needed for the robot to travel the circumference of the canister is approximately 151 seconds and the travel time between sensor deployment locations in a ring is approximately 30 seconds. Adhesives were tested using these times to simulate the time that is needed between application of the adhesive on the sensor and deployment, as well as ensure that the adhesive will properly adhere the sensors to the canister surface according to the capability of the robot.

4.4 Experimental Setup

For adhesive experimentation, we tested the Epoxy, J-B Weld Highheat and Epoxy, Loctite® M-121hp on stainless steel surface at 350 °F for various periods of time. Although the exact material of the DSC is unknown, we were informed by Orano that the DSC we will be deploying on will be made of an austenitic stainless steel alloy, specifically 304, 316, or 316L (He, 2022). We obtained scrap stainless steel from the machine shop located in the ETC to simulate the canister surface. We picked up 30 ceramic pucks from the materials lab in ETC which were utilized to simulate the HGUW sensor, also ceramic, so that we would not risk damaging the few sensors we were provided by the sensor team.

Table 4. Adhesive Test 1 Time Table

Trial Number	Sensor Carriage Loading Time (min)	Robot Deployment Time (min)	Sensor Holding Time (min)
1	10	10	15
2			30
3		20	15
4			30
5		30	15
6			30

Our first experiment consisted of testing both Epoxy, J-B Weld Highheat and Epoxy, Loctite® M-121hp. An approximate 8 mm in diameter and 2 mm in thickness amount of each adhesive was applied to a ceramic puck and six different trials were conducted for each adhesive at varying waiting times in room temperature and approximated ambient temperature of the DSC as seen in Table 4. The sensor carriage loading time for each trial was ten minutes at room temperature, which was 72°F. The possible times our team estimated that that would be required for the robot to be deployed into the DSC and onto the canister were 10, 20, and 30 minutes. Orano stated that ambient temperature within the DSC averaged to be 106°F, so we tested each of the six trials at 120°F to be conservative in our findings for these different times by applying medium heat with a hair dryer. Lastly, the ceramic pucks and adhesive were then put into the oven at 350°F onto the surface of a stainless-steel piece and were held down with a weight for the times specified above in Table 4. Results from these tests were categorized by a pass/fail verification which was determined by whether the sensor could hold up a 0.76 lb weight after each trial concluded.

Using the assumptions stated in Table 3 and after deciding to move forward with the Epoxy, Loctite® M-121hp, we conducted two additional experiments with this adhesive. In this second test, we simulated the wall-climbing robot being deployed into a DSC and completing one full ring of six deployed sensors at two different locations along the DSC. Given the DSC is approximately 6 m in length and 2.5 m in diameter, we tested the wait and holding times we would predict for deployment of six sensors along the first ring and last ring around the DSC diameter. The first ring would be the closest deployment location along the DSC upon entry and the fourth, or last, ring would be the furthest point along the DSC. In each ring, six sensors will be deployed evenly along the circumference of the DSC and held down for five minutes each with a weight. This simulates the sensor deployment mechanism being fully actuating and locking the second Bowden cable that stamps the sensor to the DSC surface which we predicted would be necessary to lock for five minutes.

4.5 Adhesive Testing Results

From our first round of adhesive experimentation, the Epoxy, J-B Weld Highheat failed the first trial and passed the remaining. This was likely due to human error when applying the adhesive and the layer being slightly too thick. The sensor did not adhere to the metal sample and the adhesive appeared very brittle and was cracking upon further observation after the failed trial. The Epoxy, Loctite® M-121hp passed all six trials. We concluded that the Epoxy, Loctite® M-121hp was more consistent in the pass/fail verification, was easier to apply, and enabled longer working times. We decided to move forward with this epoxy and conducted a second round of experiments to validate our finding.

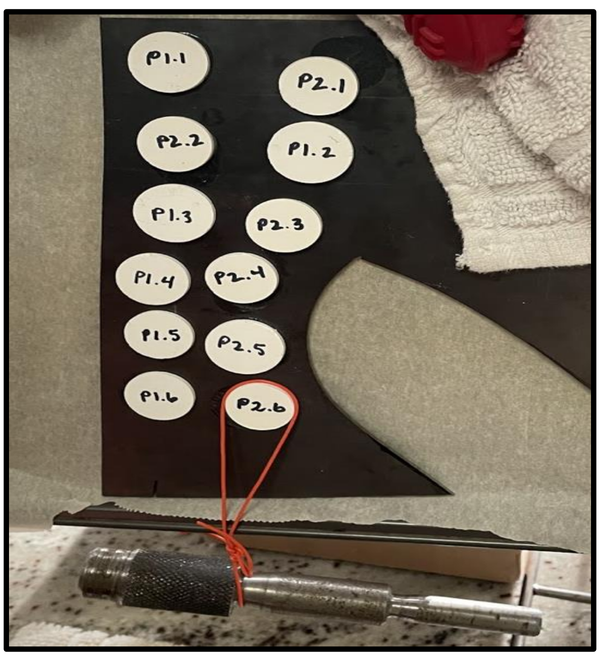

Figure 2. Adhesive Test 2 Verification

After the second experiment, we concluded that the hold time could be shortened to five minutes. This was verified by the same pass/fail verification utilized in our first experiment. All ceramic pucks hardened sufficiently within the lowered holding time and successfully held up the 0.76 lb weight as seen in Figure 2 where the last deployed sensor successfully holds the weight at a sideways orientation. Overall, the Loctite® epoxy was consistent during all experimental trials and exhibited ideal hardening and curing times given the time constraints of our estimated deployment schedule seen in Table 3. This epoxy had a favorable fluid viscosity when compared to the J-B Weld epoxy and was significantly easier to handle during application to the ceramic pucks.

5 PROJECT SOLUTION AND EVALUATION

5.1 Patent Search

The team searched for patents related to the deployment of sensors, storage and dispensing mechanisms, and mechanical actuators. Three patents are described below, as well as the features that were of interest to incorporate in our design.

Deployment of Seismic Sensor

Patent US7675821B2 describes a mechanism for the deployment of seismic sensor units consisting of sensor nodes, container for containment of a data registration and auxiliary equipment for the sensor nodes, and a releasable attachment for releasing the sensor. Figure 2. shows the key components including the sensor node (24), container for data registration equipment (11), and releasable attachment for releasing the sensor (22).

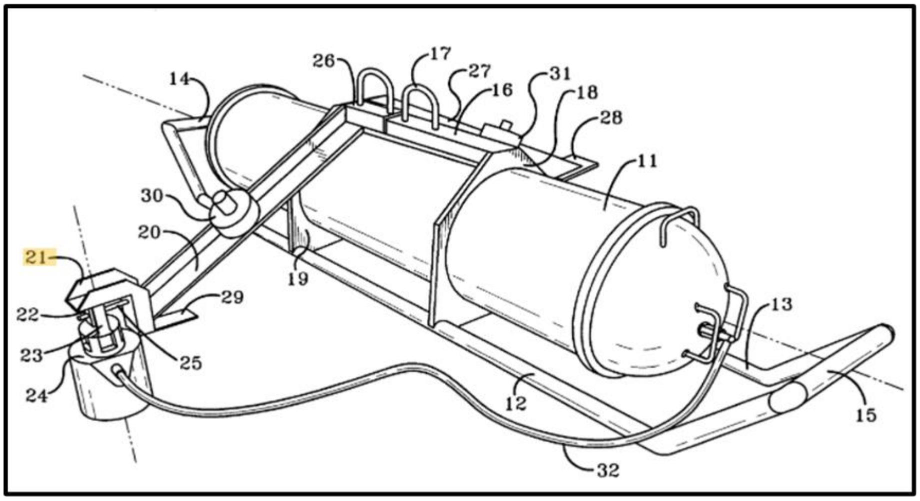

Figure 3. Key Components in Patent US7675821B2

The releasable attachment that holds the sensor node and extends downward for deployment, which is perpendicular to the seabed, was exactly how we wanted to deploy our sensors. This detail in the patent was useful in our team's concept generation. The bracket (21) has a downwardly extending releasable fastener (22) and comprises a latch pin (25) that can be pulled out with a wire to release the sensor node. Although we did not use a pin to release our sensors since the effects of gravity must be considered during the deployment of our sensors, the sensor stamp mechanism in our design was inspired by the releasable attachment in this patent.

Candy Dispensing System

Patent US5460295A describes the apparatus for storing candies and for dispensing such candies one at a time upon demand by a user. The apparatus consists of a chamber (3) for receiving a plurality of candies and having a dispensing opening (16), an arm (11) pivotally mounted to a pivot axis (9), and a push rod (13) as shown in Figure 3. The push rod is connected to the pivot axis by a second arm where the rotation of the second arm would cause lateral movement of the push rod for dispensing candy from the dispensing opening.

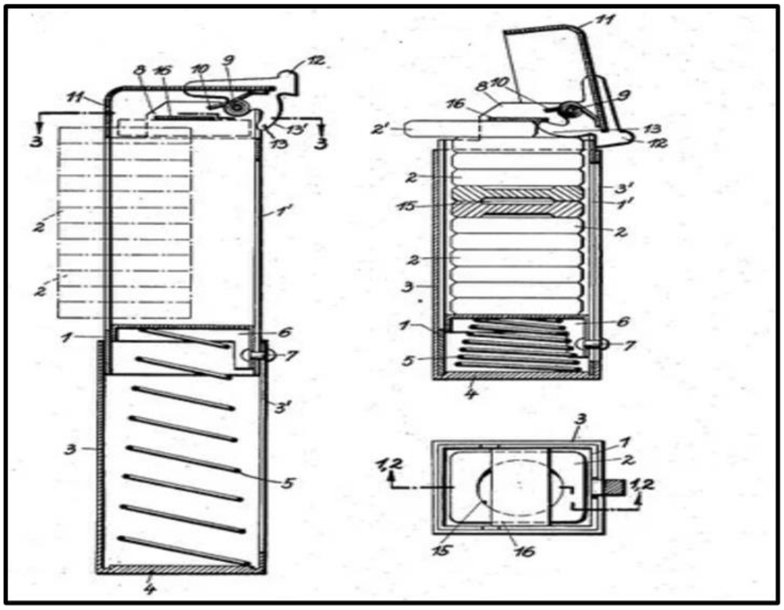

Figure 4. Key Components in Patent US5460295

The design in the patent heavily inspired our concepts for storing multiple sensors and dispensing one at a time. Key components of our design were to allow multiple sensors to be deployed before having to be reloaded and to deploy a single sensor at each deployment location. The mechanism described in this patent is intended for children and dispensing candy but the basic concept was essentially the solution for how we were going to meet our design requirements.

Mechanism for Transmitting Motion or Power

Patent US609570A describes a mechanism for transmitting power and motion. The mechanism consists of a guide-tube (A), rod (B), and lever (D) for operating the rod as shown in Figure 4 and 5.

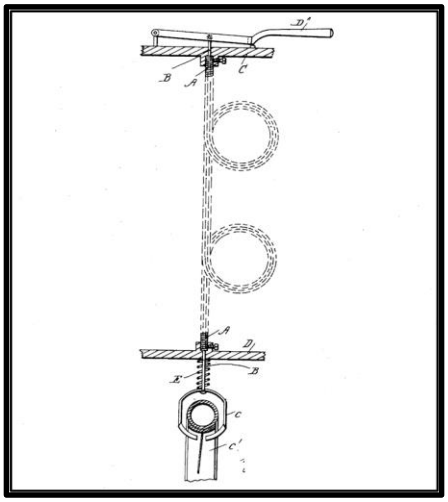

Figure 5. Key Component D in Patent US609570A

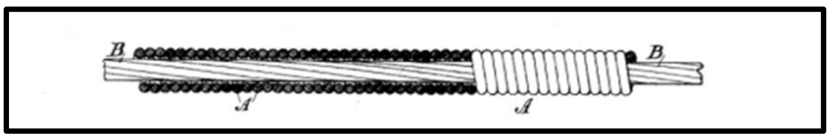

Figure 6. Key Components in Patent US609570A

There are several details in this patent that were useful to us when generating design concepts, specifically for actuating subsystems within our deployment mechanism. In order to remove the need for electric power for electronic components, we looked at the possibility of using wires to transmit force so that our mechanism would be able to store and deploy multiple sensors. The mechanism in this patent is regularly used on bike brakes to provide a way for users to apply pressure to levers and slow the rotation of the wheels and is called a Bowden cable. The rod is placed inside the guide-tube and the guide-tube protects the rod from the environment so that the rod will not rub against any material outside of the guide-tube. The Bowden cable was an ideal solution since it would transmit force while also preventing wear to components within our deployment mechanism while transmitting force. Ultimately, the team decided to move forward with using a Bowden cable for actuating the subsystems in our deployment mechanism.

5.2 Alternative Concepts

5.2.1 Alternative Concept 1

The first proposed concept is to operate by having the spring load sensors onto a rotating disc and having this disc rotate to have adhesive applied to it as seen in Figure B.1 in Appendix B. The adhesive nozzle would extend to apply the adhesive and retract when finished. The disc holding the sensor would rotate into position for the final portion of the process to take place. Lastly, a piston mechanism would push down and suction to the non adhesive side of the sensor and press the sensor onto the DSC stainless steel body canister. With this concept there were also several issues that arose. The issues with this concept were that there were too many electronics involved, the disc would not be able to rotate since the sensor rack is constantly pushed by spring, too many moving parts with multiple points of failure, little consideration for gravity, and little consideration for the small space inside the DSC.

Although several issues were found, our team did notice a few positive features. The spring loaded mechanism for urging the sensors towards the deployment position was a positive feature of this concept because it could be easily reloaded and was entirely mechanical. The stamping motion of the sensors onto the canister surface was also a positive feature because of its simplicity which led to confidence in its repeatable motion.

5.2.2 Alternative Concept 2

The second concept generated would operate by having a conveyor belt with steps that rotates to move the sensor into an open slot as seen in Figure B.2 in Appendix B. The conveyor belt would stop rotating once the sensor reached the open slot. The sensors would be loaded so that the soldered side is on the bottom. A claw with grips would grab the sides of the sensor to swivel the sensor over to where the adhesive is applied. Lastly, a piston would extend down to grab the sensor via suction and apply the sensor to the DSC stainless steel canister by extending further. The issues with this concept is that suction adhesion with piston may be difficult to execute, the swiveling of arm with claw could be difficult to execute inside the DSC, wires may get tangled or damaged when rotating claw, adhesive applicator might get plugged up, and sensors may take longer to replace if conveyor belt casing needs to be removed. Despite the issues, there were a few features that we took into consideration such as the conveyor belt mechanism and the stamping motion of the sensor onto the canister surface. The conveyor belt mechanism would allow sensors to easily be reloaded and the stamping motion was simple and repeatable. The automated claw was an extremely secure way of holding the sensor given gravity working against the deployment and, as a positive, allowed us to develop ideas of how to overcome gravity in further concepts.

5.2.3 Alternative Concept 3

The next proposed concept, shown in Figure B.3 in Appendix B, would work by having a conveyor belt with steps rotated to move the sensor into an open slot. The sensor would then be grabbed by a vacuum. The vacuum is along a track, the sensor would then be pulled with the vacuum to where the adhesive is applied. Then, based on the geometry of the track the vacuum is on, the adhesive would be flipped over to the bottom and placed onto the DSC stainless steel canister. The issues with this concept are that fine precision is required for conveyor belt assembly, the location of the vacuum when adhering sensor to the canister surface must be exact, and suction of vacuum must be strong enough to hold the sensor while rotating. Lastly, it would be very complicated to find adequate current needed for the vacuum system and conveyor belt. Despite the issues, our team considered some aspects of this concept for generating our next concepts. The sensor storage rack is an idea we carried into the final design as a way of securing the sensors and modifying that to build upon. The reduction of electronic components was also another positive and we looked to isolate and focus on the subsystems that still used electronics to try to make them entirely mechanical.

5.2.4 Alternative Concept 4

Concept 4, shown in Figure B.4 in Appendix B, would operate by having a motor drive a small gear that would drive a rack that the sensors would be held on. The end of the rack where the vacuum suction is would not be enclosed to allow for suction of the sensor to occur. The sensor would then be grabbed at this location and have the adhesive applied on the opposite side of the vacuum. The sensor would be carried along the channel by the vacuum and a pin mechanism where it would exit the lower right-hand side of the picture onto the surface of the DSC stainless steel canister. The issues with the concept are the location of the vacuum when adhering the sensor to the canister surface must be exact, suction strength of the vacuum might not be strong enough to hold on to the sensor while moving to its deployment position, sensor rack would run into the side of the housing due to its leftward direction it's driven in. Lastly, the electrical needs of the vacuum system, motor for the conveyor belt, and pin would be very complicated inside this very small housing.

Despite the issues, we noticed a few features that we would consider in implementing in our final design. The combining of multiple steps such as moving a sensor into a position that is ready for deployment and applying the adhesive at the same time was a positive feature of this concept. By reducing the amount of steps to deploy each sensor, our sensor mechanism would become simpler and efficient by not wasting time or accuracy of position on multiple steps. Another feature that our team took into consideration was the steps that the sensors would be sitting on in the rack assembly. The hole on the bottom of the step could be used for applying the adhesive before loading the rack assembly. The sensors could be placed inside carriages with a similar hole on the bottom and the carriages would be stacked on top of each other. The sensor carriage would be designed so that the adhesive on the sensor would still be in contact with the canister surface during deployment but would not be in contact with the next sensor or carriage while it is waiting to be deployed.

5.2.5 Alternate Concept 5

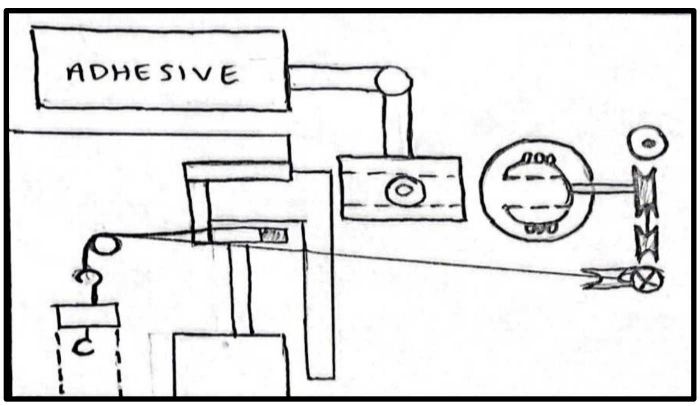

Figure 7. Alternate Concept 5 Top View Sketch

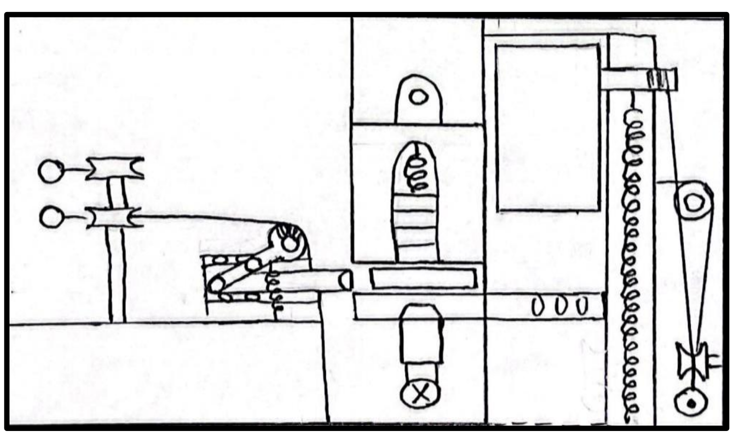

Figure 8. Alternate Concept 5 Side View Sketch

Figures 7 and 8 are sketches of the fifth concept we created. The sensors are held within sensor carriages in this concept. These carriages are then held inside a carriage housing with a spring attached to the top asserting constant downward force. At the bottom of this housing adhesive is applied to the underside of the carriage. A pushing arm is then able to move through a tiny slot in the side of the housing to push the sensor carriage along the mechanism. The arm extends the carriage all the way to the stamping mechanism. This does not allow for another sensor to be deployed inside of the carriage housing also. Through tension cables, the stamping housing has a stamp with a pin that is then pulled to pull the stamp all the way down and press the sensor carriage with the sensor inside of it onto the DSC stainless steel canister. After deployed, tension would be released from the carriage pusher and stamping pin that would allow for the return of components to their original position allowing for the process to repeat itself. This concept is entirely made of mechanical components and does not require any electronics. The issues with this design are designing around small space, figuring out the springs, and tension system to actuate movement of the components inside the mechanism.

5.3 Concept Selection

After comparing critiques of the different design approaches, we noticed that there were very similar critiques of four designs. The first four concepts had several electronic components and too many moving parts overall. It would have been extremely difficult to design these concepts given our weight and size constraints. The inclusion of motors for actuation would limit our choices during the selection of materials to use due to the weight of these electronic components and the power source that is required for them to operate. High precision would be required for these concepts with coding for the electronics and timing of each subsystem throughout deployment. With these complex designs and mechanisms for motion, the potential for wire entanglement and wire damage was a massive concern. Concept one did not consider gravity in the design which could lead to sensors falling from the deployment mechanism before deployment. Because of its relatively simple design compared to the alternative designs, its reliability for consistent and repeatable actuation, and the absence of any electronic components, our team decided to move forward with the fifth alternate concept.

5.4 Failure Mode & Effects Analysis

After deciding on the final design to move forward with, we created a failure mode and effects analysis table. This is critical to the design because this FMEA reviews as many components, assemblies, and subsystems as possible to identify potential failure modes in a system and their causes and effects. This would allow us to identify the weakest points in our design and allow for possible redesign or simply to provide that information to our sponsor. To effectively do this analysis the criteria of severity, occurrence rate, and detection were all ranked on a scale of one to ten. The product of these three criteria for each failure mode in our deployment determined what had the highest probability of failing due to earning the highest score. In our design we identified that the sensor carriage becoming stuck, sensor pusher becoming stuck, and sensor stamp connection to Bowden cable breaking were the weakest points in the design that could fail causing the mechanism to not work. The full FMEA results can be seen in Table B.2. of APPENDIX B.

5.5 Prototype

Based on the CAD models produced, we constructed a prototype that was scaled up two times the size of the final CAD model. This will provide a larger representation of our model, yet more accurately model the smaller components included in the final design.

Although this is not a required project deliverable, we created a large scale prototype to showcase the functionality and measure success of our concept outside of simulation. The prototype was created with less expensive materials and manufacturing methods than the materials that will be selected in the final bill of materials. We largely produced most of the parts of the prototype with 3D printed materials. We additionally purchased springs based on the desired length, diameter, maximum load force, and maximum compressibility based on our scaled up model. We intended to have this prototype to be completely functional. The prototype worked very inconsistently, which called for a redesign of our deployment mechanism to fix these issues. Had this prototype not been constructed the flaws we discovered would have been much harder to detect via CAD models.

Furthermore, after using the prototype we discovered that the three main failure modes detected in the FMEA did turn out to be the true failures in the real life model. The aforementioned failures are the sensor stamp connection to Bowden cable breaking, sensor pusher, and sensor carriage becoming stuck. In addition, we also learned from our prototype that the linearly unconstrained spring we initially had in our first iteration of design caused most of the failures in our mechanism. As a result of these failures in initial design, we were able to move forward to optimize our design to fix these issues. A photo of our prototype can be seen in Figure 9 and the bill of materials for this prototype can be seen in Table C.1.

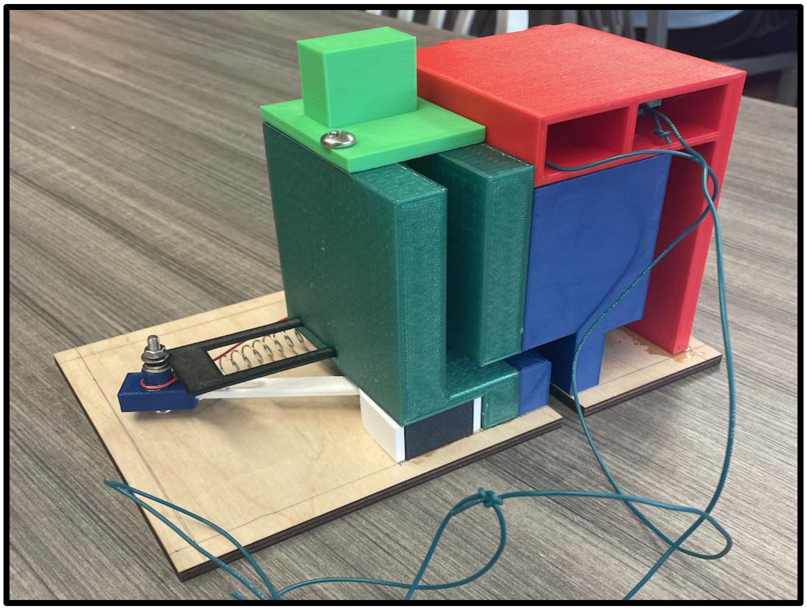

Figure 9. Image of Prototype

5.6 Optimized CAD Model

After reviewing the prototype and the CAD model that it was based on, we began optimizing the design of the sensor deployment mechanism with a focus on manufacturability, repairability, and overall functionality. Below is a breakdown of each sub-assembly in our optimized model. Some components are repeated in sub-assemblies to give a better understanding of the full design. A parts list can be found in Table B.1 of APPENDIX B.

5.6.1 Sensor Pusher Sub-Assembly

The sensor pusher is the sub-assembly that moves the sensors from storage to the stamping position. The sensor pusher sub-assembly contains a 25' knob-operated push/pull Bowden cable - 6161K13 (27), one ⅝"-18 threaded zinc-plated carbon steel clevis rod end (28), seven 0.125" x 0.5" PEEK plastic dowel pins (2), and one 9657K48 steel compression spring (11) all purchased from McMaster-Carr®. All material that is not bought pre-assembled will be machined out of 6061 aluminum-T6, including the spring slider (12), sensor pusher guide (13), bottom of sensor pusher (10), and the sensor pusher spring holder (9).

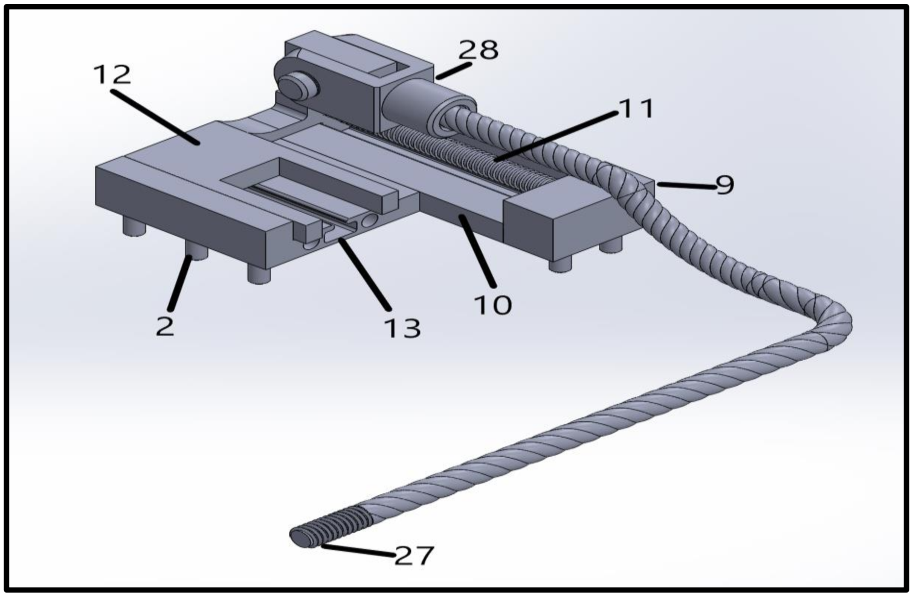

Figure 10. Sensor Pusher Sub-Assembly

The sub-assembly is 2.39” in length, 2.03” in width, and 0.94” in height and it weighs 0.1 pounds. Aluminum 6061-T6 was chosen for the spring slider and sensor pusher spring holder because they are experiencing a force from the Bowden cable and resisting spring bending respectively. The same material was selected for the guide and bottom. These components required low friction to allow for the stamp slider to move but also needed to resist fatigue deformation and failure. Manufactured parts in this sub-assembly will be machined and a quote from Xometry.com has priced materials and production as $832.96 per sensor pusher sub-assembly (Xometry).

The sub-assembly is attached to the mechanism floor (29) by 7 dowel pins. A Bowden cable is attached via a threaded connection to a clevis rod end. The Bowden cable is actuated with a force of 0.46 lbf causing the spring slider to move linearly compressing the pusher spring. The spring slider maintains its linear motion due to a slot cut into the sensor pusher guide. Additionally, the sensor pusher spring holder serves a guide to eliminate bending of the spring. After moving a distance of 1.13”, the spring slider returns to its original position.

Our prototype provided necessary insight that contributed to iterations of our design to improve linear motion. Rather than using a rotating lever arm and guided slot to generate linear motion, the Bowden cable is attached parallel to the desired direction of motion reducing the number of moving components.

5.6.2 Sensor Storage Assembly

The sensor storage sub-assembly is modeled after a Pez® dispenser and houses six sensor carriages until they are dispensed to the stamp sub-assembly. Components purchased from McMaster-Carr include twenty 0.125" x 0.5" PEEK plastic dowel pins (2), four 90046A106 high strength steel hex head screws (8), and one 9657K412 compression spring (6). 6 sensor carriages (42) will be machined out of 6061 aluminum-T6. The rest of the components will be 3D printed out of Ultem® 1010 PEI Plastic which includes, the storage cap (7), storage spring face (5), sensor storage back (1), front (3), bottom 1 (4), and bottom 2 (24).

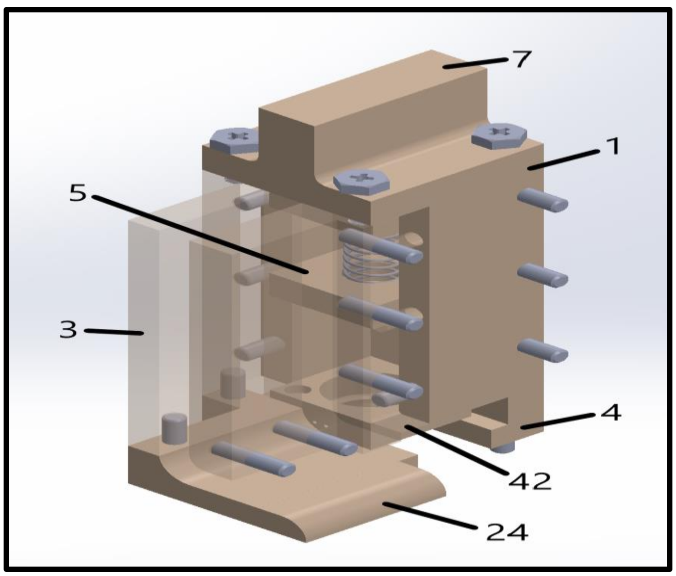

Figure 11. Sensor Storage Sub-Assembly

The sub-assembly is 2" in length, 1.52" in width, and 3.60" in height. The mass of the manufactured components is 0.239 pounds. PEI plastic is utilized because of its low density of

0.045lbin3 and high max service temperature of 354°F. Plastic typically does not do well in radioactive environments; however, Ultem® 1010 is within the polyimide family and has a radioactivity resistance of 10,000 KGY (Nordian) which satisfies our constraints. Aluminum 6061 was chosen over PEI plastic for the sensor carriages because it has a higher max service temperature and can withstand being in contact with the DSC. All PEI components are 3D printed and aluminum components are machined (Xometry). The manufactured components of this sub-assembly have a quoted cost of $496.47.

The four hex head screws can be unscrewed to remove the storage cap, spring and push face. Adhesive will be applied before inserting six sensor carriages into the chamber. As the sensor pusher enters the storage housing it contacts the sensor carriage which is guided along storage bottom 1. Once the carriage fully exits the storage chamber, the next carriage is loaded by the spring and push face. Slots were incorporated into the storage front and bottom 2 to allow the sensor wires to travel out of the sub-assembly without becoming stuck.

Our 3D model and review for manufacturability guided our optimized design for the storage sub-assembly. The most significant design change was the inclusion of PEEK dowels for structural integrity and to simplify 3D prints. The slot for the sensor pusher had to be adjusted to accommodate the changes to the sensor pusher. Finally, filets were added to the wire slots to allow for smoother motion and reduce the possibility of the wires catching and becoming stuck.

5.6.3 Sensor Stamp Sub-Assembly

The sensor stamp sub-assembly deploys the sensor onto the DSC surface and is actuated by the Bowden cable once the carriage is fully ejected from the storage sub-assembly. The parts that can be purchased from McMaster-Carr include one 1583K19 carbon steel corrosion-resistant clevis rod end (28), one 9657K384 compression spring (22), one 9271K602 Hinge Torsion Spring (16), one 25' knob-operated push/pull Bowden cable - 6161K13 (27), six dowels shared with the storage sub-assembly, five dowels shared with the mechanism floor, and six additional dowels holding the components together (2). The components 3D printed out of PEI plastic include the stamp pin rail guide slot (21), spring hinge 1(14), hinge 2 (15), stamp pin rail guide front (20), and rail guide back (19). The parts that will be machined out of aluminum 6061 T4 includes the stamp spring holder (18) and the hinge pin (17). The stamp slider (12) was originally going to be made from aluminum 6061 T4. After a fatigue simulation it was discovered that the stamp slider would only last 20.4 cycles; therefore, the slider will be machined out of AISI 4140 steel.

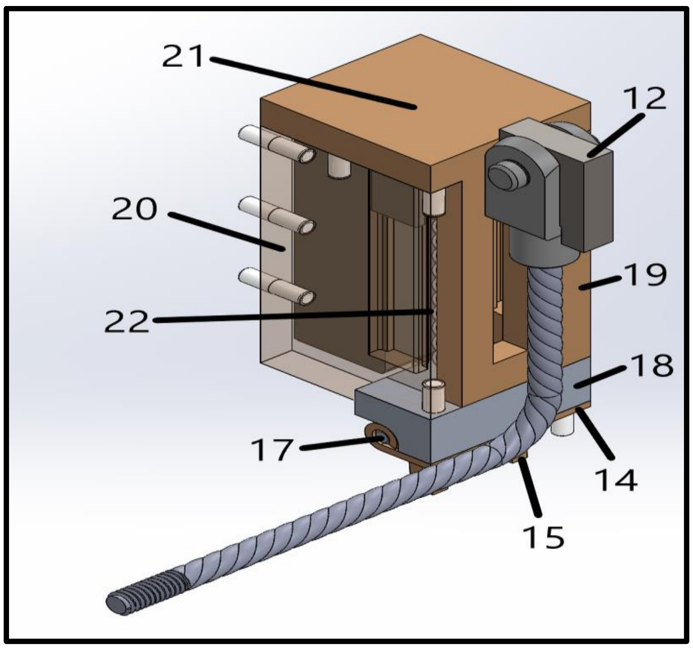

Figure 12. Sensor Stamp Sub-Assembly

The sub-assembly weighs 0.58 lbs and is 2.04 inches in length, 1.27 inches in width, and 3.53 inches in height when the trap door is opened fully After a fatigue simulation it was discovered that the stamp slider would only last 20.4 cycles; therefore, the slider will be machined out of AISI 4140 steel instead of aluminum. AISI 4140 steel was selected for the stamp slider because of its improved physical qualities including a higher strength of 60,200 psi in comparison to aluminum’s 40,000 psi (Theenzone). 6061 is used on the components that do not directly receive force but need to remain rigid in order to reduce weight. PEI plastic is used for housing, rail, and hinge components because they do not share the same physical property requirements. Utilizing PEI allows us to reduce weight and by using a low density material and reduce manufacturing cost by using 3D printing instead of machining. The machined components of the sensor stamp will cost $676.94 while the 3D printed components will cost $155.81 (Xometry).

Once the Bowden cable is pulled, a downward force of 1.93 lbf is exerted on the stamp slider causing it to move downwards 1.38” and the spring to be compressed. The stamp slider will push open the hinged door and extend beyond it to hold the sensor carriages in contact with the DSC surface. As the carriage clears the trap door, magnets on the carriage and slider ensure that the carriage does not fall before it can be contacted with the surface. The slider will remain in the deployed position for 5 minutes to allow the adhesive to cure. After 5 minutes, the Bowden cable is released and the spring causes the slider to move back to its original position.

The 3D model allowed us to review and optimize the design for the stamp. First, manufacturability was improved by splitting the stamp housing into multiple smaller components connected by dowels. This is because the original design would be difficult to successfully 3D print due to its complex shape. Secondly, the Bowden cable connection was improved with the addition of a clevis rod end. Finally, the spring holder was added to be sure that the spring moves linearly.

5.6.4 Cable System Assembly

The cable system assembly allows for guided motion of our Bowden cables and wires connected to the sensors. Components procured from McMaster-Carr include two 6161K13 Bowden cables with threaded ends (27), nine 0.125 x 0.5 PEEK dowels (2), and two 1583K19 carbon steel corrosion-resistant clevis rod ends (28). Components 3D printed out of PEI plastic include the Bowden cable guide (26), sensor storage front (3), cable top guide (25), mechanism floor (29), sensor storage bottom 1 (4), and bottom (2).

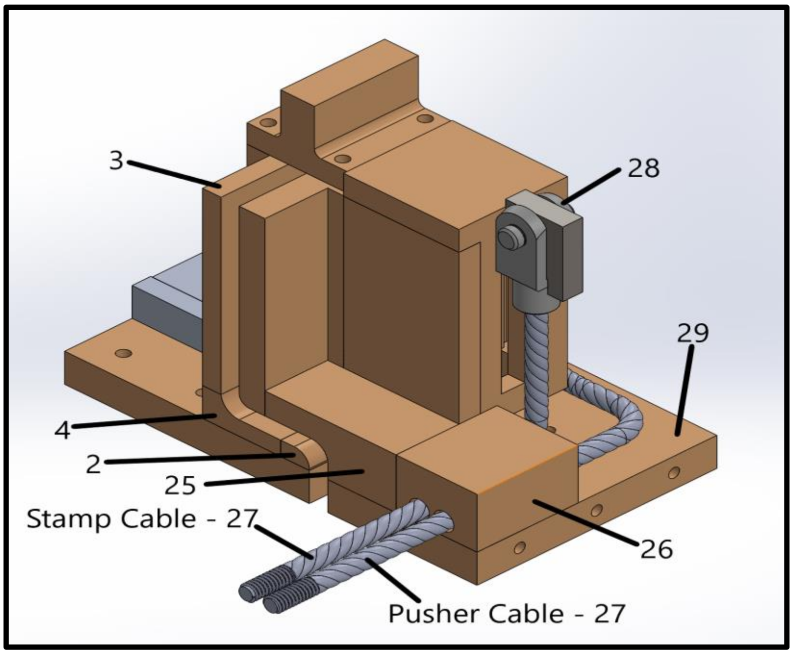

Figure 13. Cable System Sub-Assembly

Each Bowden cable has a diameter of 0.31" and a length of 25' to allow for it to extend outside the DSC. The Bowden cables are knob-operated push/pull with a maximum stroke radius of 3" and a bend radius of 6" (McMaster-Carr). The load capacity of the cables is 25 lbs and they are serviceable in a temperature range of -40 degrees to 225 degrees Fahrenheit (McMaster-Carr). The Bowden cable guide has dimensions of 1.18" x 0.94" x 0.69". The combination of components that guide the sensor cables have dimensions of 2.26" x 0.78" x

2.75”. The mechanism floor which all components rest on has dimensions of 4.82” x 2.8” x 0.39”. All cable system components are PEI plastic because they serve as guides and structure without receiving any direct forces from the bowden cable. The cost to 3D print the cable system components is $74.58 (Xometry).

The stamp and pusher cables are passed through their respective holes on the Bowden cable guide. The other side of the Bowden cable guide is fileted to allow the stamp cable to move smoothly along the 90-degree upwards turn to its connection point. The pusher cable makes a 90 degree turn behind the stamp and storage housing to connect via a threaded clevis rod end. The slot in the sensor storage front component allows the sensor wires to move downwards as sensors are deployed. When the sensor carriage is pushed to the stamp assembly, slots in the sensor bottoms, cable top guide, and mechanism floor provide an exit path for the sensor wires.

Our prototype review and research on Bowden cables resulted in a change in the design for the cable system sub-system. In the middle of showcasing our prototype the cable broke. This in conjunction with receiving the cables and realizing that they will not bend to the desired geometry caused us to add a Bowden cable guide and reduce the number of turns to a single 90 degree cable turn. Furthermore, two unnecessary components were removed by utilizing clevis rod ends and a direct threaded connection to the components that require force to be applied. Finally, filets were added to the sensor wire slots to reduce the possibility of wires getting caught on corners.

5.6.5 Housing Sub-Assembly

The sensor housing sub-assembly contains all components of the design and will be connected to the vehicle team's robot with the SDM carrier (38). The purchased components from McMaster Carr are four aluminum hex nuts, 8-32 - 93181A009 (39), four ⅜”-16 hex head screws - 91268A535 (40), four hex nuts - 93181A009 (34), two 18-8 flat head screws - 92210A193(33), two 18-8 flat head screws - 92210A197 (32), one surface-mount hinge with holes - 1586A22 (31), and thirty-nine 0.125 x 0.5 Dowels (2). The remaining components will be 3D printed out of PEI plastic including the SDM carrier (38), mechanism floor (29), housing top (41), front (30), left (35), right (36), and connection (37).

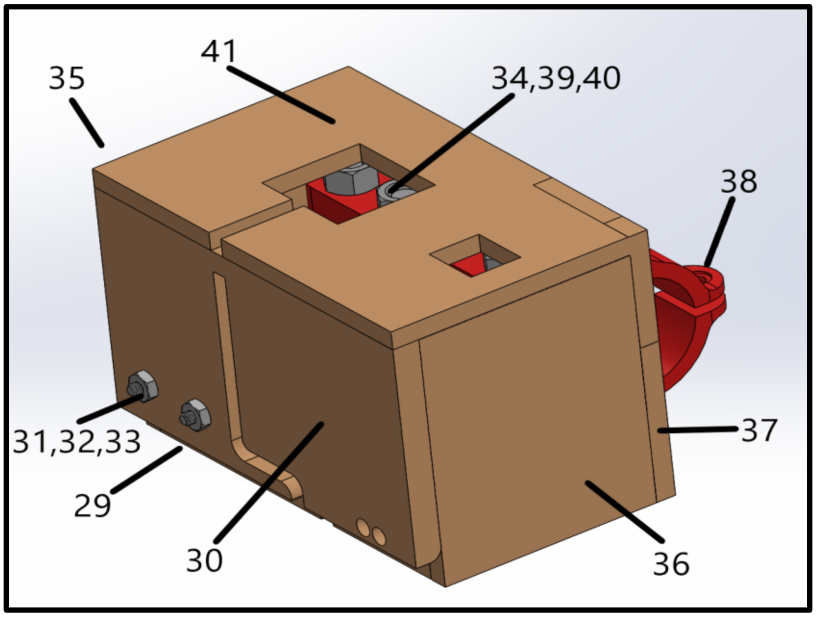

Figure 14. Housing Sub-Assembly

The weight of the manufactured components, excluding the SDM carrier as this is in the vehicle team’s scope, is 1.01 lbs. The housing is 5.28 inches in length, 3.38 inches in width, and 3.7 inches in height. PEI plastic was chosen for the housing because of its low density, high max service temperature, decent physical properties, and radioactivity resistance. The manufactured components for the housing equals $659.69 (Xometry).

Our original design did not allow for easy access to the interior components. The optimized model is designed for repairability as the housing top can slide off and the housing front will hinge down so an operator can perform troubleshooting and repair.

5.7 Finite Element Analysis

The following sections describe the parameters and values used for performing simulations and finite element analysis techniques in SolidWorks® to observe how the stamp slider would behave under normal operating conditions due to this part being the most likely to fail due to yielding and deformation.

5.7.1 Sensor Stamp Thermal Simulation

To set up the simulation in SolidWorks, the solution type of the simulation was set to transient, and the total time was set to 300 seconds and the time increment was set to 60 seconds to simulate the stamp slider (23) temperature during the five minute holding time for sensor deployment. The material selected for the stamp slider is AISI 4140 steel and the sensor carriage is 6061-T4 aluminum alloy. The initial temperature of the stamp slider was set to 106 F which is the ambient temperature within the dry-cask storage container and the bottom of the sensor carriage (42) was set to 350 F to represent the surface temperature of the canister. Figure 15 shows the setup of the thermal simulation.

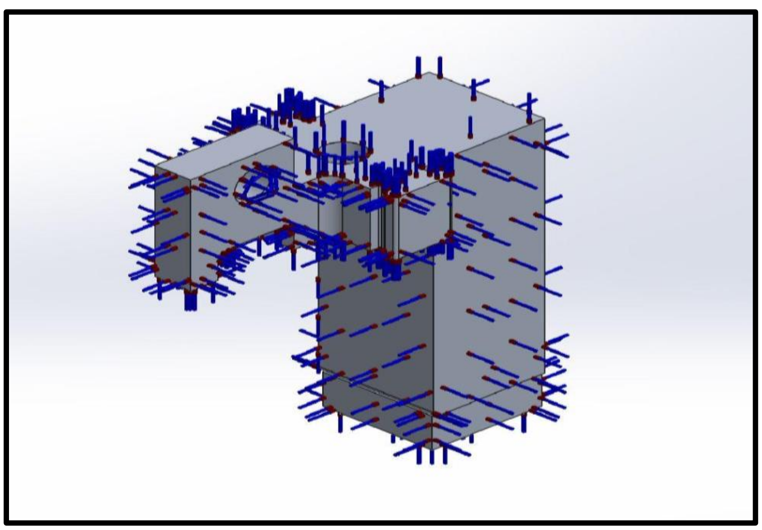

Figure 15. Stamp Slider Thermal Simulation Setup

The FEA output shows that the maximum temperature of the stamp slider is approximately 320 F when the stamp slider has been in contact with the sensor carriage for five minutes in the deployment position. The temperature of the stamp slider at the fifth step of the thermal simulation will be used in the static simulation on the same assembly. Figure 16 shows the results of the thermal simulation.

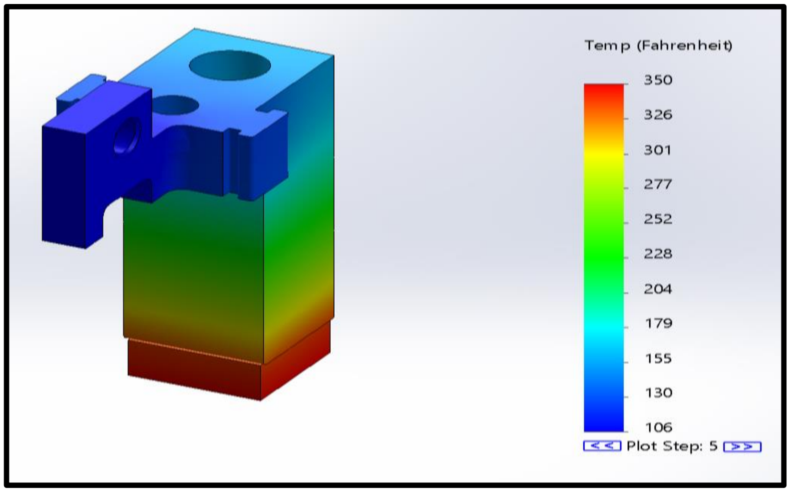

Figure 16. Sensor Stamp Thermal Simulation Results

5.7.2 Sensor Stamp Static Simulation

To set up the static simulation, the rectangular faces of the stamp slider were given a roller fixture to simulate the sliding motion of the stamp slider. Thermal effects were included in the static simulation from the fifth step of the thermal simulation. A 1.92913-lbf force was applied to the bottom of the attachment point for the Carbon Steel Corrosion-Resistant Clevis Rod End - 1583K19 (28) to represent the force needed to compress the spring by 1.38 inches, which is the maximum displacement of the stamp slider that is needed for sensor deployment. A 1.92913 lbf force was also applied to the bottom face of the stamp slider near the sliding hole to represent the force of the spring on that face. Figure 17 shows the setup for the sensor stamp static simulation.

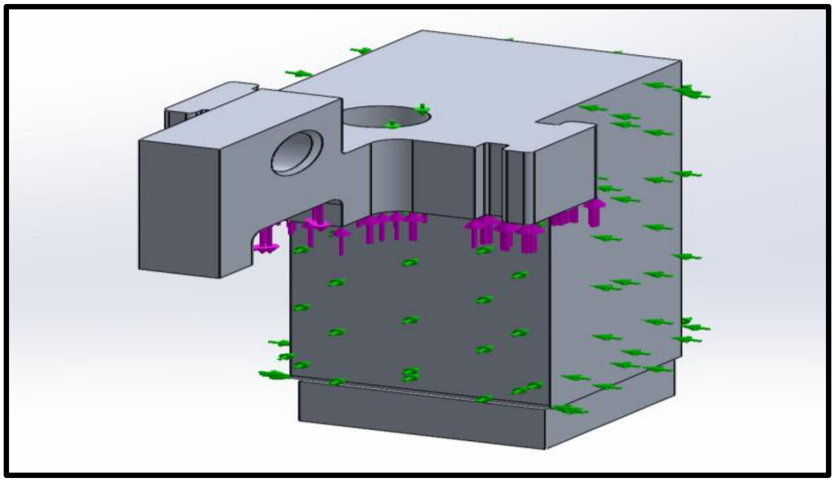

Figure 17. Stamp Slider Static Simulation Setup

The output for this simulation demonstrated that the area around the hole for the rod of the stamp spring holder and the rectangular faces experienced the highest stresses when the stamp slider was in the deployment position. The yield strength for AISI 4140 steel is 710 MPa, and the highest stress on the stamp slider and stamp spring holder calculated by SolidWorks was 899 MPa. The thermal load was the largest contributor to the stress on the component. The stamp slider will yield and deform in areas that experience stresses above the yield strength. Figure 18 shows the stress distribution on the stamp slider.

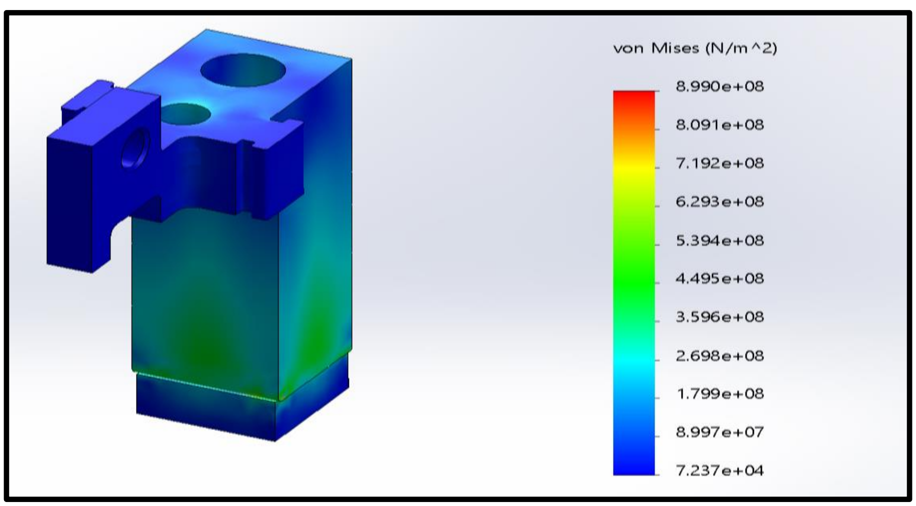

Figure 18. Stamp Static Simulation Stress Output

The largest deformation occurred at the bottom face of the stamp slider that is in contact with the sensor carriage. Figure 19 shows the deformation results from the static simulation. The largest deformation on the stamp slider is approximately 0.06 mm each time the stamp slider deploys a sensor onto the canister surface.

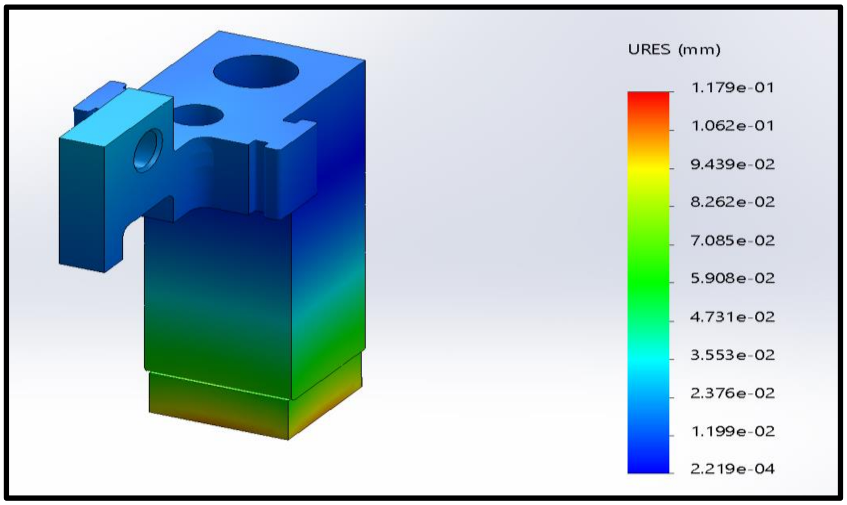

Figure 19. Stamp Static Simulation Deformation Output

5.7.3 Sensor Stamp Fatigue Simulation

Fatigue simulation is necessary to determine the reusability of our design and to determine when the mechanism will fail, especially after reviewing the results of the static simulation of the stamp slider. To set up the simulation in SolidWorks, we included the same assembly and materials used in the sensor stamp static simulation. The fatigue loading was to the constant amplitude setting and the loading type was zero based meaning that the loading conditions would oscillate from zero to the loading conditions set in the static simulation. The number of cycles was set to 960 to observe the total life of the stamp slider when experiencing the loading conditions in the static simulation for the deployment of 24 sensors in 40 dry cask storage containers. Figure 20 shows the results of the fatigue simulation.

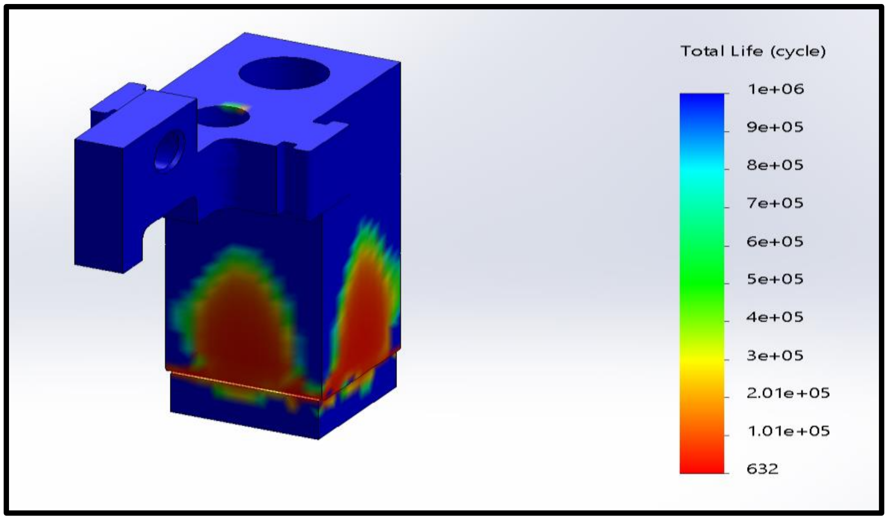

Figure 20. Fatigue Simulation Total Life Results

The results of the fatigue simulation show that the minimum number of cycles experienced by any part of the stamp slider is 632. The stamp slider will be going through 24 cycles to deploy all four rings of sensors in a single dry-cask storage container and could be used in up to 26 dry-cask storage containers.

6 DELIVERABLES

Due to the inability of human personnel to monitor the internal condition of DSCs, improving the methods of inspecting DSCs through non-destructive processes is essential to the safety of the environment and workers. Through the use of robots, DSCs can be visually monitored and inspected internally, however, constant corrosion monitoring cannot be done without the use of the sensors. The HGUW sensors will enable Orano to continuously monitor the current condition and longevity of their equipment. Additionally, through the use of sensors, localization of cracks, leaks, and corrosion can be detected early on. Our team's goal this semester is to design a sensor deployment mechanism that attaches to a wall-climbing robot and will effectively enable Orano to monitor the integrity and condition of their DSCs. By the end of the semester, our team will provide our detailed CAD model of our design, bill of materials, and concept of operations to our sponsor, Mitchell Pryor, and the UTNRG. The detailed design will include our CAD model and FEA simulation results.

6.1 SolidWorks Models

The SolidWorks models that we will provide to our sponsor will serve as a way for the design to be visualized as well as seeing how the design is constructed. Furthermore, the SolidWorks models would allow for the continuation of the project with quick redesign abilities through the models before fabrication. The dimensions of the entire assembly are 3.40” length, 5.32” width, and 3.42” height, which meets our geometric constraints. An isometric view of the assembly can be seen in Figure 21.

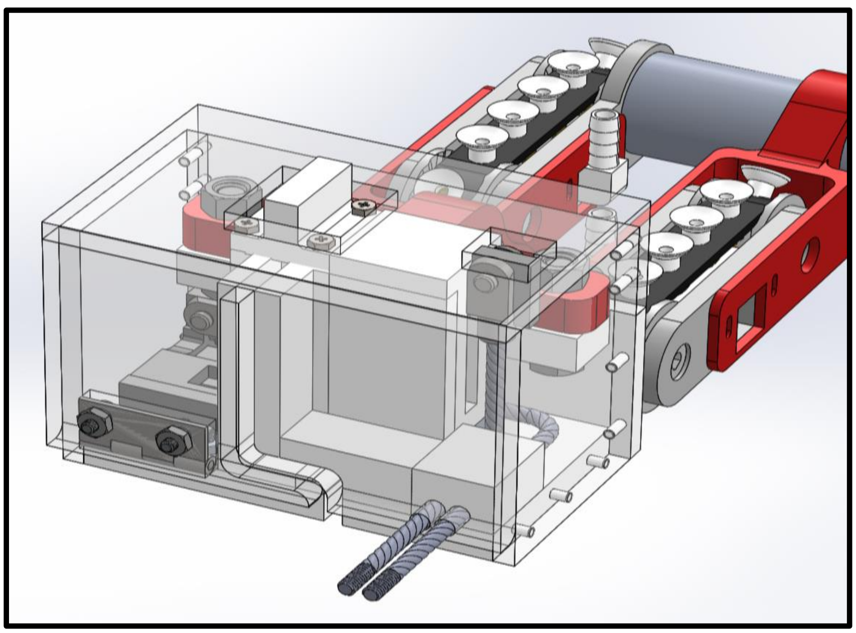

Figure 21. Isometric View of Sensor Deployment Mechanism Assembly

Isometric views for the SolidWorks models of our deployment mechanism can be seen in Figures B.10 - B.38 of APPENDIX B and the B-size drawings of these models can be seen after APPENDIX F. Front, top, and side views of the assembly can be seen in Figures B.6 - B.9 as well.

6.2 Bill of Materials

Upon finalizing our design, our team selected the necessary components to purchase for assembling the deployment mechanism and other components required for system actuation and deployment. As requested by our sponsor, all components are easily accessible to purchase online. We selected all of our materials from McMaster-Carr® due to ease of purchase and reliability in the company and their products. The bill of materials directly corresponds to our parts list, which can be found in Table D.1 of APPENDIX D, and includes website links, required quantity for design assembly/deployment, and the cost of each component. Our total material cost for the materials is $753.14 which does not include the manufacturing cost. Utilizing the proposed components selected for the sensor deployment mechanism, instructions for proper assembly can be viewed in APPENDIX F.

These materials were selected for because they are able to withstand low levels of radiation, exhibit higher yield strength and creep resistance, and are lightweight materials. The lightweight materials are a necessity due to our deployment mechanism as a whole being attached to the wall climbing robot with a restricted amount of suction power that supports our mechanism as well. Aside from selecting non-degradable materials that could withstand a radioactive environment with elevated temperatures, selecting relatively lightweight materials was an additional priority to ensure our mechanism is not heavier than the wall-climbing robot's suction capabilities.

6.3 Concept of Operations

Our Concept of Operations (ConOps) provides instructions and quantitative requirements for the potential user of our sensor deployment mechanism. Project background information and system details are also included to understand the purpose and intended use of our mechanism. The quantitative requirements of our system include the amount of adhesive applied to each sensor, the maximum number of sensors that can be loaded into the system, the holding time during deployment actuation which are included below along with instructions.

To prepare the mechanism for entrance into the DSC, the operator of our system will be expected to open the external housing and remove the top of the storage compartment. HGUW sensors will then be placed into sensor carriages with the two thin wires soldered to each sensor being placed through the corresponding holes on the carriage. A coaxial cable will be attached to the pair of wires of each sensor. An 8 mm in diameter by 2 mm in height amount of Epoxy, Loctite® M-121hp will then be applied to the bottom of each sensor. Six of these sensor, carriage, and adhesive assemblies will then be placed vertically into the storage of our system with the wires facing towards the aft end of the vehicle and deployment mechanism.

After the vehicle has entered the DSC and is in the desired location to deploy the first sensor, the first Bowden cable will be actuated to activate the sensor pusher arm and move the sensor forward in the system in preparation for deployment. The second Bowden cable will then be actuated to activate the sensor stamp and press the sensor to the surface of the canister. This second Bowden cable will be locked in a fully actuated position for five minutes to ensure proper adhesion between the canister surface and the sensor. After this time has passed, the Bowden cable is then released and the vehicle will move to the next desired location. The process of Bowden cable actuation and deployment will repeat for the number of sensors loaded into the system.

7 ECONOMIC ANALYSIS

Current NDE practices used to monitor stress corrosion cracking and other imperfections of the stainless-steel equipment within DSCs are not extremely accurate and exhibit many limitations. A few current testing techniques include visual inspection (VT), bulk ultrasonic testing (UT), guided ultrasonic wave (GUW) testing, and eddy current testing (Meyer, RM, et al, 2016). These practices require higher levels of qualification, experience time, and training time. Costs allocated to proper use of technology and accurately conducting and evaluating NDE practices are to be considered when comparing the benefit of our system. Qualifications and code requirements for NDE personnel are dependent on the standards and written practices of the nuclear industry as well as third party certifications (World Nuclear Association, 2014). The combined manufacturing and material cost per unit of our sensor deployment mechanism is $3381.54 and the manufacturing cost analysis is summarized in Table E.1 of APPENDIX E. The introduction of robots being used for DSC inspection purposes “can drive down the costs of periodic canister inspections by 90% (Warren, 2022).”

Dr. Pryor received a quote from Invert Robotics and the cost for their base platform wall-climbing robot was $58,000 and custom platform was $98,000. Due to the permanent attachment of the sensors to the canister surface within the DSC, a payback should be seen over time when using HGUW sensors for the inspection of DSCs when it is compared to the net cost of periodic inspections that utilize these robots. In regards strictly to our deployment mechanism, it is designed to be simple to operate which would allow for reduced operation costs due to special operation training not being necessary unlike other examination systems.

The cost of the 3D printed components per unit is $1,158.01 and the cost for machined components is $1,738.44 (Xometry). After adding the cost for pre-manufactured components, the cost per unit is $3,271.16. There are 1075 horizontal DSCs on the market and each unit has capability to inspect 26 DSC’s based on the number of cycles until fatigue failure for the stamp slider. We will be able to inspect every DSC with 50 units (20% contingency). The quoted cost is significantly reduced to $1,479.12 per unit when 50 units are manufactured (Xometry).

8 CONCLUSIONS AND RECOMMENDATIONS

Throughout the research and design of this project, our team prioritized the various requirements and constraints that were stated by Orano, our sponsor, the sensor team, as well as the vehicle team. Our sensor deployment mechanism design as well as material and adhesive selection all satisfy the constraints listed in this report. Our design selections were optimized to satisfy the requirements of this project, but validation of this is highly contingent on real world application and use of our system. Our team's overall project solution for optimization of our sensor deployment mechanism and adhesive selection are presented in sections 4 and 5 on this report. Although we were not required to build a functional prototype, this enabled us to evaluate the components of our design that functioned well and the components to be optimized which were presented in our final model. Additionally, adhesive testing and selection were not part of our initial requirements, but it became evident that it was a crucial feature to specify in our project solution to aid in the security of these sensors when deployed within DSCs.

If provided more time to continue optimizing our design, our team would strongly recommend altering the design of our connection mechanism to the wall-climbing robot. To ensure a rigid attachment and even clearance to the DSC surface, our mechanism could be designed to fit within the design of the wall-climbing robot rather than on the aft end of the vehicle via motor attachment. This would allow for consistent distance between the robot, deployment mechanism, and DSC surface rather than trying to ensure rigid connection which could prove to be challenging with the space constraints.

Additionally, the adhesive research and testing could be continued further given more information on the required times for vehicle preparation and entrance into the DSC to prepare for deployment. Various adhesives with longer hardening times, temperature ratings, and fluid consistencies could be researched and purchased for experimentation. A more controlled testing environment with furnaces and temperature-regulated spaces would be optimal to make formal conclusions regarding each adhesive.

Material selection for the stamp slider component should also be reconsidered. Although the FEA fatigue simulation results showed that the life cycle of the part could be serviceable for up to 624 sensor deployments, it would be preferable to select a material that could retain its desirable mechanical properties at temperatures greater than 400 F. This would increase the life cycle of the part and reduce costs due to the reduction in frequency of part replacement.

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APPENDIX A. Gantt Chart

Table A.1 Gantt Chart

Phase 1: BACKGROUND & RESEARCH					
First Sponsor Meeting	25-Jan	1	25-Jan	1	100%
Contact Sponsors	21-Jan	1	21-Jan	1	100%
First Joint Meeting with Sponsor	1-Feb	1	1-Feb	1	100%
Meeting with Orano Employees	4-Feb	1	4-Feb	1	100%
Background Research	4-Feb	18	6-Feb	10	100%
Patent Research	4-Feb	18	6-Feb	16	100%
Sign NDA with Orano	9-Feb	1			0%
Review CAD Models of DSC from Orano	14-Feb	4			0%
Meet with Salvatore Salamone & Team	11-Feb	1	9-Feb	1	100%
Meet with Faculty Advisor: Dr. Mitchell Pryor	22-Feb	1	16-Feb	1	100%
Phase 2: CONCEPT GENERATION					
Draft Specifications Sheet	18-Feb	2	14-Feb	3	100%
Review Requirements	19-Feb	2	16-Feb	2	100%
Concept Generation	20-Feb	5	14-Feb	8	100%
Identify Candidate Solutions	23-Feb	2	20-Feb	2	100%
Research Adhesives	26-Feb	14	21-Feb	10	100%
Select Leading Concept	26-Feb	1	23-Feb	1	100%
Final sync with other K Team before ordering	3-Mar	1	2-Mar	1	100%
Generate CAD Models	1-Mar	5	23-Feb	5	100%
Generate Assembly of CAD Models	7-Mar	1	28-Feb	6	100%

Phase 3: PROTOTYPING & EXPERIMENTATION

Draft Functional Prototype Bill of Materials	8-Mar	2	7-Mar	1	**100%**
Draft an FMEA	11-Mar	1	10-Mar	1	**100%**
Research Materials	20-Mar	14	24-Mar	21	**100%**
Perform FEA Analysis on CAD Models	20-Mar	5	22-Mar	5	**100%**
Build a Functional Protoype of Subsystem	25-Mar	3	31-Mar	4	**100%**
Experiment / Adjust Prototype of Subsystem	30-Mar	3	1-Apr	5	**100%**
Build a Functional Protoype of Subsystem	25-Mar	1	1-Apr	6	**100%**
Experiment / Adjust Prototype of Subsystem	30-Mar	3	4-Apr	3	**100%**
Adhesive Testing	31-Mar	7	6-Apr	6	**100%**
Update Drawings / BOM/ Budget	31-Mar	2	10-Apr	3	**100%**
Update FMEA	1-Apr	1	10-Apr	1	**100%**
Update CAD Models	1-Apr	3	10-Apr	4	**100%**
Generate Final Assembly of CAD Models	7-Apr	2	15-Apr	2	**100%**
Draft Concept of Operations	8-Apr	3	18-Apr	4	**100%**
Draft Final BOM	8-Apr	3	18-Apr	2	**100%**
Review Deliverables with Sponsor	13-Apr	1	13-Apr	1	**100%**
Prepare Assembly Instructions	13-Apr	5	18-Apr	5	**100%**

Phase 4: FINAL DOCUMENTATION					
Final Report	18-Apr	12	25-Apr	7	**100%**
Prepare for Final Presentation	15-Apr	6	15-Apr	6	**100%**
Final Oral Presentation	18-Apr	7	18-Apr	4	**100%**

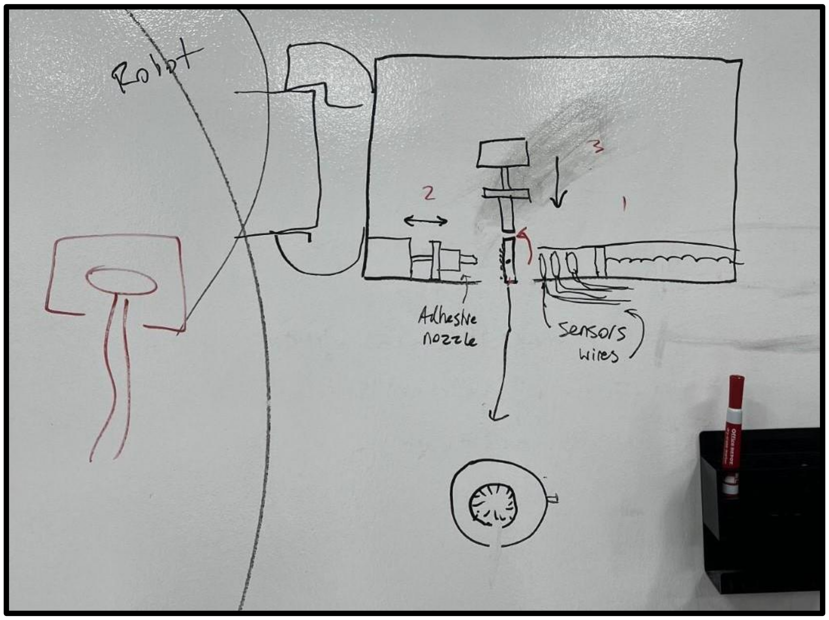


Figure B.1 Alternative Concept 1 Sketch

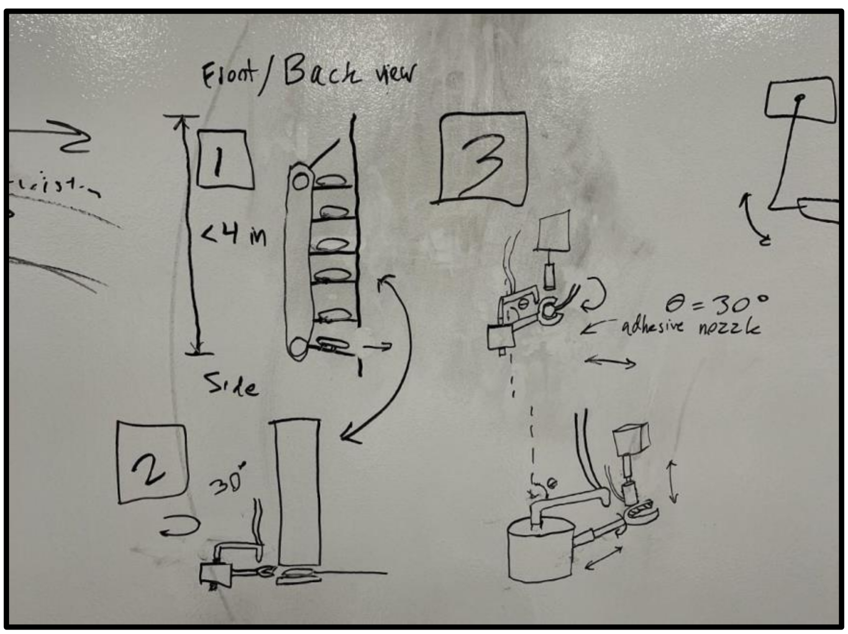


Figure B.2 Alternative Concept 2 Sketch

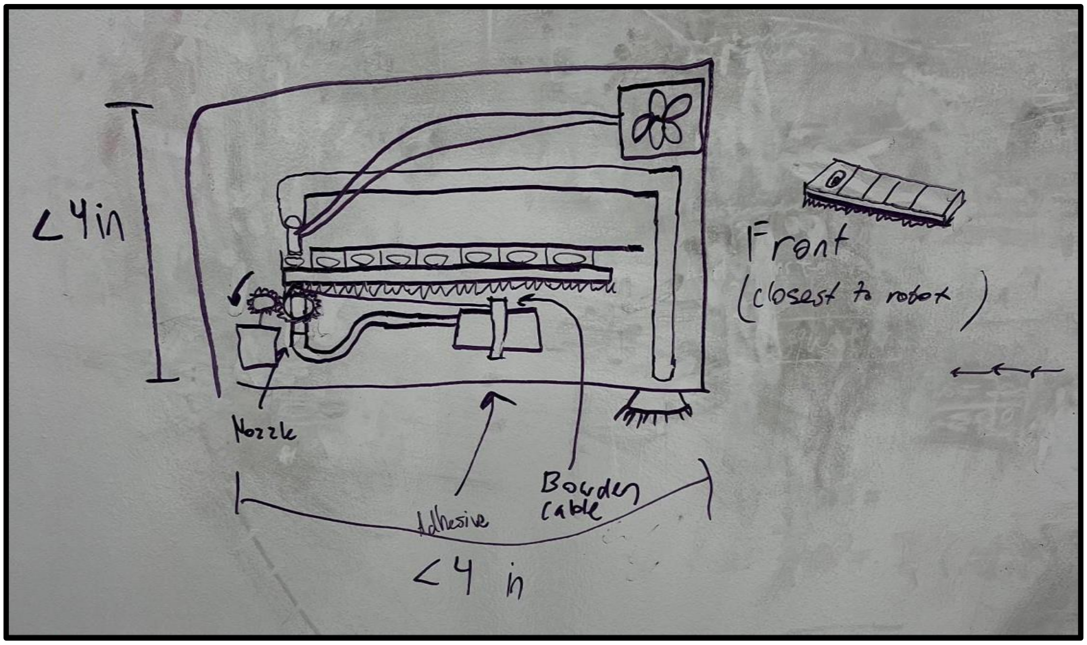


Figure B.3 Alternative Concept 3 Sketch

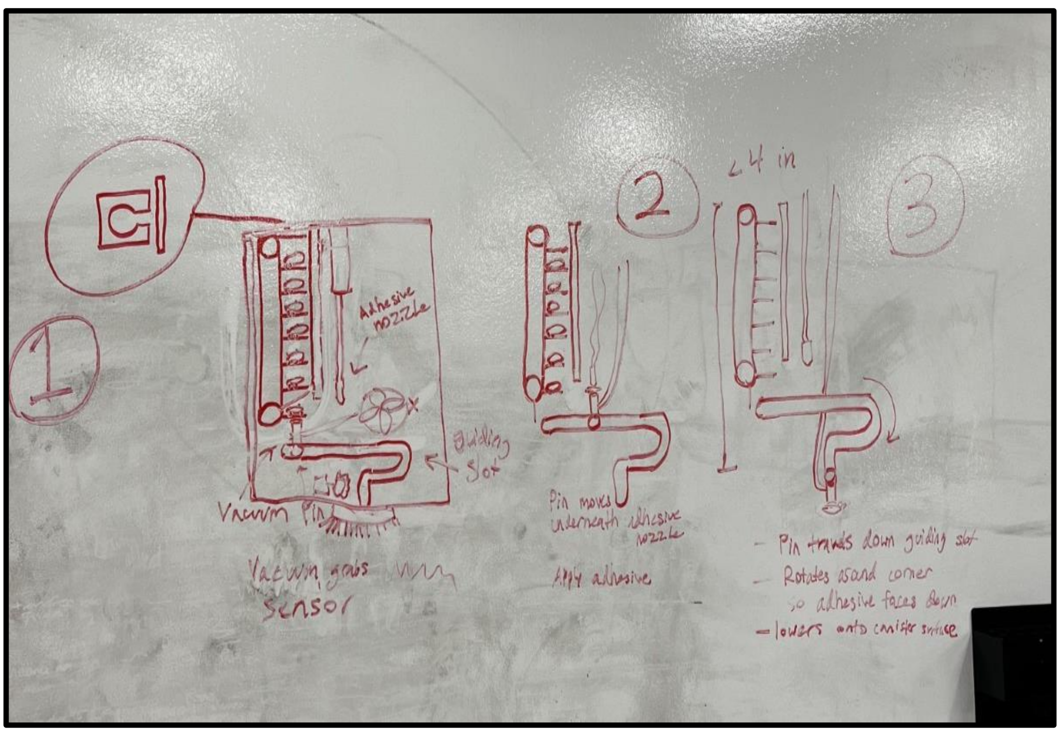


Figure B.4 Alternative Concept 4 Sketch

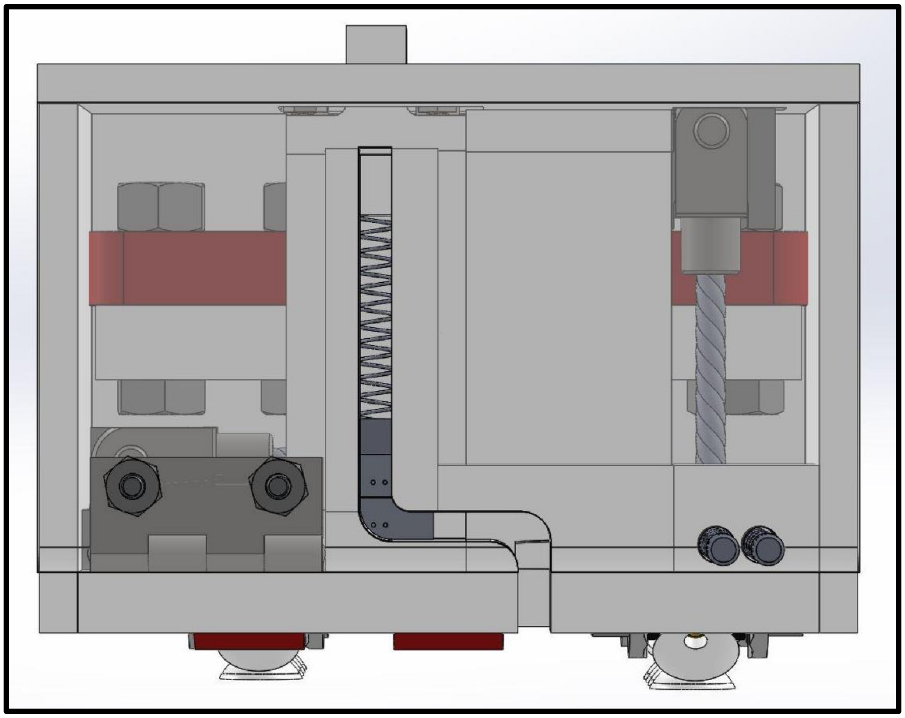


Figure B.5 Front View of Sensor Deployment Mechanism

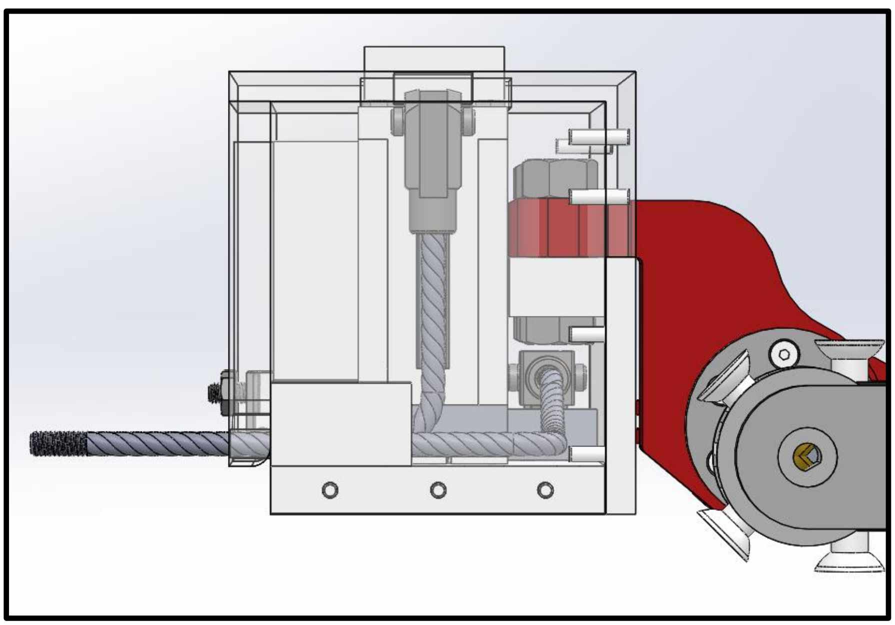


Figure B.6 Side View of Sensor Deployment Mechanism

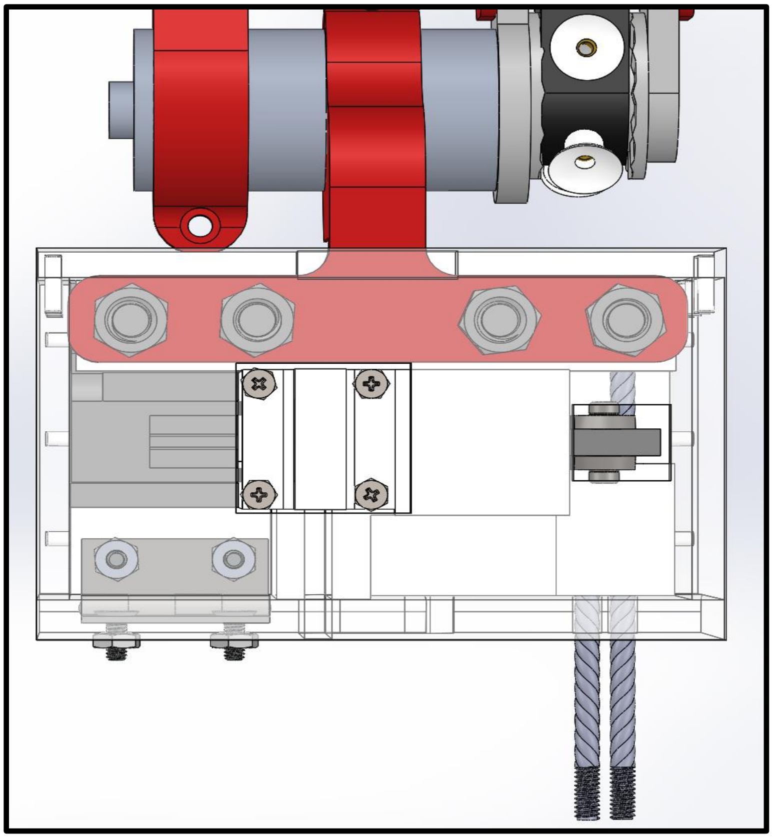


Figure B.7 Top View of Sensor Deployment Mechanism

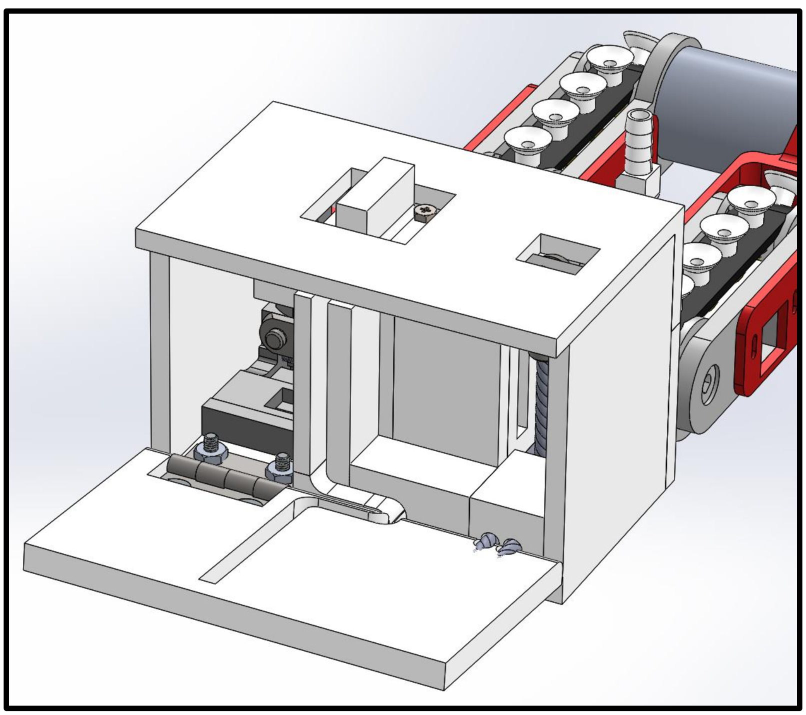


Figure B.8 Isometric View of Sensor Deployment Mechanism With Open Front

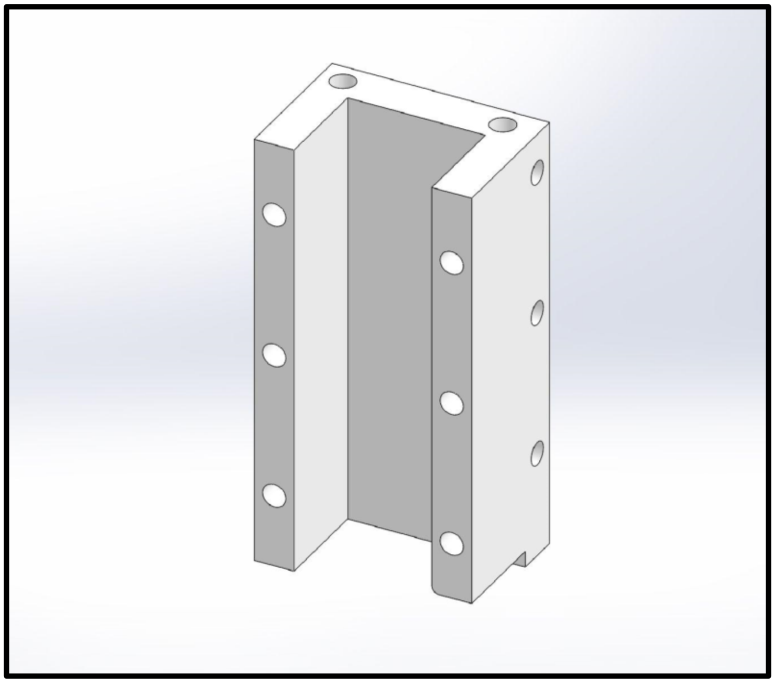


Figure B.9 Sensor Storage Back

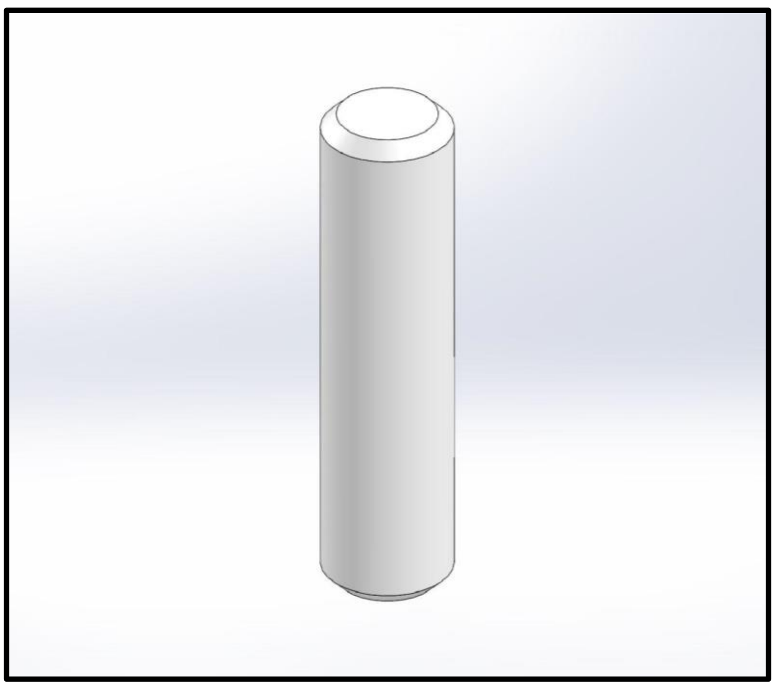


Figure B.10 0.125 in x 0.5 in Dowel

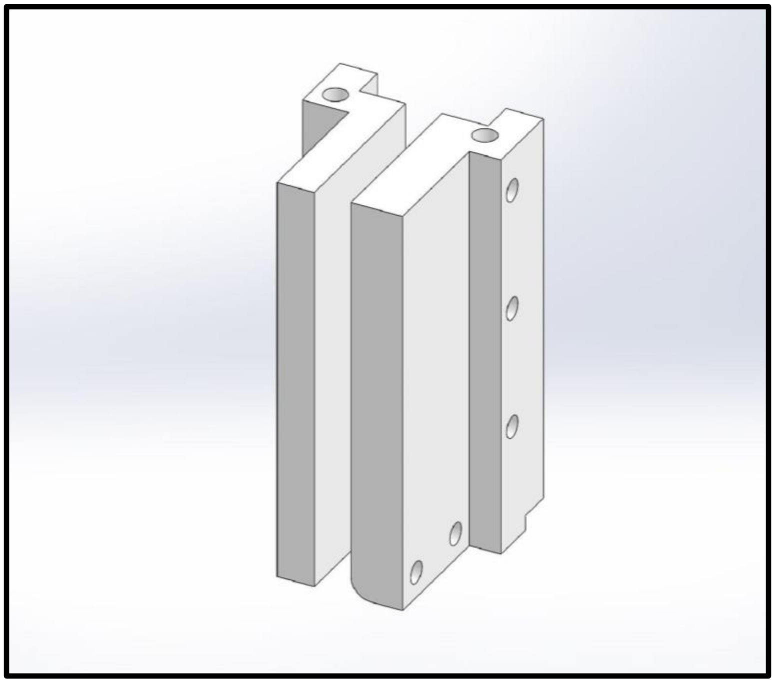


Figure B.11 Sensor Storage Front

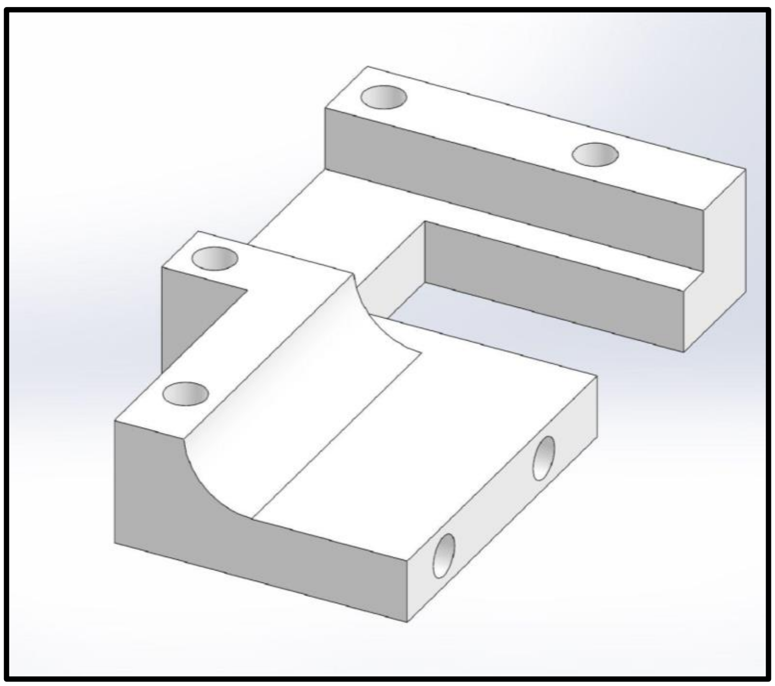


Figure B.12 Sensor Storage Bottom 1

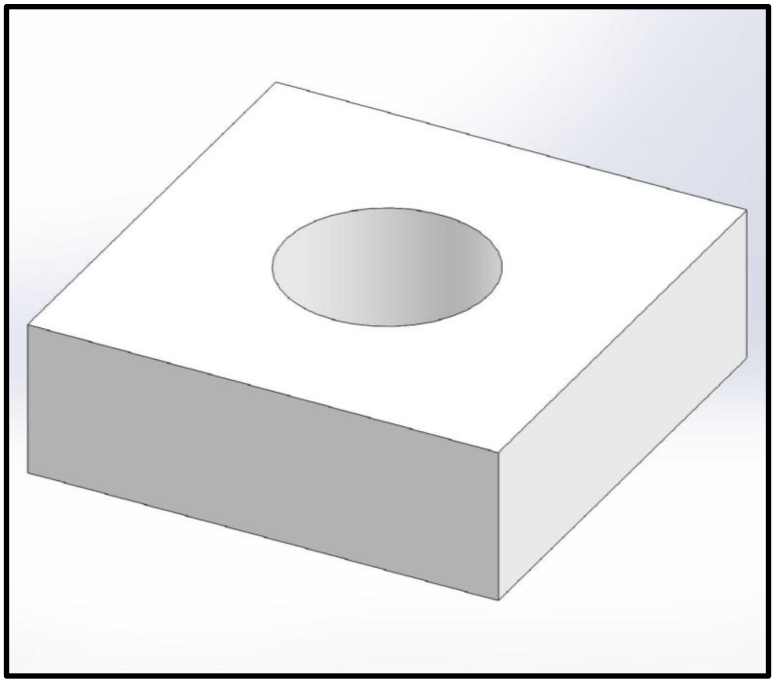


Figure B.13 Storage Spring Face

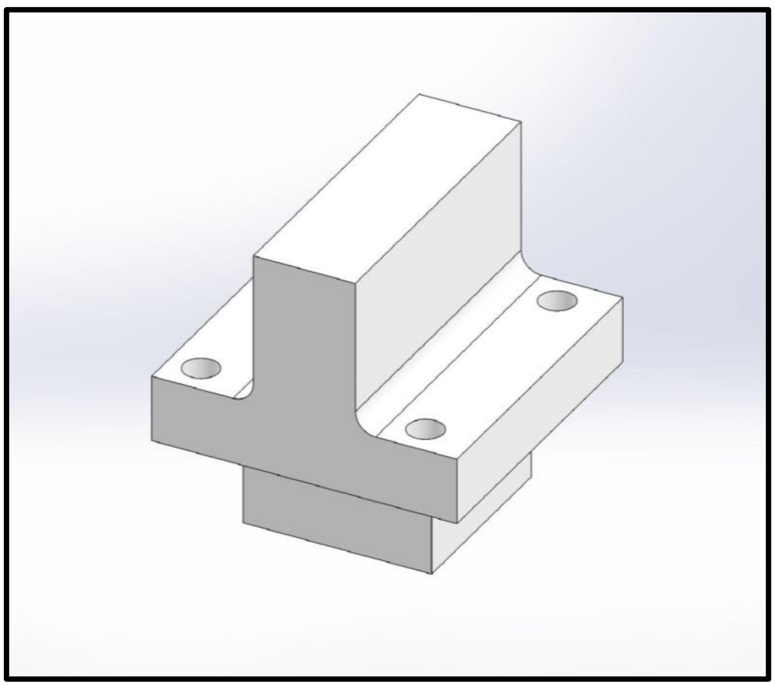


Figure B.14 Storage Cap

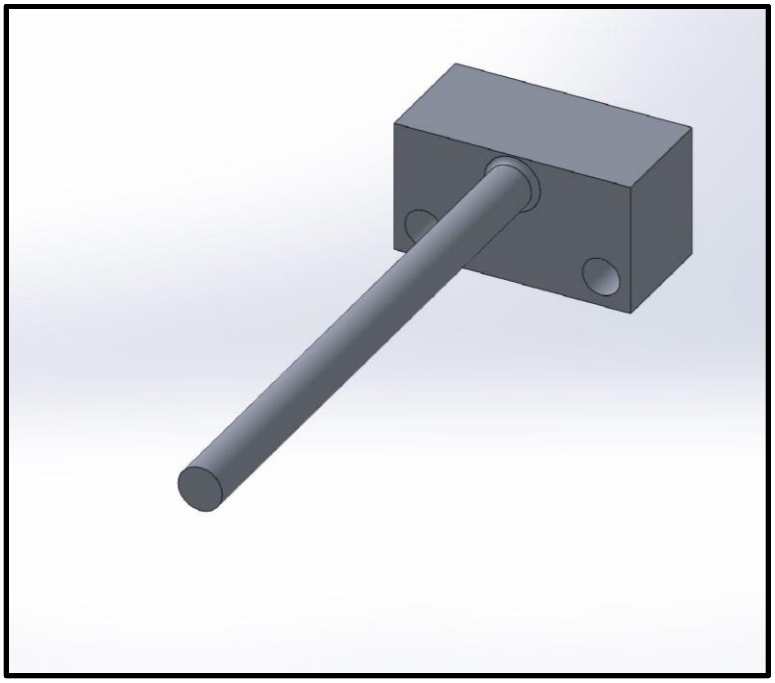


Figure B.15 Sensor Pusher Spring Holder

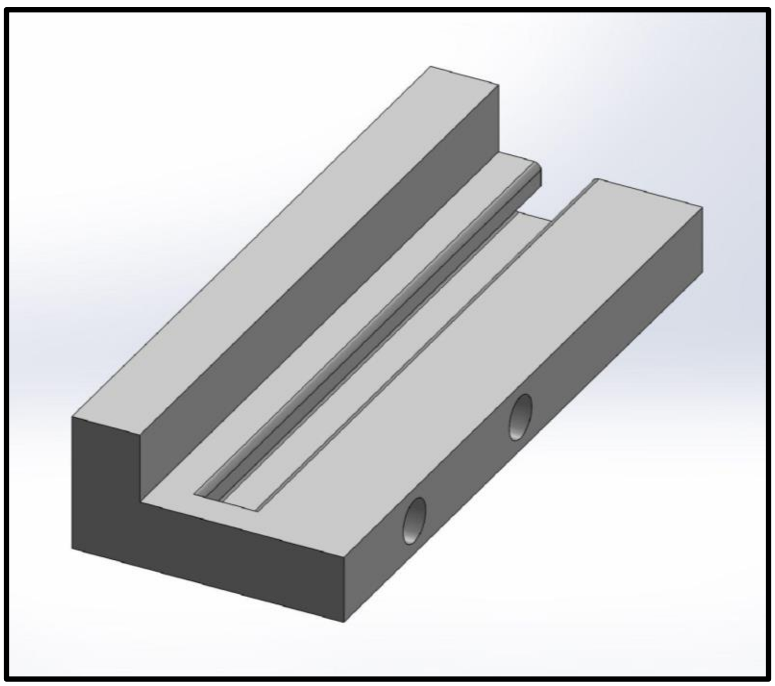


Figure B.16 Bottom of Sensor Pusher

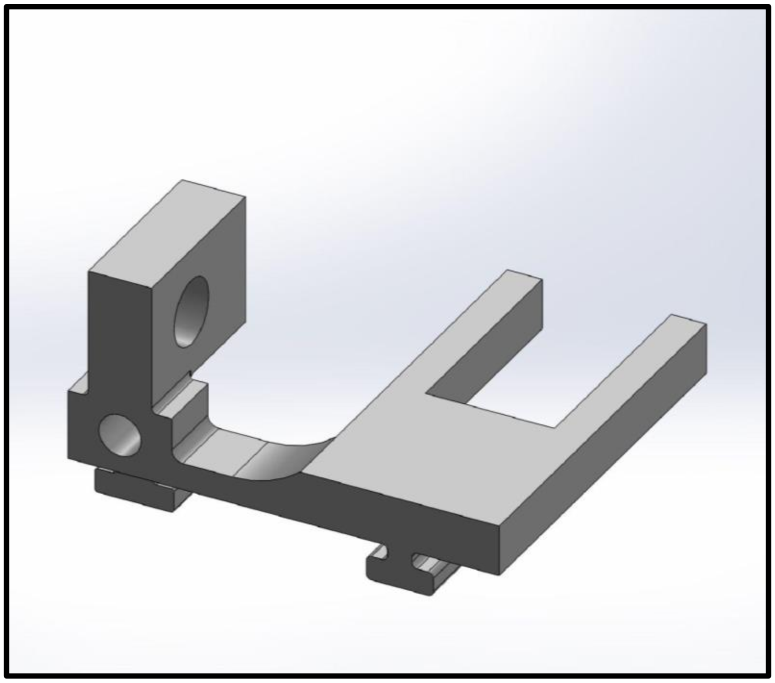


Figure B.17 Spring Slider

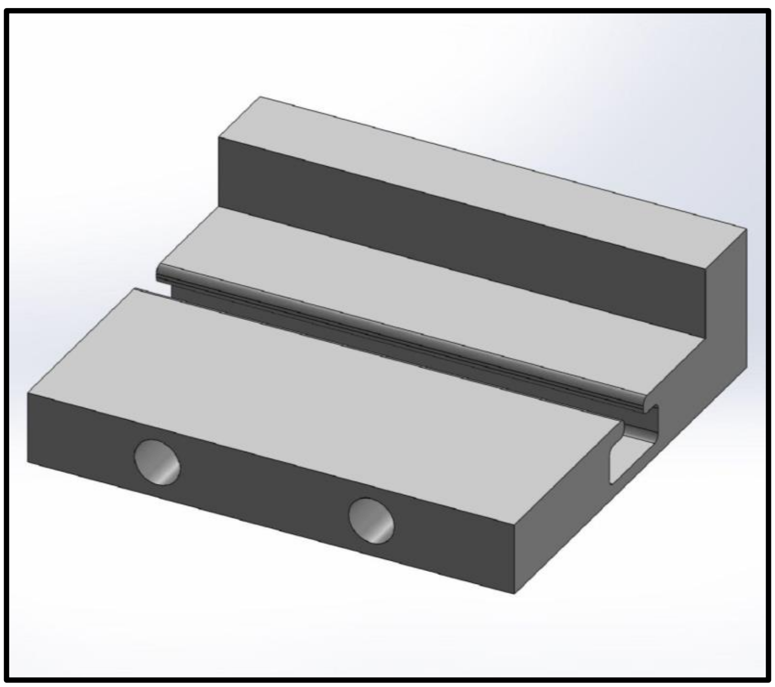


Figure B.18 Sensor Pusher Guide

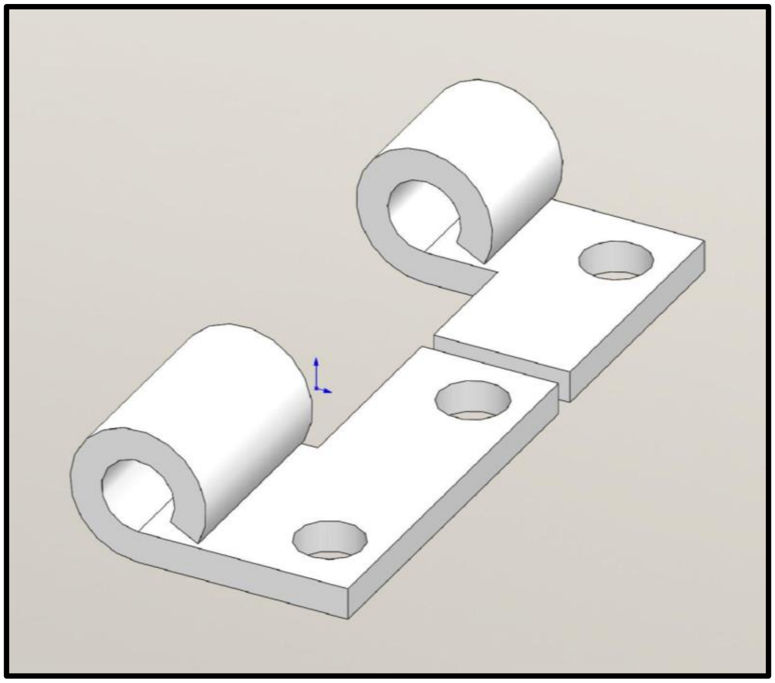


Figure B.19 Spring Hinge 1

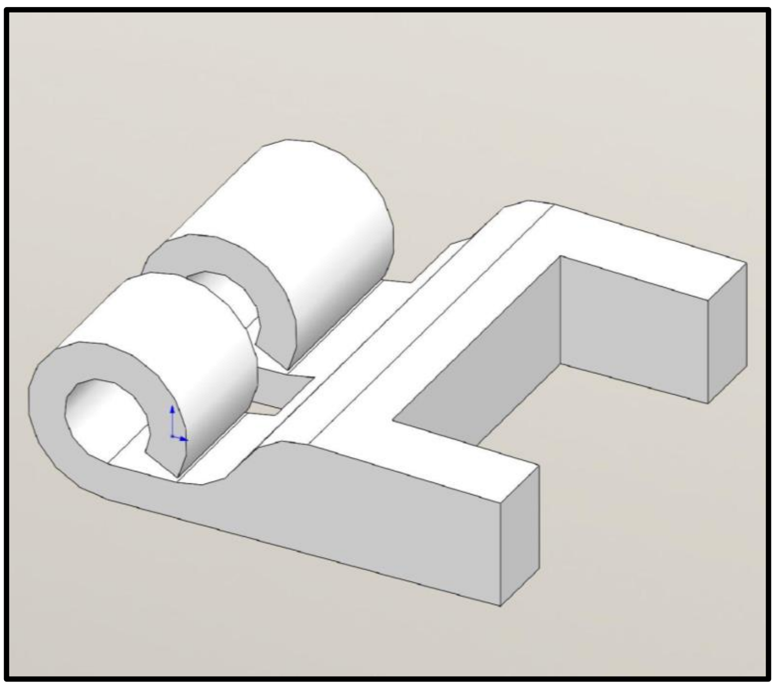


Figure B.20 Spring Hinge 2

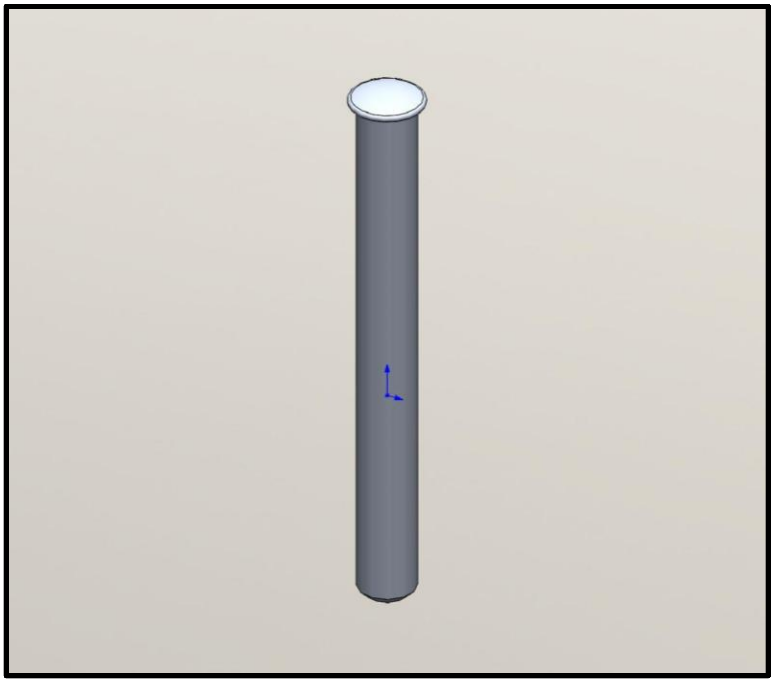


Figure B.21 Hinge Pin

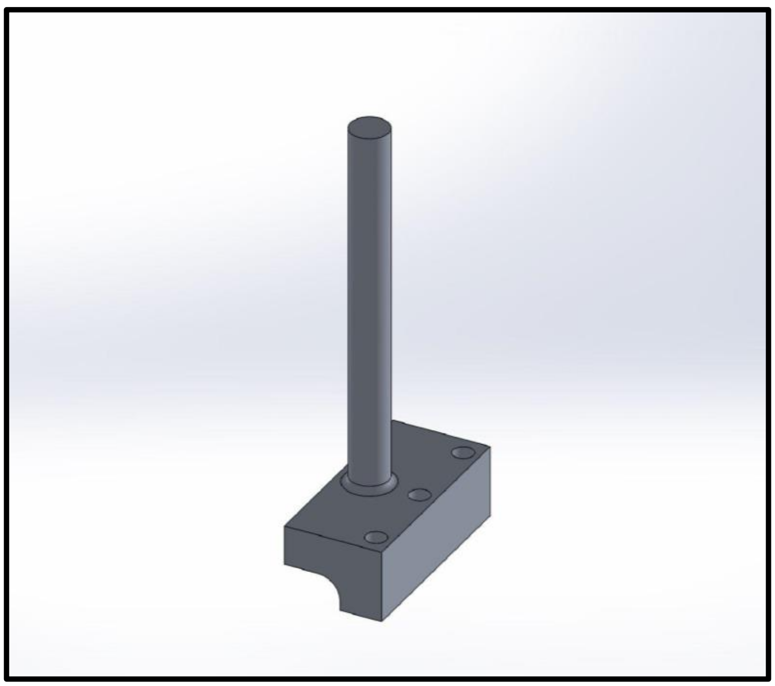


Figure B.22 Stamp Spring Holder

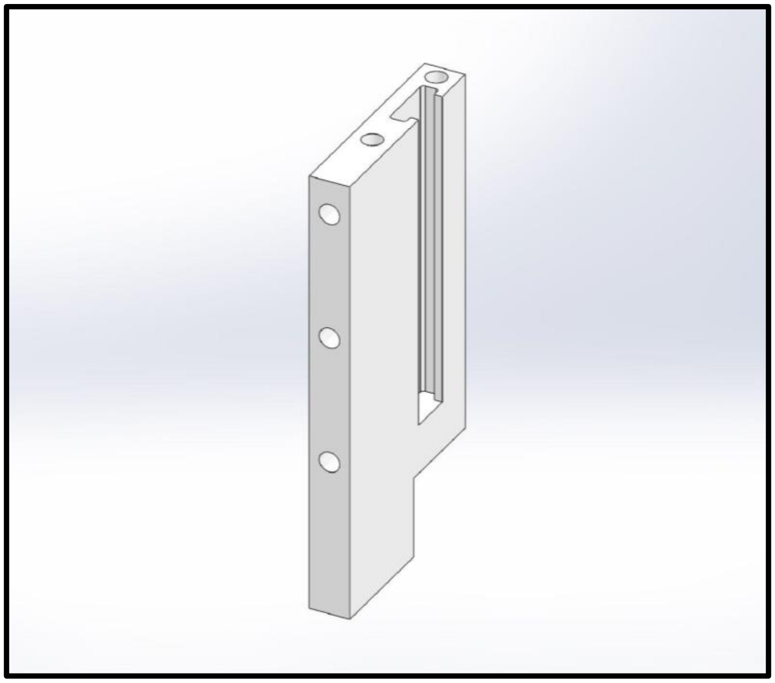


Figure B.23 Stamp Pin Rail Guide Back

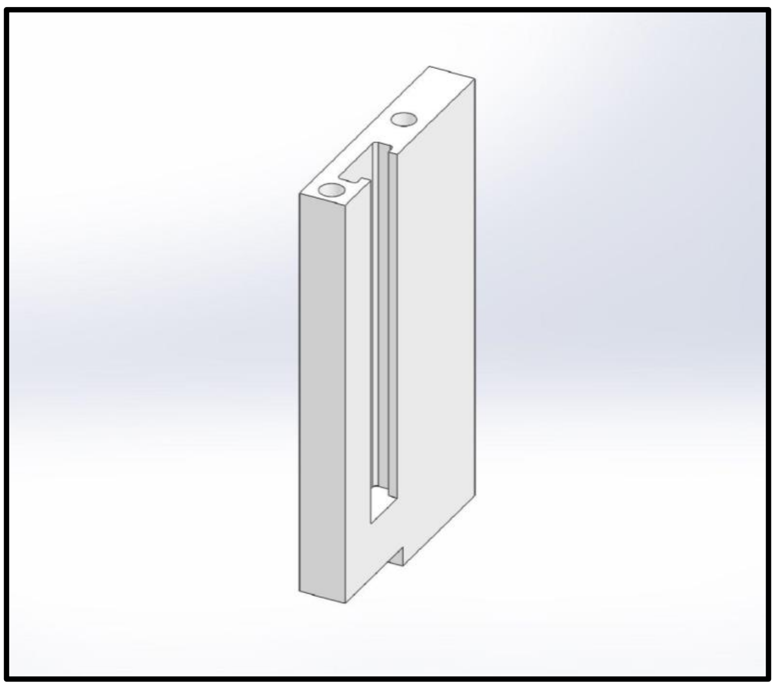


Figure B.24 Stamp Pin Rail Guide Front

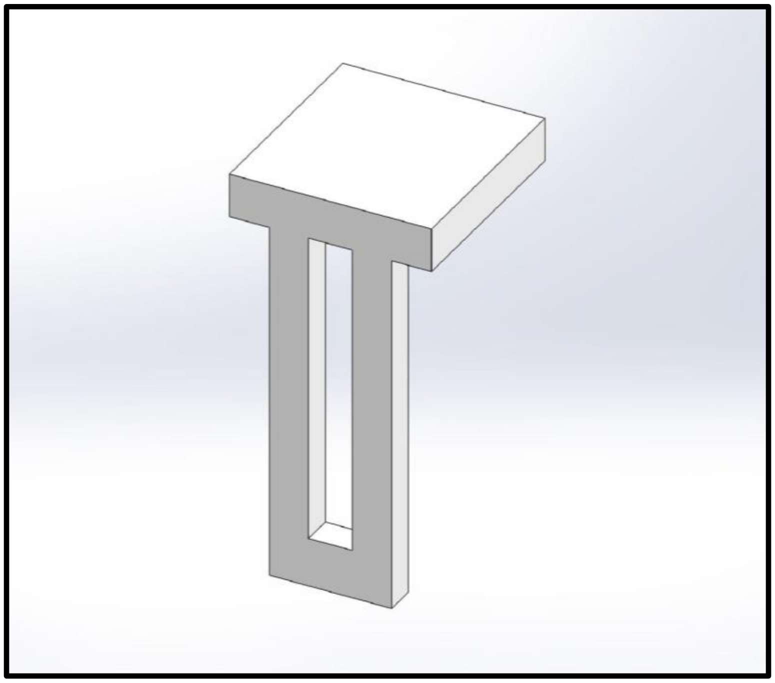


Figure B.25 Stamp Pin Rail Guide Slot

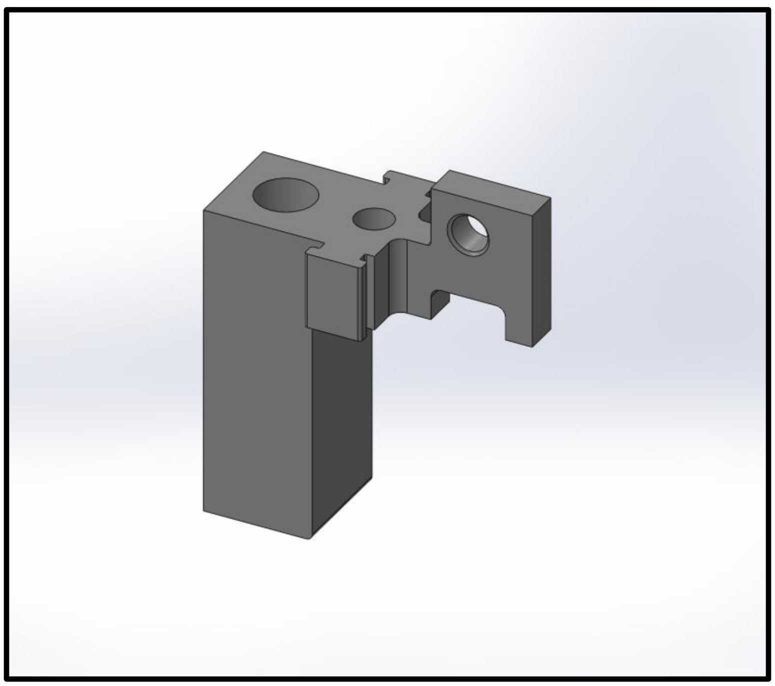


Figure B.26 Stamp Slider

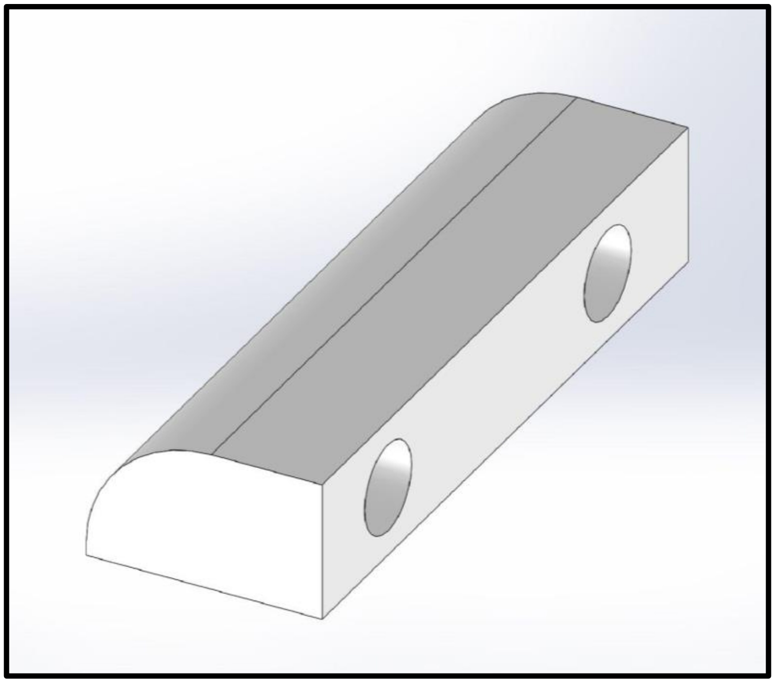


Figure B.27 Sensor Storage Bottom 2

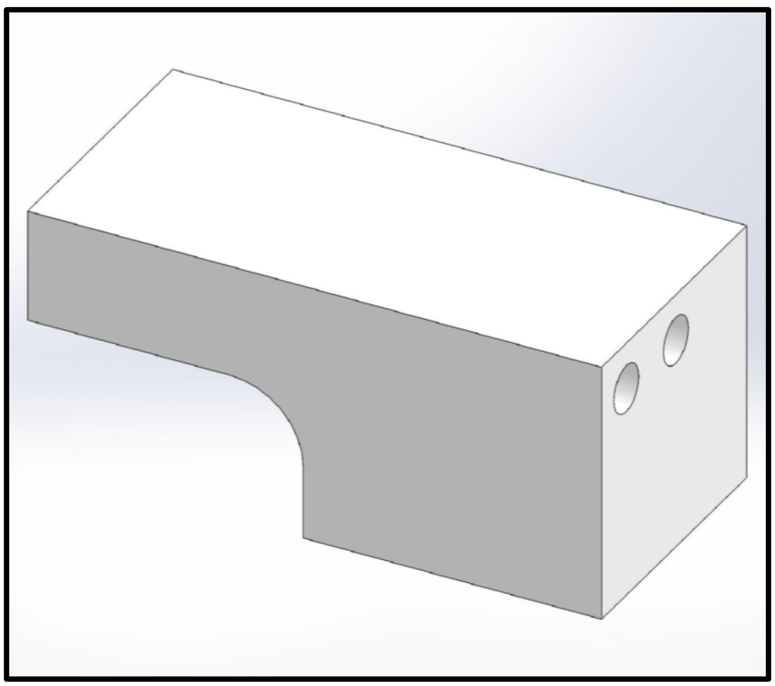


Figure B.28 Cable Top Guide

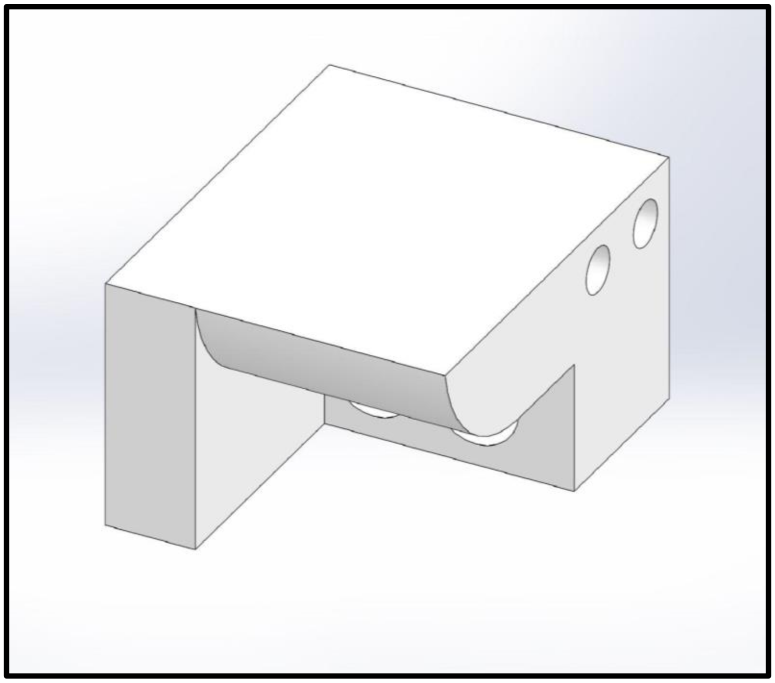


Figure B.29 Bowden Cable Guide

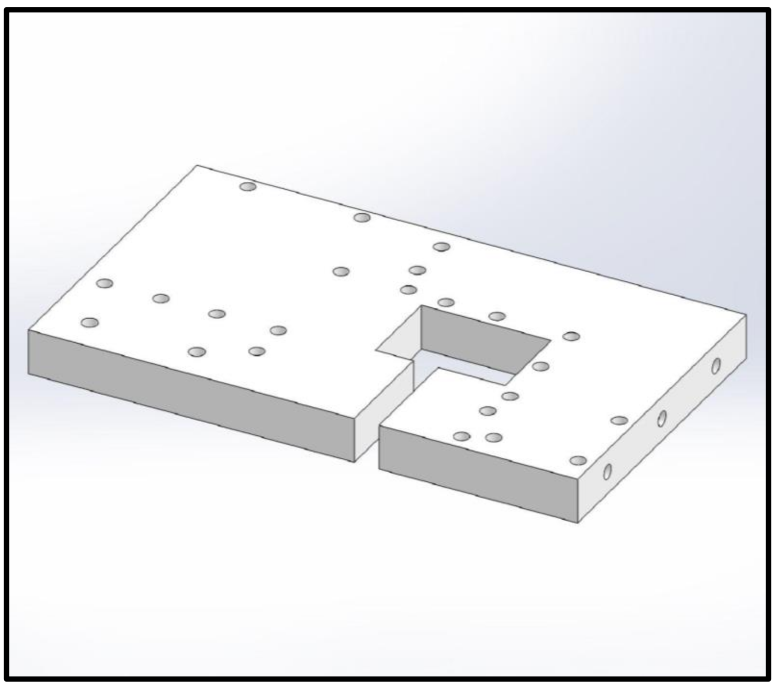


Figure B.30 Mechanism Floor

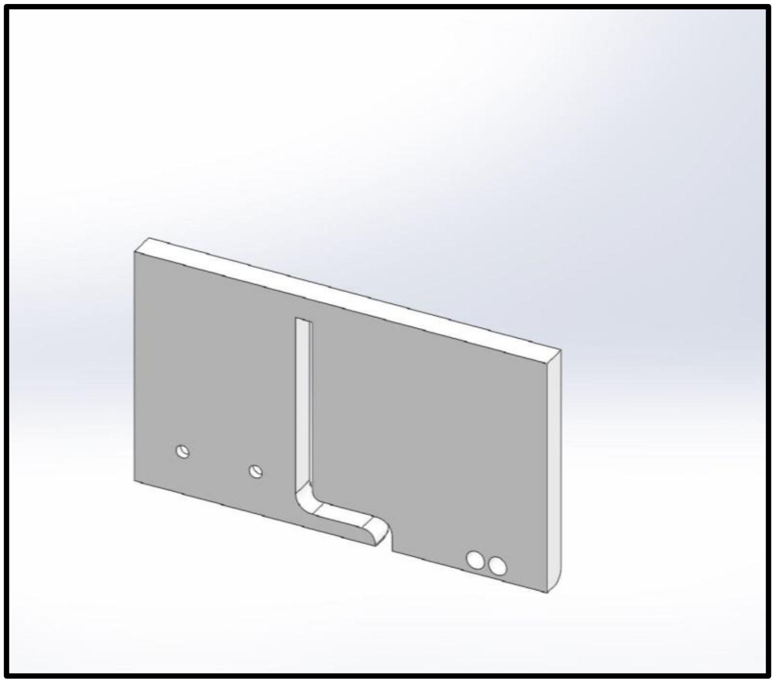


Figure B.31 Housing Front

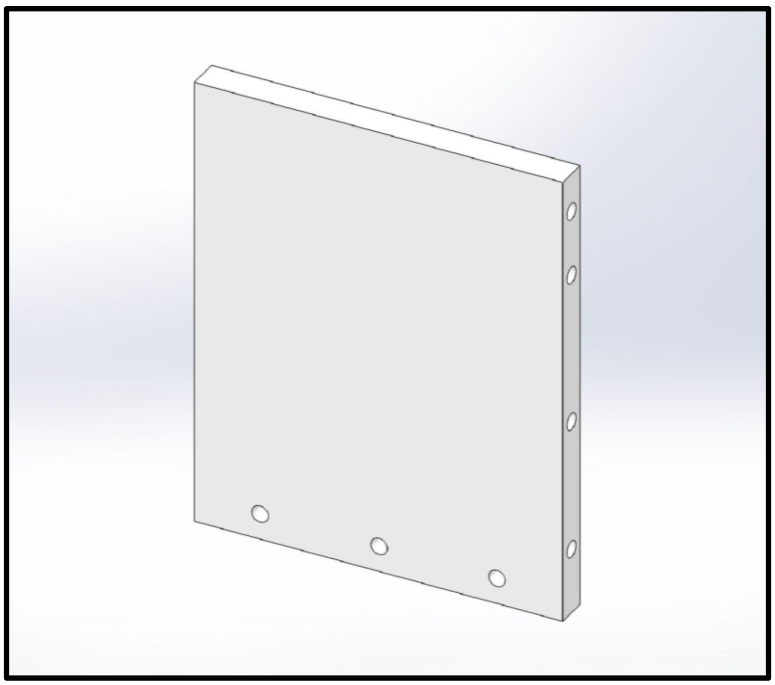


Figure B.32 Housing Left

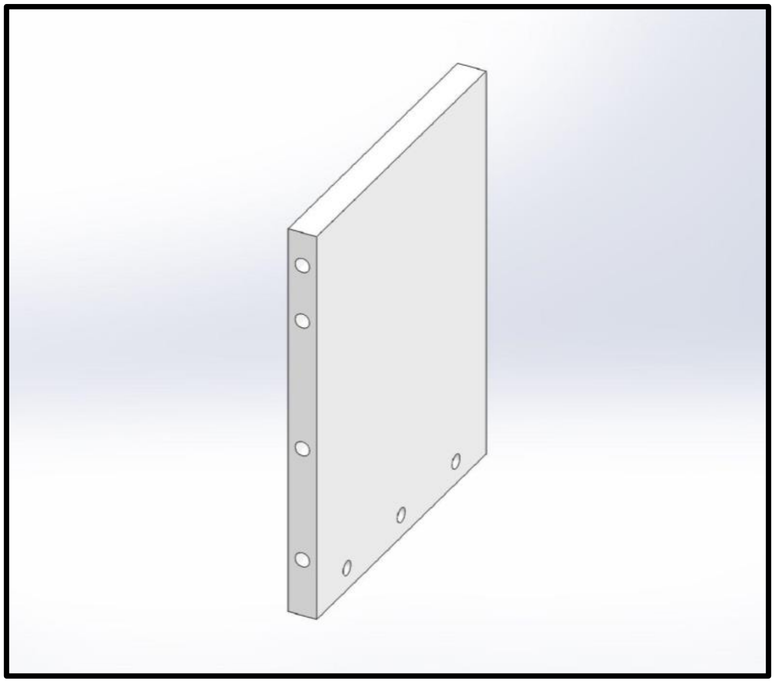


Figure B.33 Housing Right

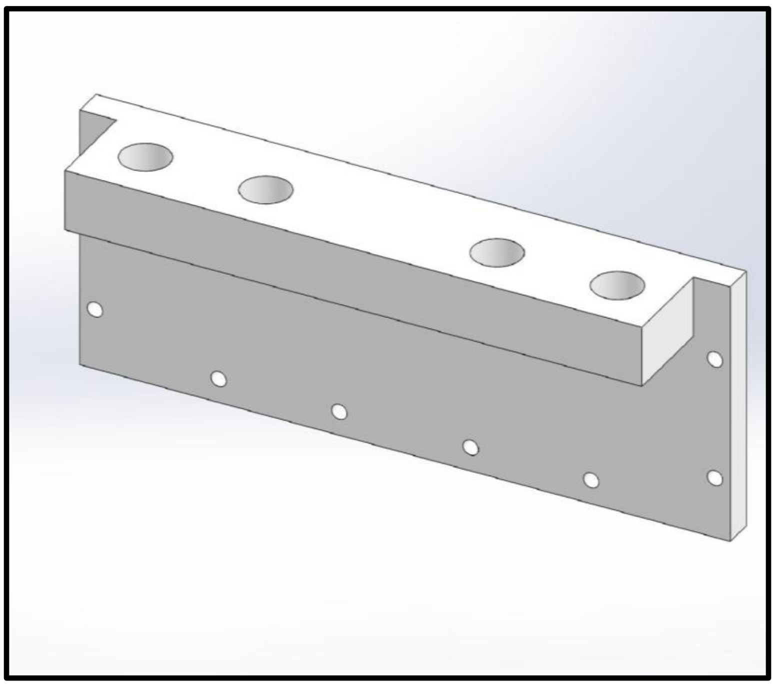


Figure B.34 Housing Connection

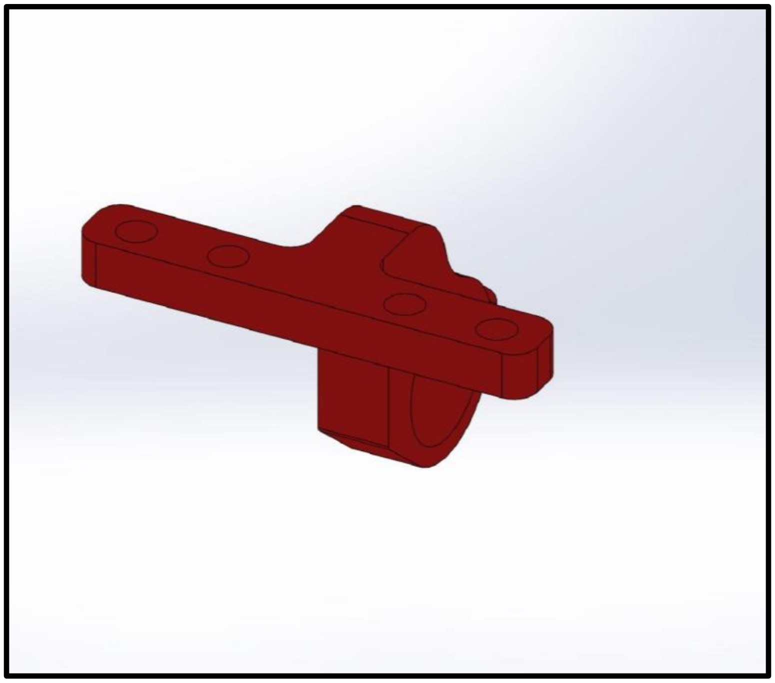


Figure B.35 SDM Carrier

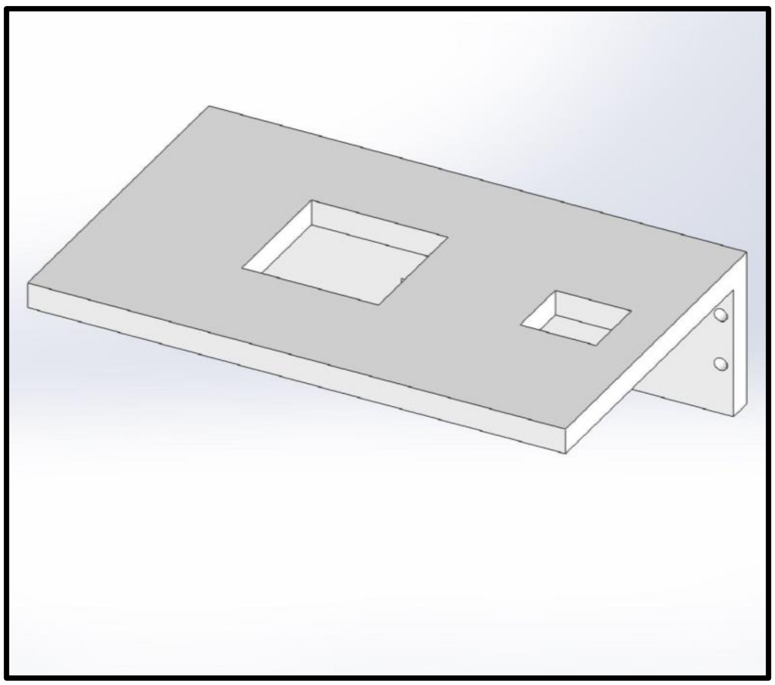


Figure B.36 Housing Top

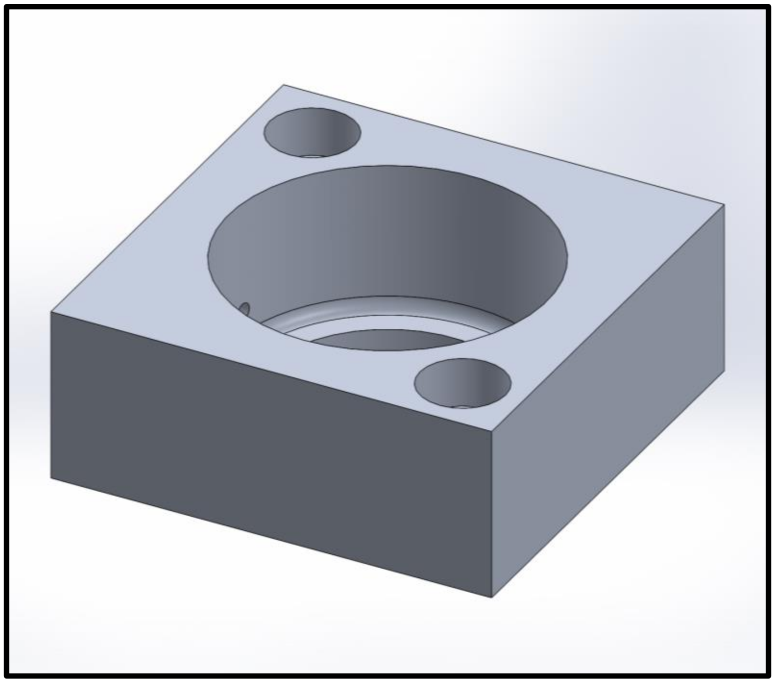


Figure B.37 Sensor Carriage

Table B.1 Parts List

ITEM NO.	PART DESCRIPTION	QTY.
1	Sensor Storage Back	1
2	0.125 in x 0.5 in Dowel	81
3	Sensor Storage Front	1
4	Sensor Storage Bottom 1	1
5	Storage Spring Face	1
6	Storage Spring - 9657K412 Compression Spring	1
7	Storage Cap	1
8	90046A106 High Strength Steel Hex Head Screw	4
9	Sensor Pusher Spring Holder	1
10	Bottom of Sensor Pusher	1

11	Pusher Spring - 9657K48 Compression Spring	1
12	Spring Slider	1
13	Sensor Pusher Guide	1
14	Spring Hinge 1	1
15	Spring Hinge 2	1
16	9271K602 Torsion Spring	1
17	Hinge Pin	2
18	Stamp Spring Holder	1
19	Stamp Pin Rail Guide Back	1
20	Stamp Pin Rail Guide Front	1
21	Stamp Pin Rail Guide Slot	1
22	Stamp Spring - 9657K384 Compression Spring	1
23	Stamp Slider	1
24	Sensor Storage Bottom 2	1
25	Cable Top Guide	1
26	Bowden Cable Guide	1
27	Knob-Operated Push/Pull Bowden Cables - 6161K13	2
28	Carbon Steel Corrosion-Resistant Clevis Rod End - 1583K19	2
29	Mechanism Floor	1
30	Housing Front	1
31	1586A22 Surface-Mount Hinge with Holes	1
32	92210A197 18-8 Flat Head Screw	2
33	92210A193 18-8 Flat Head Screw	2

34	93181A009 Hex Nut	4
35	Housing Left	1
36	Housing Right	1
37	Housing Connection	1
38	SDM Carrier	1
39	Aluminum Hex Nuts, 8-32 - 93181A009	4
40	91268A535 ⅜"-16 Hex Head Screw	4
41	Housing Top	1
42	Sensor Carriage	6
43	Dispensing Gun for Two-Part Cartridge	1
44	Mixer Nozzle for Two-Part Adhesive Cartridges	1
45	Epoxy, Loctite® M-121hp, 1.69 oz. Cartridge	1

Table B.2 Failure Mode & Engineering Analysis

Potential Failure Mode	Potential Failure Effects	Severity	Potential Causes	Occurance Rate	Current Process Controls	Detection	Risk Priority Number
Sensor Carriage becomes stuck	Sensor will not deploy, Deployment device does not work	7	Misalignment of the Sensor Carriage in the shaft	7	Spring applies constant pressure to Sensor Carriage, should cause carraige to remain flush to the shaft	8	392
			Wires attached to the Sensor Carriage become stuck	5	Rounded edges allow for smooth sliding of the wires	8	280
Sensor Stamp cannot reach the surface of the DSC	Sensor Carriage cannot be deployed on the surface of the DSC	6	Deployment Mechanism is not close enough to the surface of the DSC	6	Vehicle robot is as close as possible	7	252
		5	Not enough tension applied against the Stamping Pin to fully deploy Sensor	3	Feedback from the actuation of the bowden cable, it can only be pulled so far	7	105
Wires of sensor become stuck on the Deployment Mechanism	Sensor Carriage cannot move and is stuck in the housing ultimately not allowing for deployment	7	Sensor wires become snagged on a part of the Deployment mechanism	2	Rounded edges allow for smooth sliding of the wires	8	112
Sensor Pusher assembly becomes stuck	Failure to deploy the sensor onto the surface of the DSC, sensors could	8	Spring actuating return motion is not attached properly	2	Secure fastening of spring on pusher mechanism	8	128
		8	Adhesive gets stuck on the surface the pusher slides along, effectively gluing it inplace	5	Proper clearance heights should allow for adhesive to not contact the Sensor Pusher	8	320
Stamp Mechanism cannot detach from sensor	Deployment Mechanism device becomes stuck in one place	9	The Sensor Stamp magnets/vacuum is stronger than the adhesive at the point we want to detach	5	Have an alotted amount of time for adhesive to beomce stronger than the magnet/vacuum before detaching	6	270
	Deployment Mechanism cannot deploy other sensors on other areas of the DSC	8	Sensor Stamp is fully extended, the robot cannot move as a result of it being extended all the way out	4	Spring under the sensor stamp pin pushes the stamp back up to its original position	8	256
Stamp Mechanism cannot be retrieved from extended position	Stamp does not extend straight down, causing stamp to get stuck on sensor carriage	6	Misalignment inside of the Stamp Mechanism between sensor carriage and Stamp	4	Tolerances of mechanism should not allow for this to happen	8	192
	Adhesive is leftover at bottom of stamp and causes sticking	3	Over flow of adhesive onto the Stamp Mechanism causing adhesion	4	A controlled amount of adhesive is applied so this should not be able to happen	5	60
Sensor Deployment Mechanism becomes detached from vehicle	No way to retrieve sensor deployment mechanism from DSC	10	Connection point to robot was not solid or had been loosened throughout use	3	Listed torque requirements, modeled and tested connections. Mandatory pre-Use equipment checks.	7	210
Subsystems of Deployment Mechanism detach from each other	Sensor will not be deployed correctly and sensor or subsystem may fall in DSC	9	Connections between subsystems not rigid or tightly screwed together	2	Subsytems work together to push sensor forward and deploy the sensor	7	126
Bowden Cable detachment from components	Sensor deployment mechanism cannot be activated. Vehicle will need to be removed from DSC to reattach Bowden cable	6	Connections are not rigid and become loose	4	Bowden cables will actuate the the sensor pusher and the sensor stamp	8	192
Bowden Cable breaking	Sensor will not stick fully/at all to DSC surface. Sensors may become stuck together	9	Stress on cable to higher than allowable stress	2	Bowden cables will actuate the the sensor pusher and the sensor stamp	9	162
Improper application of Adhesive	Sensor will not stick fully/at all to DSC surface	8	Human error - adhesive is applied to sensors before deploying vehicle in DSC	2	Adhesive is utilized to adhere the sensor to the DSC wall	6	96
Sensor Stamp Pin breaks	Bowden cable attached to pin will not be able to actuate the sensor pusher and sensor cannot be deployed	9	Pin yields due to too much stress from bowden cable or a weak material is chosen	4	One bowden cable is attached to sensor stamp pin to pull down the sensor stamp	9	324

APPENDIX C. Bill of Materials for Prototype

Table C.1 Bill of Materials for Prototype

Material/Part	Link	Description	Quantity	Price	Total Price ($)
Acryllic - 1/8" Thickness	https://inventionworks.engr.utexas.edu/	24" x 24"	1	$9.77	9.77
Baltic Birch Plywood - 1/8" Thickness	https://inventionworks.engr.utexas.edu/	12" x 20"	1	$1.39	1.39
Baltic Birch Plywood - 1/4" Thickness	https://inventionworks.engr.utexas.edu/	12" x 20"	1	$1.72	1.72
Epoxy, J-B Weld Highheat, 2 oz. Stick	https://www.mcmaster.com/7605A3	Structural Adhesive, Begins to harden in 60 minutes, Temp Rating: -20 to 450 degF	1	$7.97	7.97
Dispensing Gun for Two-Part Cartridge	https://www.mcmaster.com/74695A71/		1	$24.48	24.48
Epoxy, Loctite® M-121hp, 1.69 oz. Cartridge	https://www.mcmaster.com/7370A37/	Structural Adhesive, Begins to harden in 2 hrs, Temp Rating: -65 to 300 degF	1	$29.17	29.17
Mixer Nozzle for Two-Part Adhesive Cartridges	https://www.mcmaster.com/5623N22	Twist Lock Connection, Taper Tip, 0.039" Opening ID, 3" Long	1	$1.31	1.31
Compression Spring (6 pack)	https://www.homedepot.com/p/Everbilt-Zinc-Plated-Compression-Spring-6-Pack-16087/202045468?MERCH=REC-_-pip_alternatives-_-203133714-_-202045468-_-N	3 different sized compression springs (2 each), zinc-plated	1	$4.32	4.32
Total					**$80.13**

APPENDIX D. Bill of Materials for Production

Table D.1 Bill of Materials for Production

Material/Part	Part Number	Link	Quantity	#/Package	Price/Package ($)	Total Price ($)
9271K602 Hinge Torsion Spring	16	https://www.mcmaster.com/9271K602/	1	6	$5.01	$0.84
Carbon Steel Corrosion-Resistant Clevis Rod End - 1583K19	28	https://www.mcmaster.com/1583K19/	2	1	$31.38	$62.76
1/8” x 1/2" PEEK Dowels	2	https://www.mcmaster.com/dowel-pins/material~aluminum/material~plastic/	70	10	$10.57	$73.99
Stamp Spring - 9657K384 Compression Spring	22	https://www.mcmaster.com/9657K384/	1	6	$7.26	$1.21
Pusher Spring - 9657K48 Compression Spring	11	https://www.mcmaster.com/9657K48/	1	12	$8.02	$0.67
Storage Spring - 9657K412 Compression Spring	6	https://www.mcmaster.com/9657K412/	1	6	$7.49	$1.25
90046A106 High Strength Steel Hex Head Screw	8	https://www.mcmaster.com/90046A106/	4	1	$5.23	$20.92
18-8 Stainless Steel Hex Drive Flat Head Screw, 3/4" Long	32	https://www.mcmaster.com/92210A197/	2	100	$11.50	$0.23
18-8 Stainless Steel Hex Drive Flat Head Screw, 7/16" Long	33	https://www.mcmaster.com/92210A193/	2	100	$8.61	$0.17
Aluminum Hex Nuts, 8-32 - 93181A009	39	https://www.mcmaster.com/93181A009/	4	100	$5.94	$0.24
1586A22 Surface-Mount Hinge with Holes	31	https://www.mcmaster.com/1586A22/	1	1	$9.57	$9.57
91268A535 ⅜”-16 Hex Head Screw	40	https://www.mcmaster.com/91268A535/	1	5	$8.84	$1.77
Knob-Operated Push/Pull Control Cable - 6161K13	27	https://www.mcmaster.com/6161K13/	2	1	$72.98	$145.96
Dispensing Gun for Two-Part Cartridge	43	https://www.mcmaster.com/74695A71/	1	1	$24.48	$24.48
Mixer Nozzle for Two-Part Adhesive Cartridges	44	https://www.mcmaster.com/74695A967/	1	1	$1.49	$1.49
Epoxy, Loctite® M-121hp, 1.69 oz. Cartridge	45	https://www.mcmaster.com/7370A37/	1	1	$29.17	$29.17
Multipurpose 4140 Alloy Steel Bar - 2-1/4" x 2-1/4" x 1/2'	23	https://www.mcmaster.com/4140/multipurpose-4140-alloy-steel-bars/	1	1	$88.07	$88.07
Multipurpose 6061 Aluminum Bar - 25 mm x 50 mm x 6 ft.	9,10,12,13,17,18,42	https://www.mcmaster.com/9146T84-9146T846/	1	1	$143.00	$143.00
High-Temperature 3D Printer PEI Plastic Filament	1,3,4,5,7,14,15,19,20,21, 24,25,26,29,35,36,37,38, 41	https://www.mcmaster.com/pei/shape~wire/	1.44 (lbs)	1.1 (lbs)	$112.57	$147.36
Total						**$753.14**

APPENDIX E. Manufacturing Cost Analysis

Table E.1 Manufacturing Cost Analysis

Part Name	Material	Density (lbs/in^3)	Volume (in^3)	Mass (lbs)	Manufacturing Method	Manufacturing & Material Cost / Unit	Cost / Unit (50 Units)	Manufacturing Cost (50 Units)
Sensor Storage Back	PEI	0.045	1.21	0.05445	3D Printing	$65.70	$49.61	$2,480.50
Cable Top Guide	PEI	0.045	0.56	0.0252	3D Printing	$36.67	$25.16	$1,258.00
Sensor Storage Bottom 2	PEI	0.045	0.05	0.00225	3D Printing	$11.24	$11.27	$563.50
Sensor Storage Bottom	PEI	0.045	0.43	0.01935	3D Printing	$34.19	$23.13	$1,156.50
Sensor Storage Front	PEI	0.045	1.63	0.07335	3D Printing	$88.50	$88.50	$4,425.00
Stamp Pin Rail Guide Back	PEI	0.045	0.72	0.0324	3D Printing	$40.49	28.3	$1,415.00
Stamp Pin Rail Guide Front	PEI	0.045	0.65	0.02925	3D Printing	$37.75	$26.04	$1,302.00
Storage Spring Face	PEI	0.045	0.11	0.00495	3D Printing	$12.67	$11.27	$563.50
Sensor Housing Cap	PEI	0.045	0.82	0.0369	3D Printing	$55.63	$40.95	$2,047.50
Housing Left	PEI	0.045	2.39	0.10755	3D Printing	$72.39	$55.40	$2,770.00
Housing Right	PEI	0.045	2.39	0.10755	3D Printing	$59.32	44.11	$2,205.50
Housing Front	PEI	0.045	4.99	0.22455	3D Printing	$98.86	$78.89	$3,944.50
Housing Connection	PEI	0.045	4.47	0.20115	3D Printing	$146.96	$122.11	$6,105.50
Housing Top	PEI	0.045	5.45	0.24525	3D Printing	$163.46	$137.28	$6,864.00
Bowden Cable Guide	PEI	0.045	0.52	0.0234	3D Printing	$37.91	$26.17	$1,308.50
Spring Hinge 2	PEI	0.045	0.06	0.0027	3D Printing	$12.69	$11.27	$563.50
Spring Hinge 1	PEI	0.045	0.04	0.0018	3D Printing	$8.46	$8.46	$423.00
Stamp Pin Rail Guide Slot	PEI	0.045	0.7	0.0315	3D Printing	$56.42	$41.64	$2,082.00
Mechanism Floor	PEI	0.045	4.79	0.21555	3D Printing	$118.70	$96.51	$4,825.50
Bottom of Sensor Pusher	6061 Aluminum-T6	0.1	0.3	0.03	Machining	$165.13	$17.00	$850.00
6x Sensor Carriages	6061 Aluminum-T6	0.1	0.48	0.048	Machining	$228.54	$26.22	$1,311.00
Hinge Pin	6061 Aluminum-T6	0.1	0.02	0.002	Machining	$109.66	$5.71	$285.50
Sensor Pusher Guide	6061 Aluminum-T6	0.1	0.31	0.031	Machining	$192.82	$19.23	$961.50
Spring Slider	6061 Aluminum-T6	0.1	0.23	0.023	Machining	$308.30	$29.51	$1,475.50
Sensor Pusher Spring Holde	6061 Aluminum-T6	0.1	0.16	0.016	Machining	$166.71	$13.86	$693.00
Stamp Spring Holder	6061 Aluminum-T6	0.1	0.34	0.034	Machining	$169.18	$16.53	$826.50
Stamp Slider	AISI 4140 Steel	0.284	1.52	0.43168	Machining	$398.10	$50.28	$2,514.00
70x Dowels	PEEK	0.05	0.7	0.035	Purchased	$73.99	$73.99	$3,699.50
2x Clevis Rod Hangers	Plain Carbon Steel	0.28	0.3	0.084	Purchased	$31.38	$31.38	$1,569.00
Surface Mount Hinge	AISI 304	0.31	0.13	0.04	Purchased	$5.01	$5.01	$250.50
Total:				2.21378		$3,006.83	$1,214.79	$60,739.50

APPENDIX F. Assembly Instructions

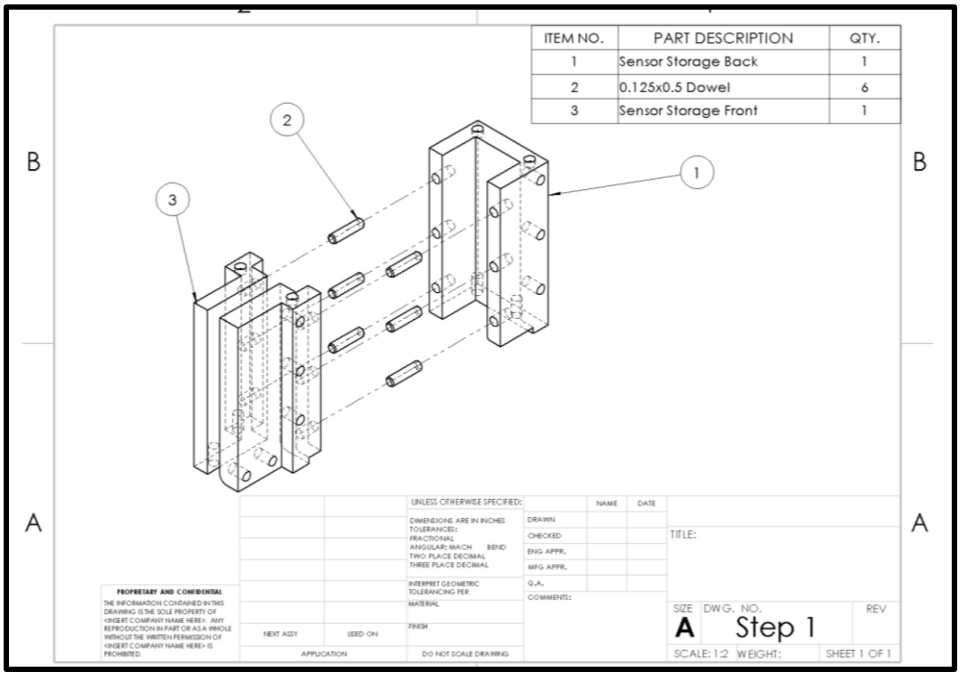


Figure F.1 Step 1

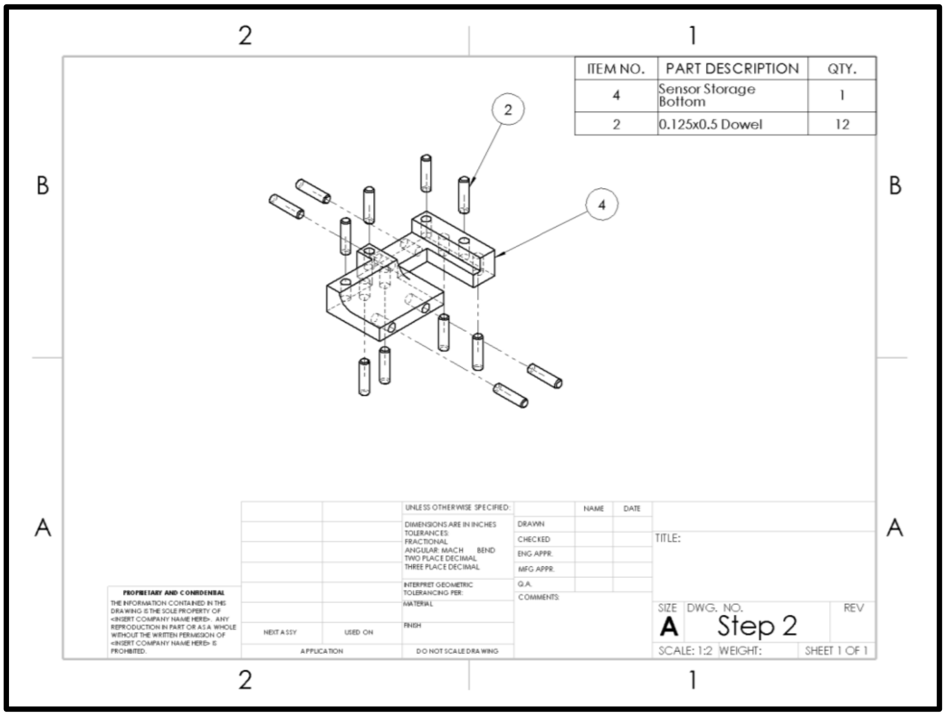


Figure F.2 Step 2

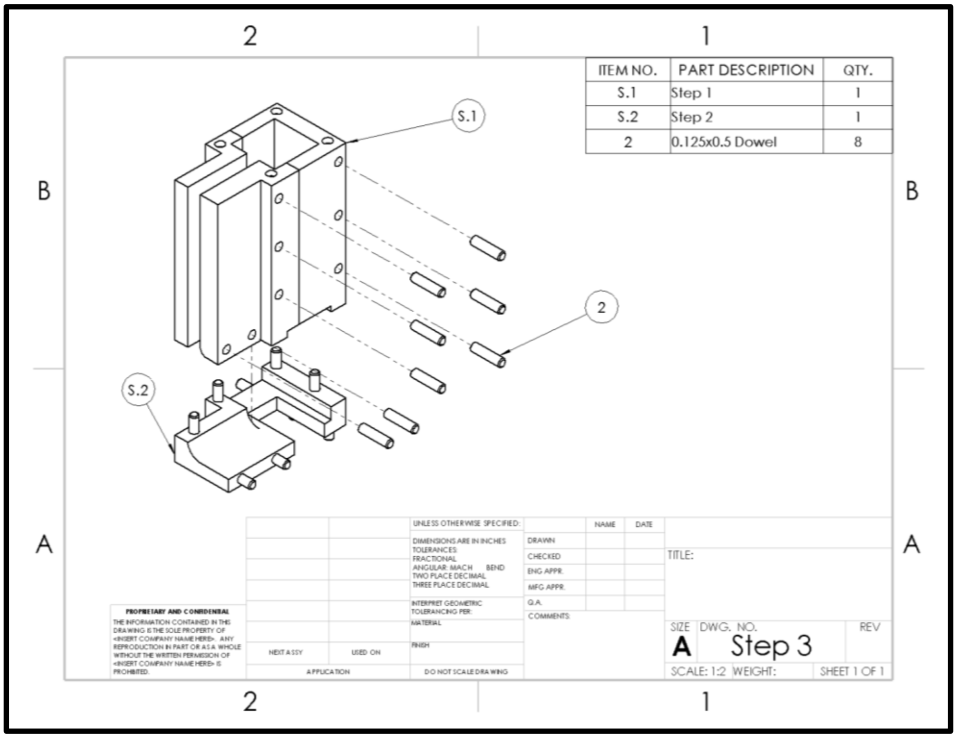


Figure F.3 Step 3

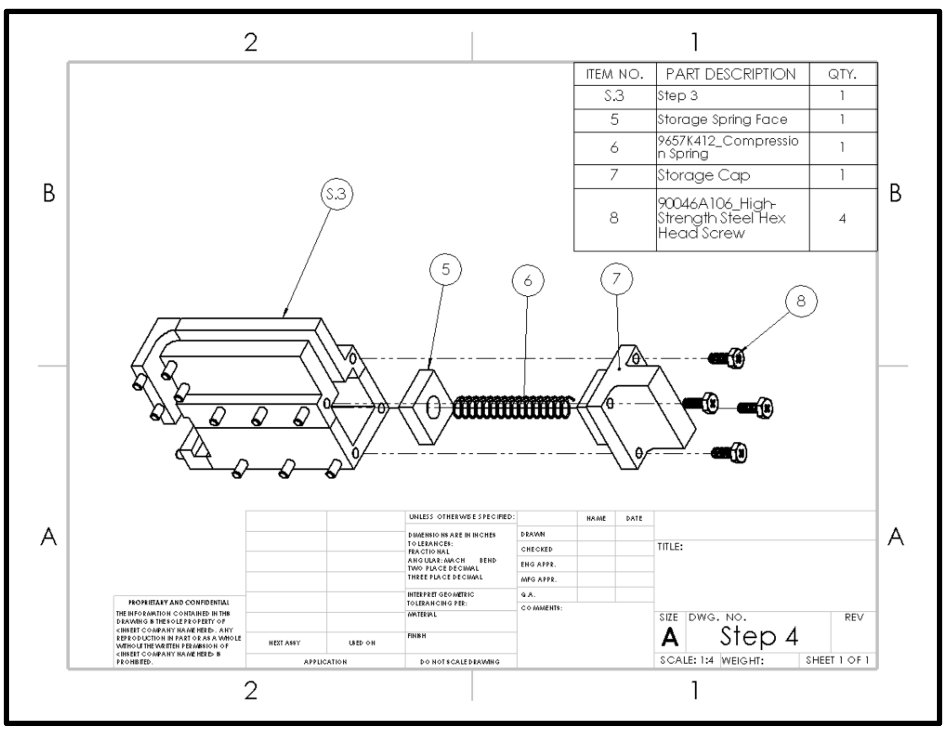


Figure F.4 Step 4

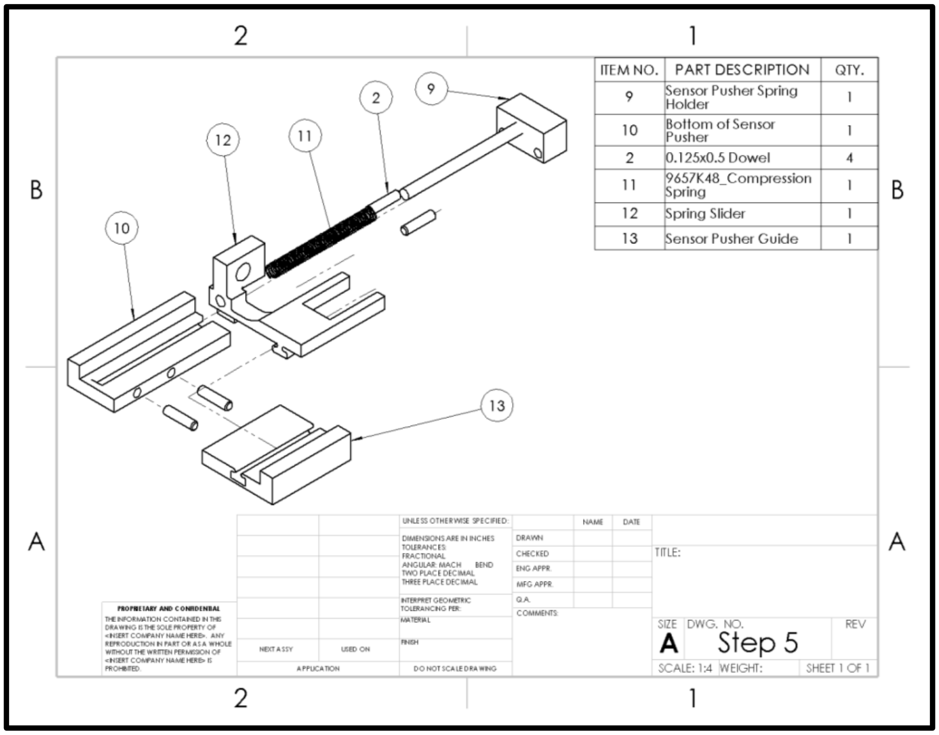


Figure F.5 Step 5

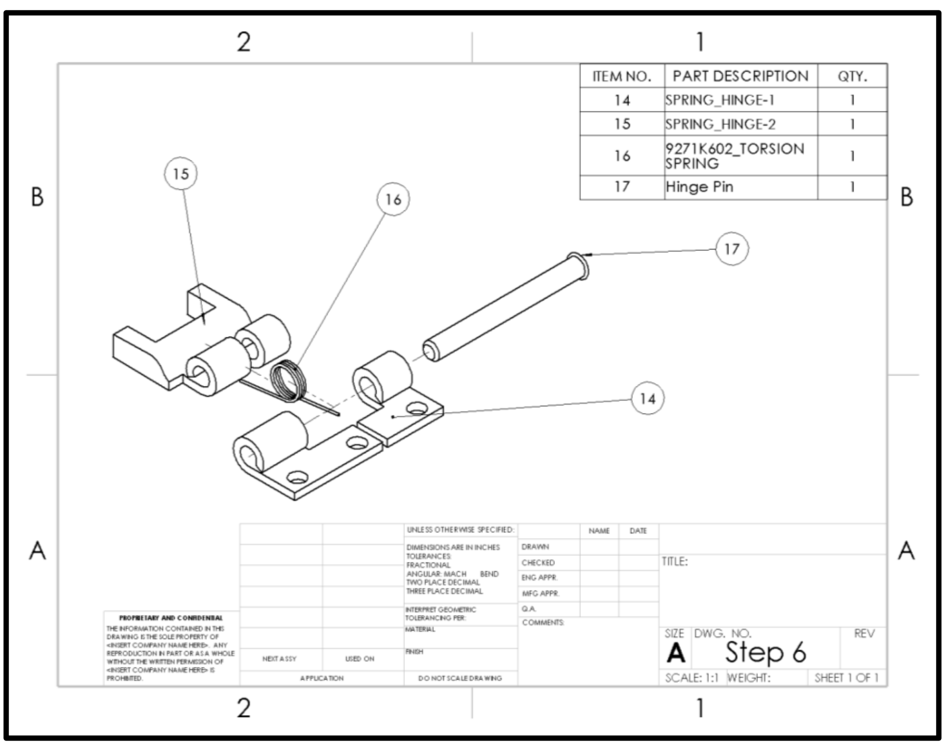


Figure F.6 Step 6

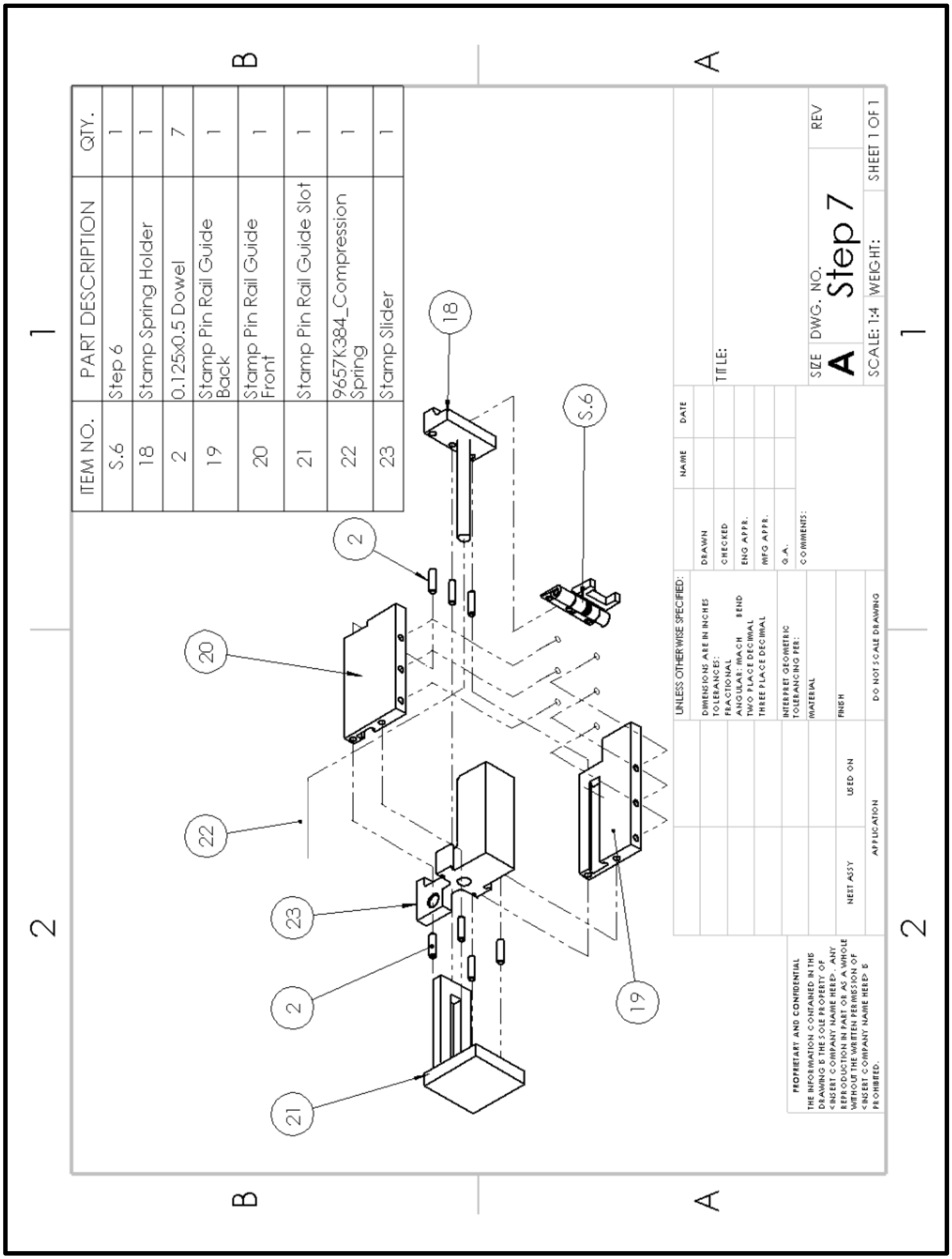


Figure F.7 Step 7

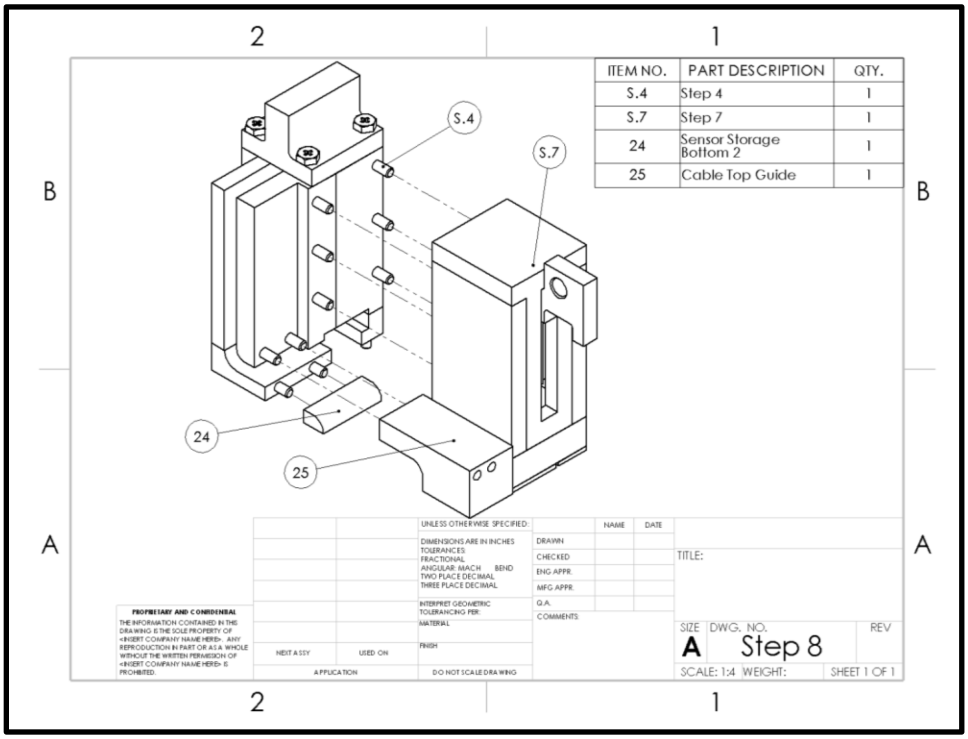


Figure F.8 Step 8

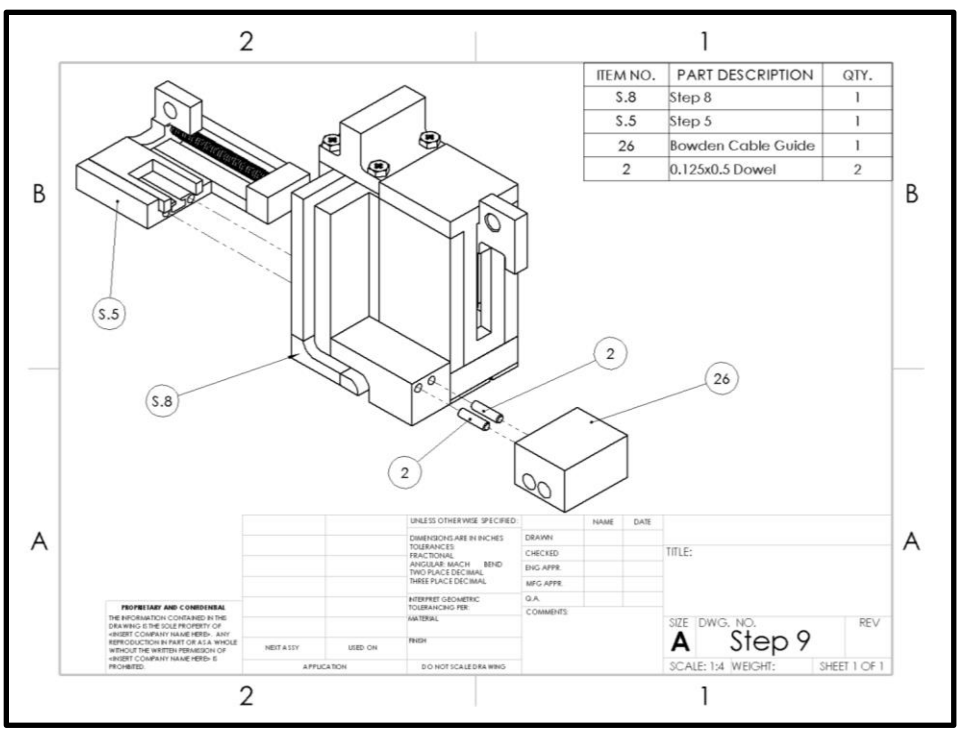


Figure F.9 Step 9

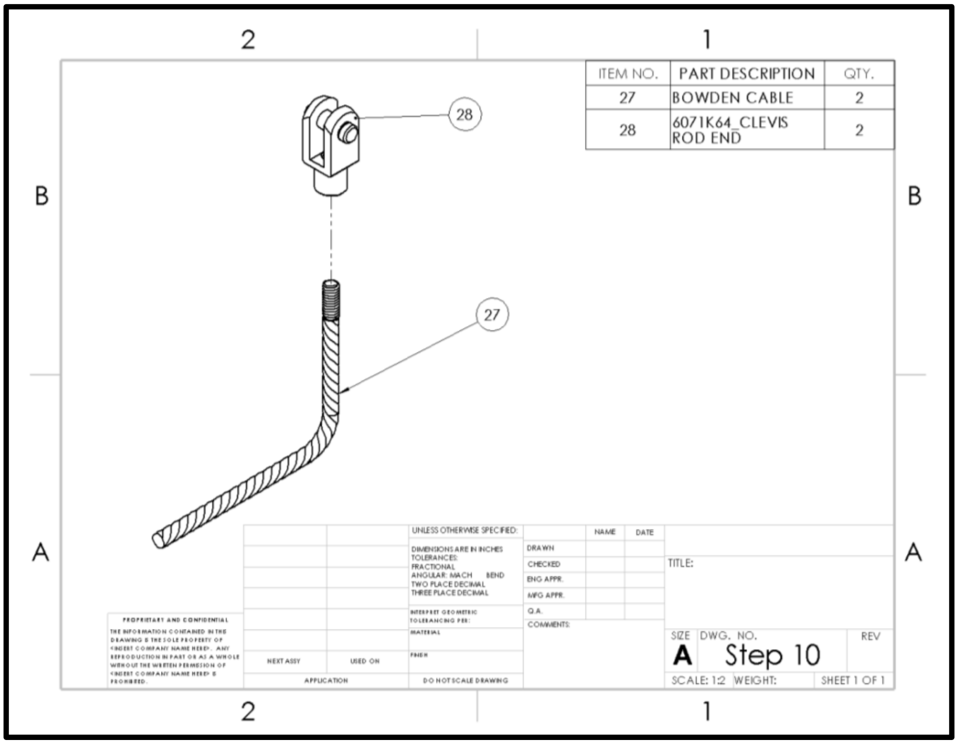


Figure F.10 Step 10

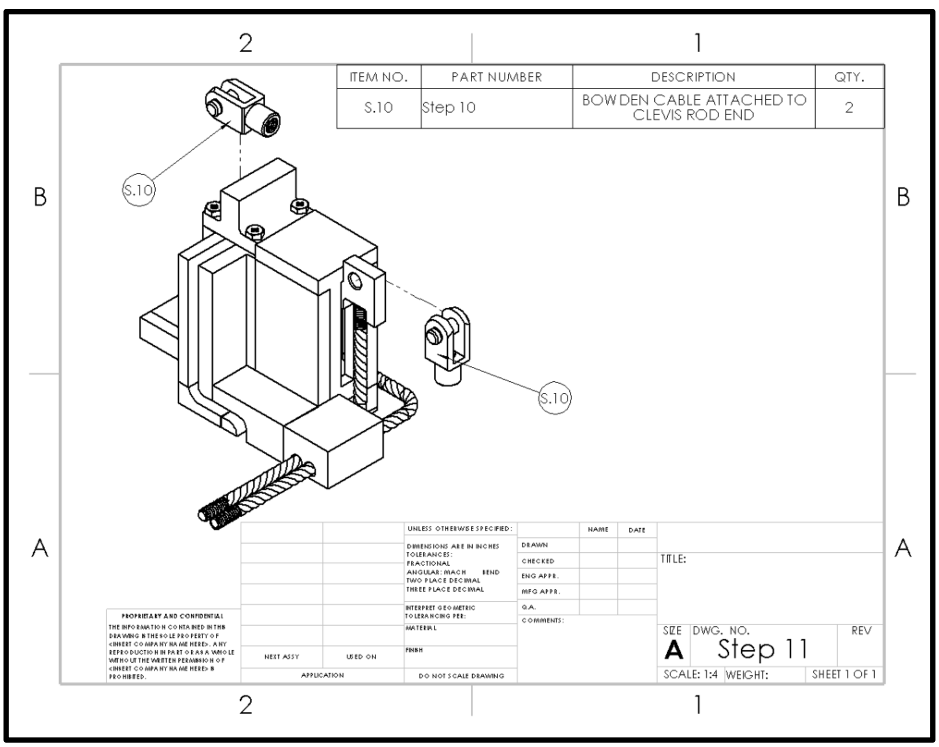


Figure F.11 Step 11

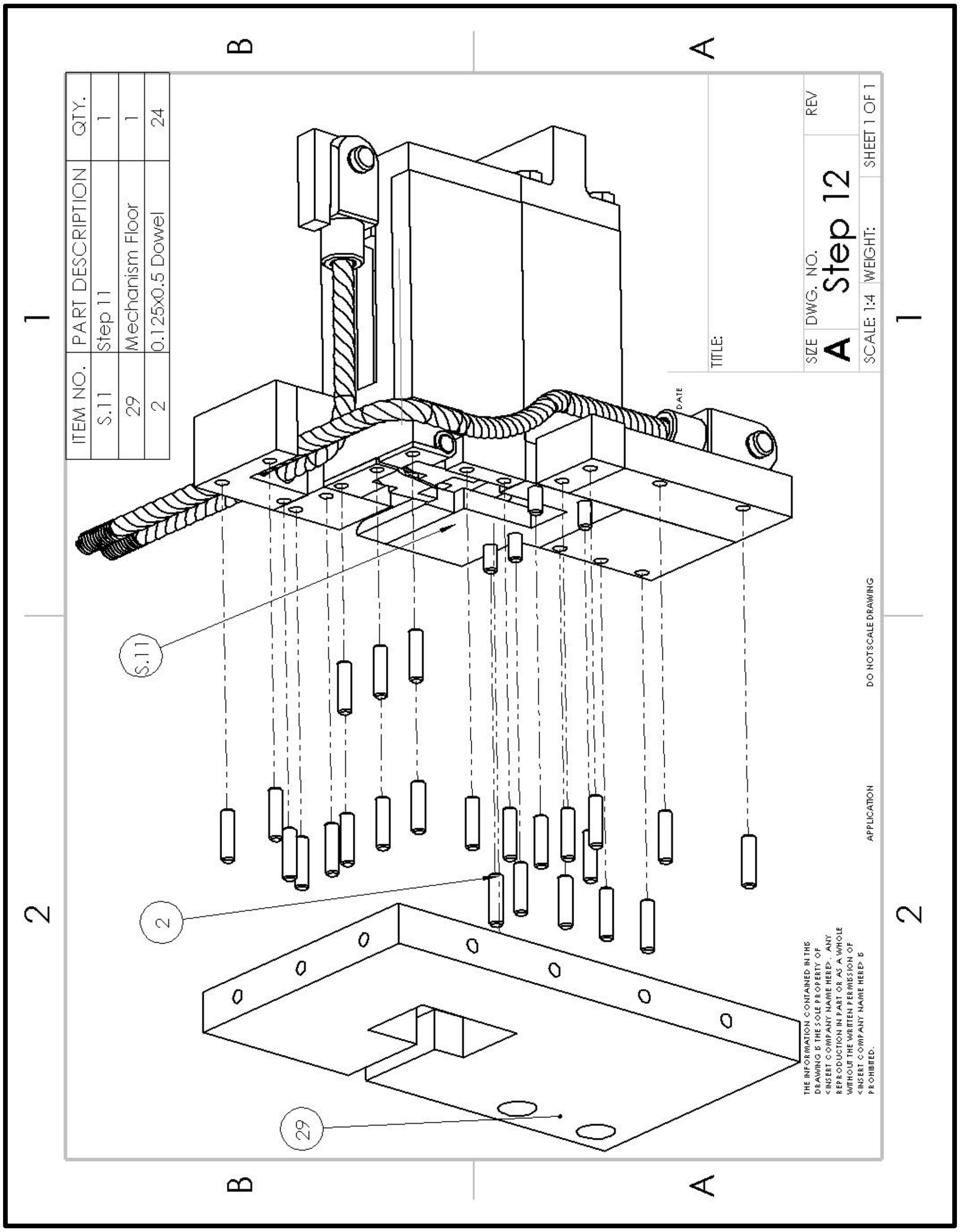


Figure F.12 Step 12

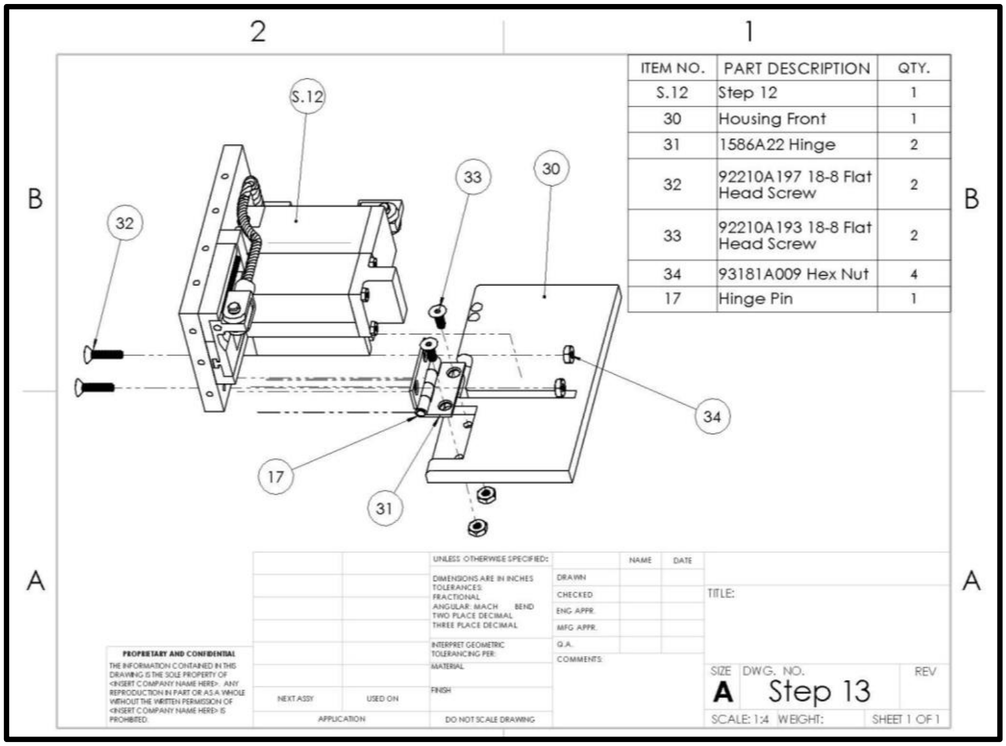


Figure F.13 Step 13

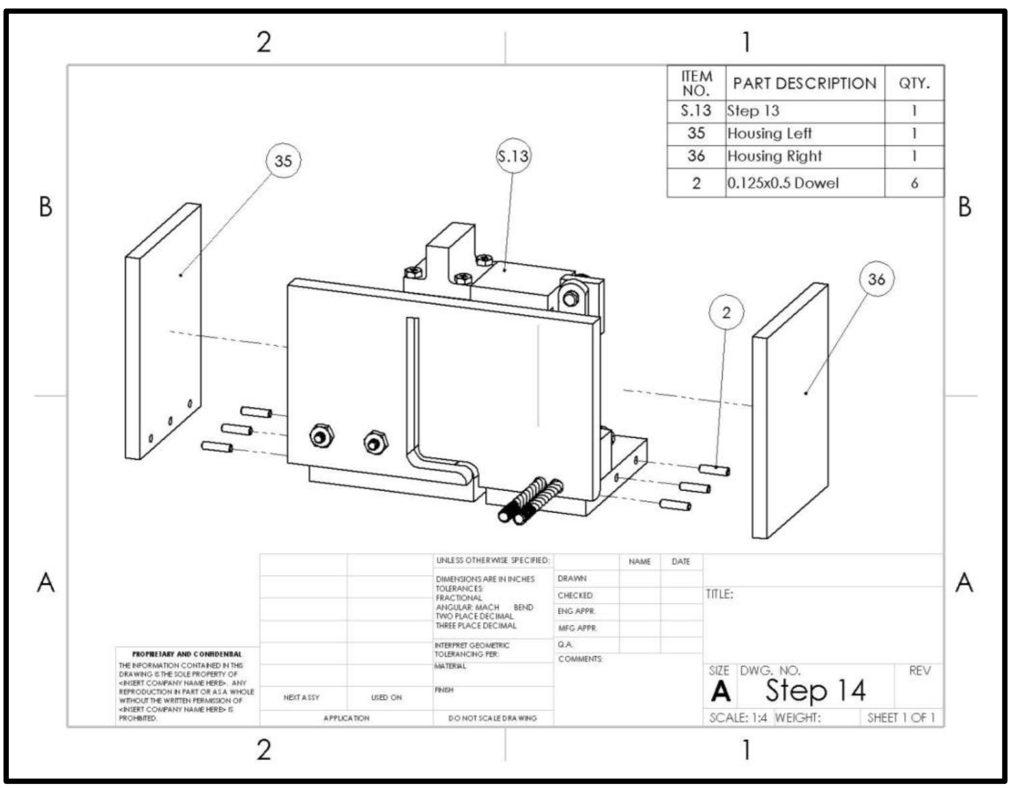


Figure F.14 Step 14

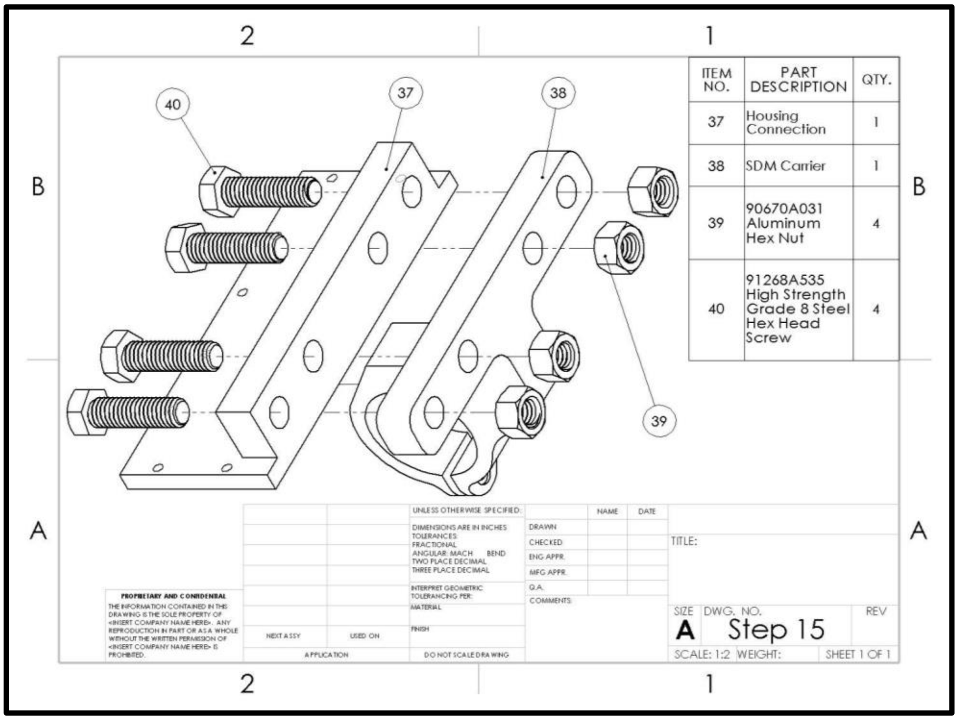


Figure F.15 Step 15

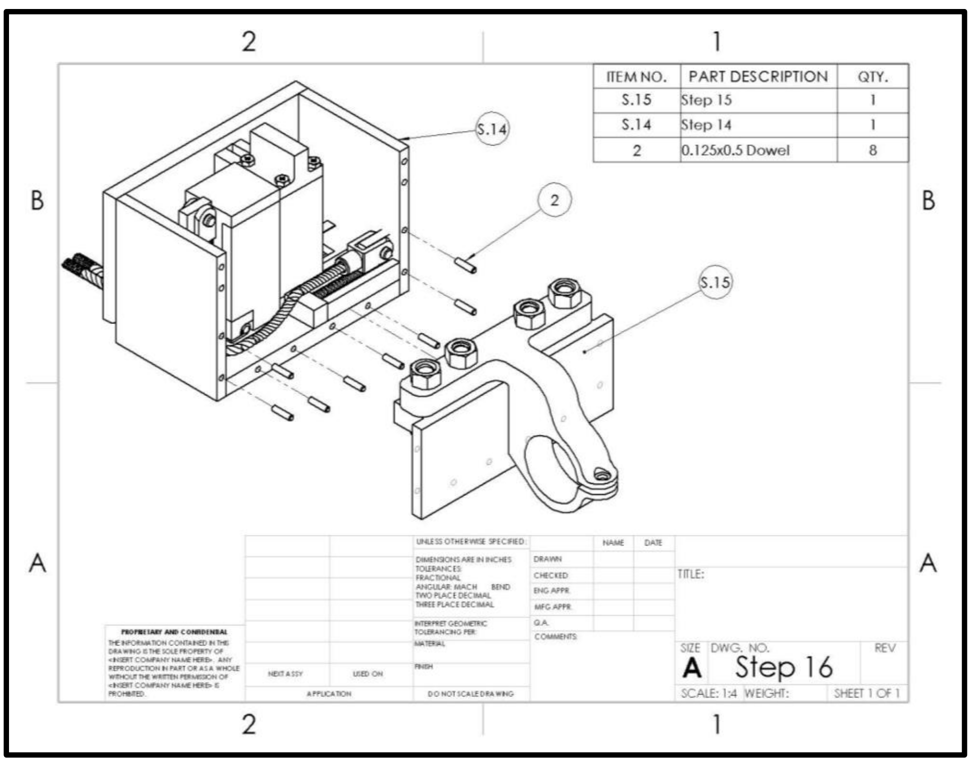


Figure F.16 Step 16

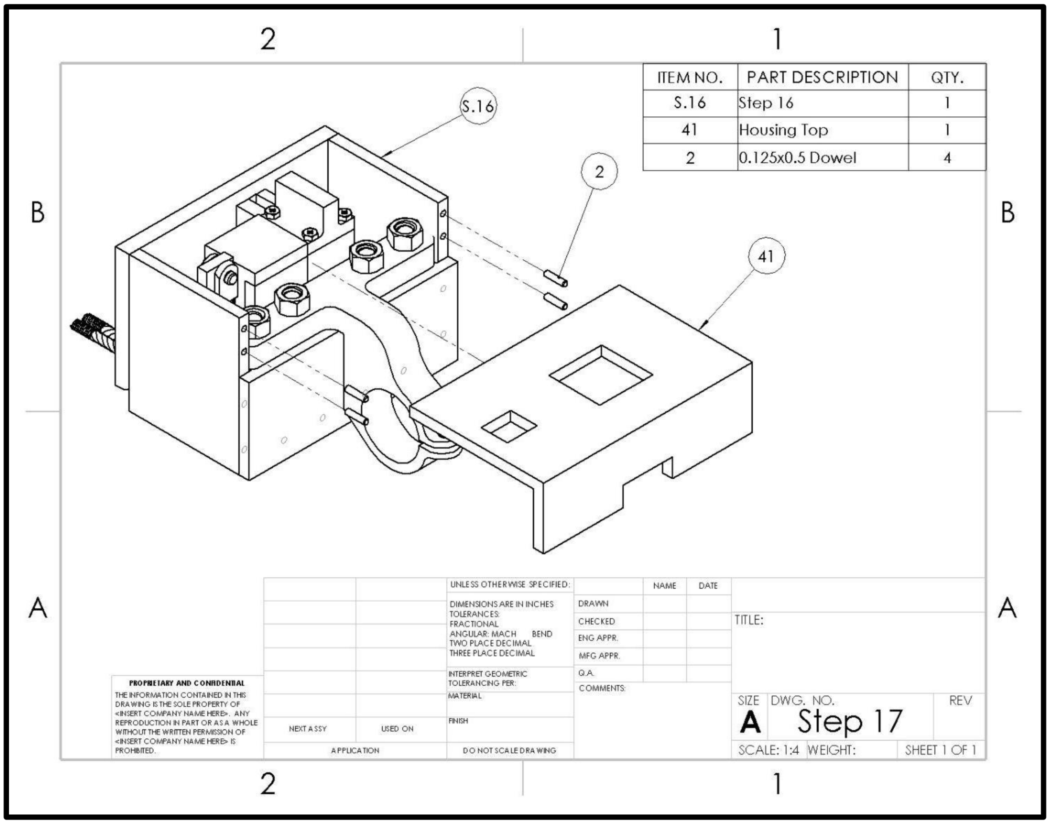
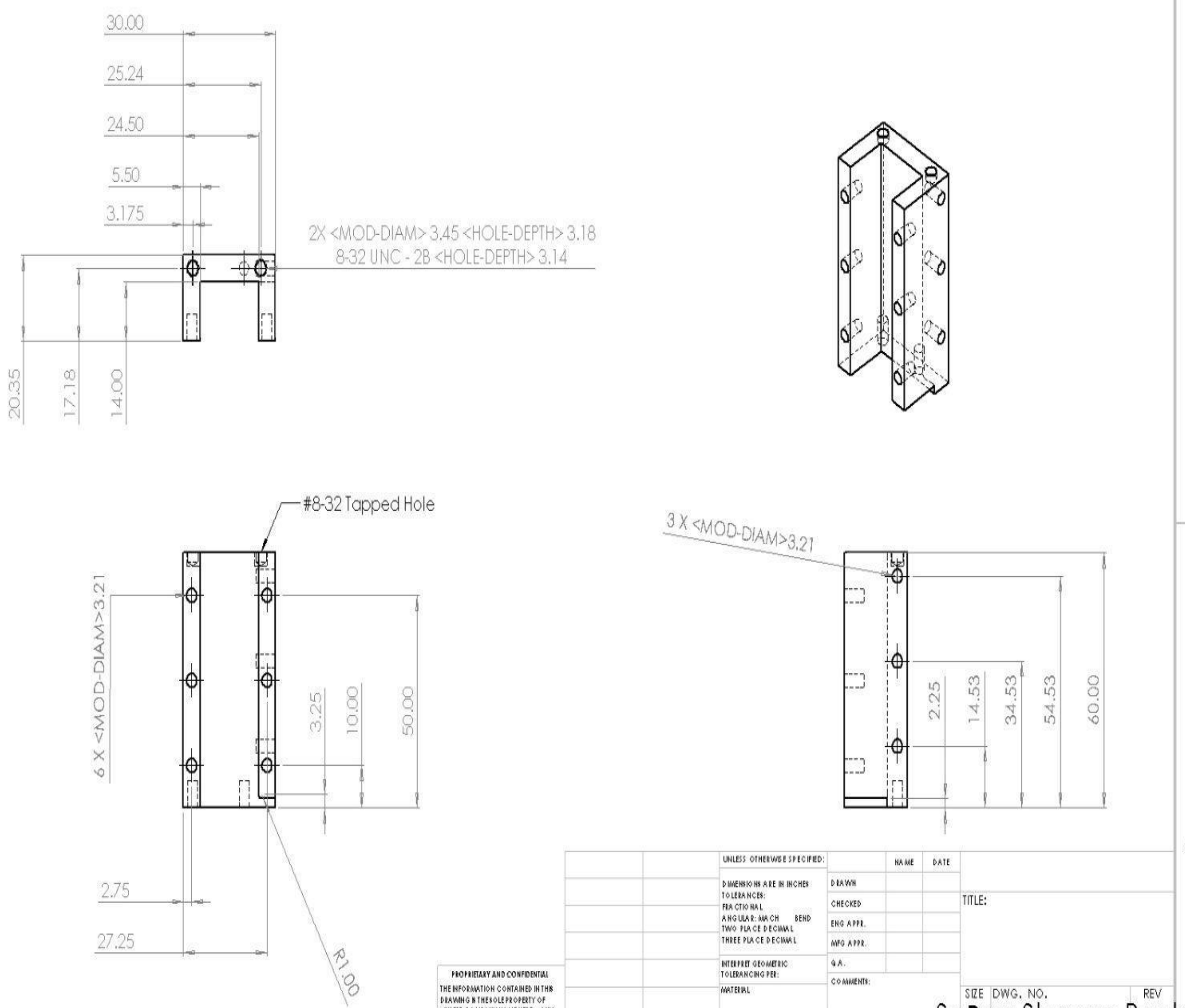


Figure F.17 Step 17



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ANGULAR: MACH BEND TWO PLACE DECIMAL THREE PLACE DECIMAL	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

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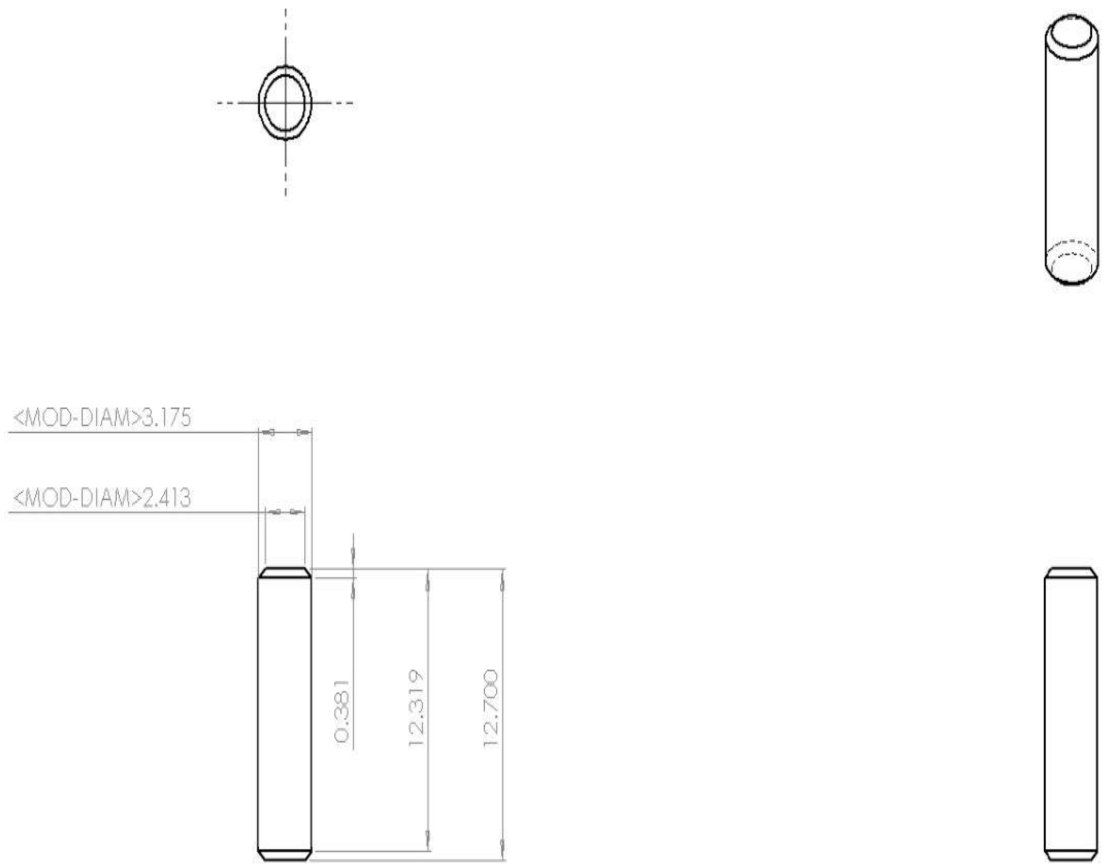
TITLE:

SIZE DWG. NO. REV

Sensor Storage Back

SCALE: 1:1 WEIGHT: SHEET 1 OF 1



PROPRIETARY AND CONFIDENTIAL

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL
ANGULAR: MACH BEND
TWO PLACE DECIMAL
THREE PLACE DECIMAL

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

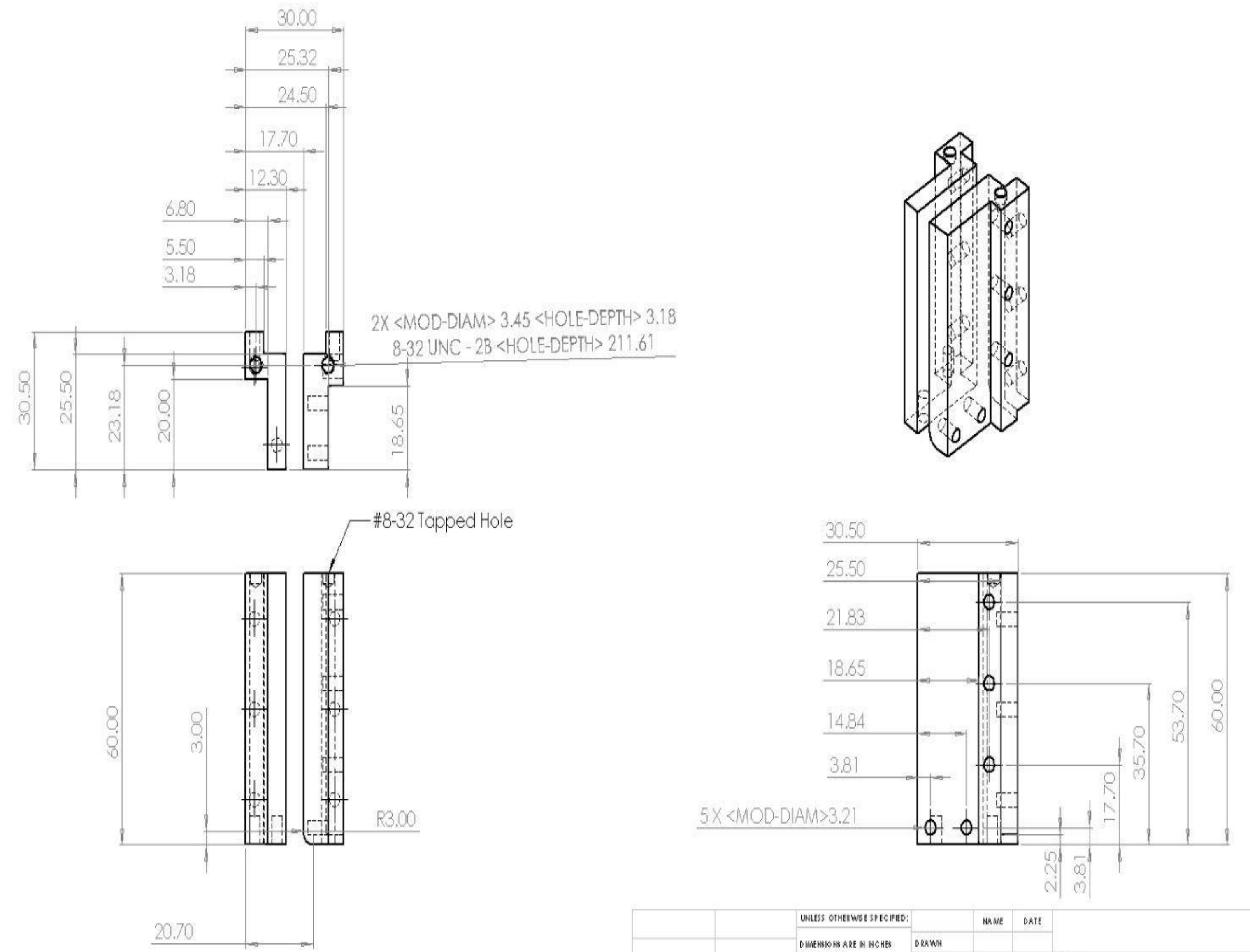
DO NOT SCALE DRAWING

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

TITLE:

SIZE	DWG. NO.	REV
B	0.125x0.5 Dowel	

SCALE: 4:1 WEIGHT: SHEET 1 OF 1



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		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ANGULAR: MACH BEND TWO PLACE DECIMAL THREE PLACE DECIMAL	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

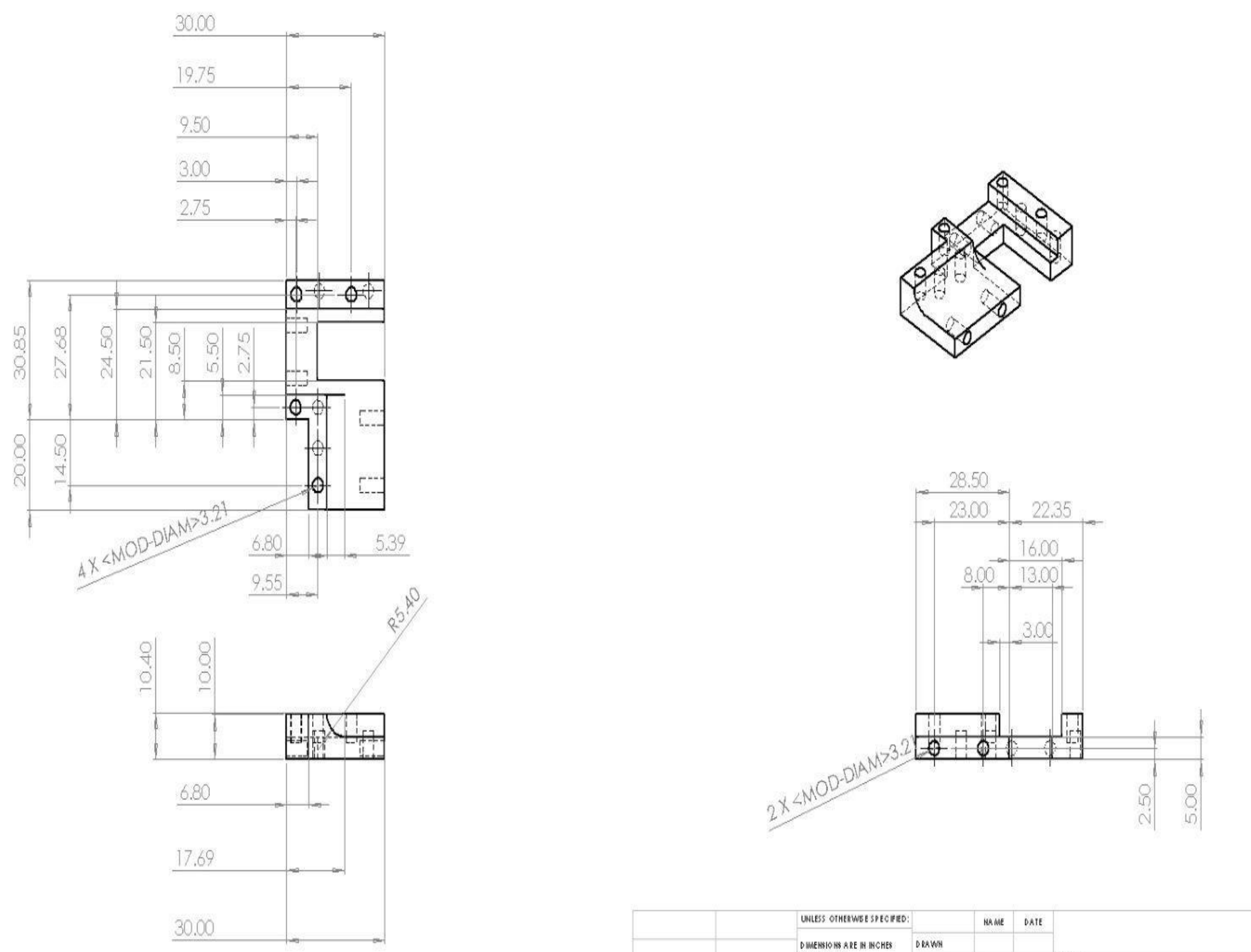
TITLE:

SIZE DWG. NO. REV

B

Sensor Storage Front

SCALE: 1:1 WEIGHT: SHEET 1 OF 1



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			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

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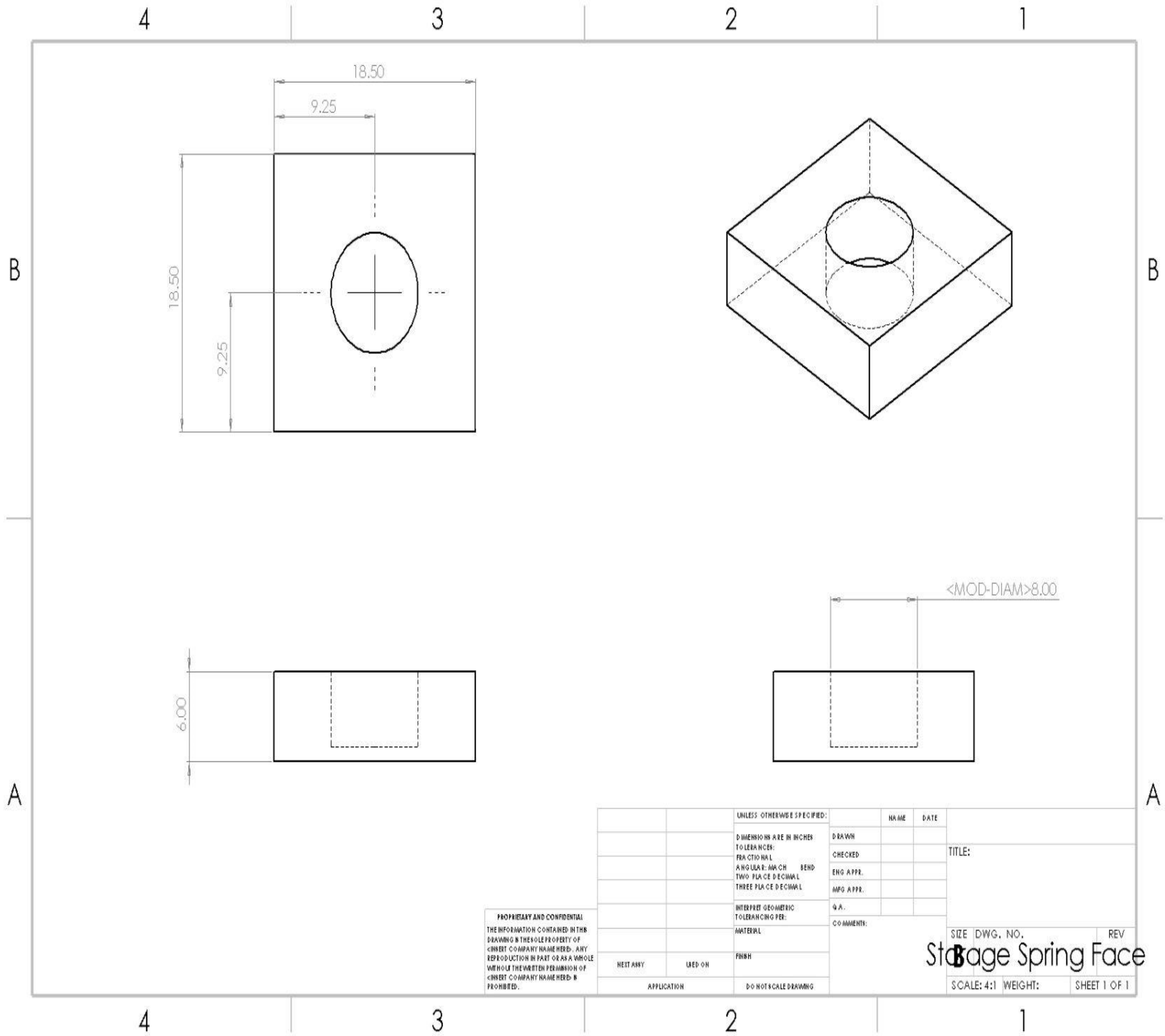
TITLE:

SIZE B DWG. NO. REV

Sensor Storage Bottom

SCALE: 1:1 WEIGHT: SHEET 1 OF 1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18.50
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UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
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ANGULAR: MACH BEND
TWO PLACE DECIMAL
THREE PLACE DECIMAL
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
B
DWG. NO.
REV
Storage Spring Face
SCALE: 4:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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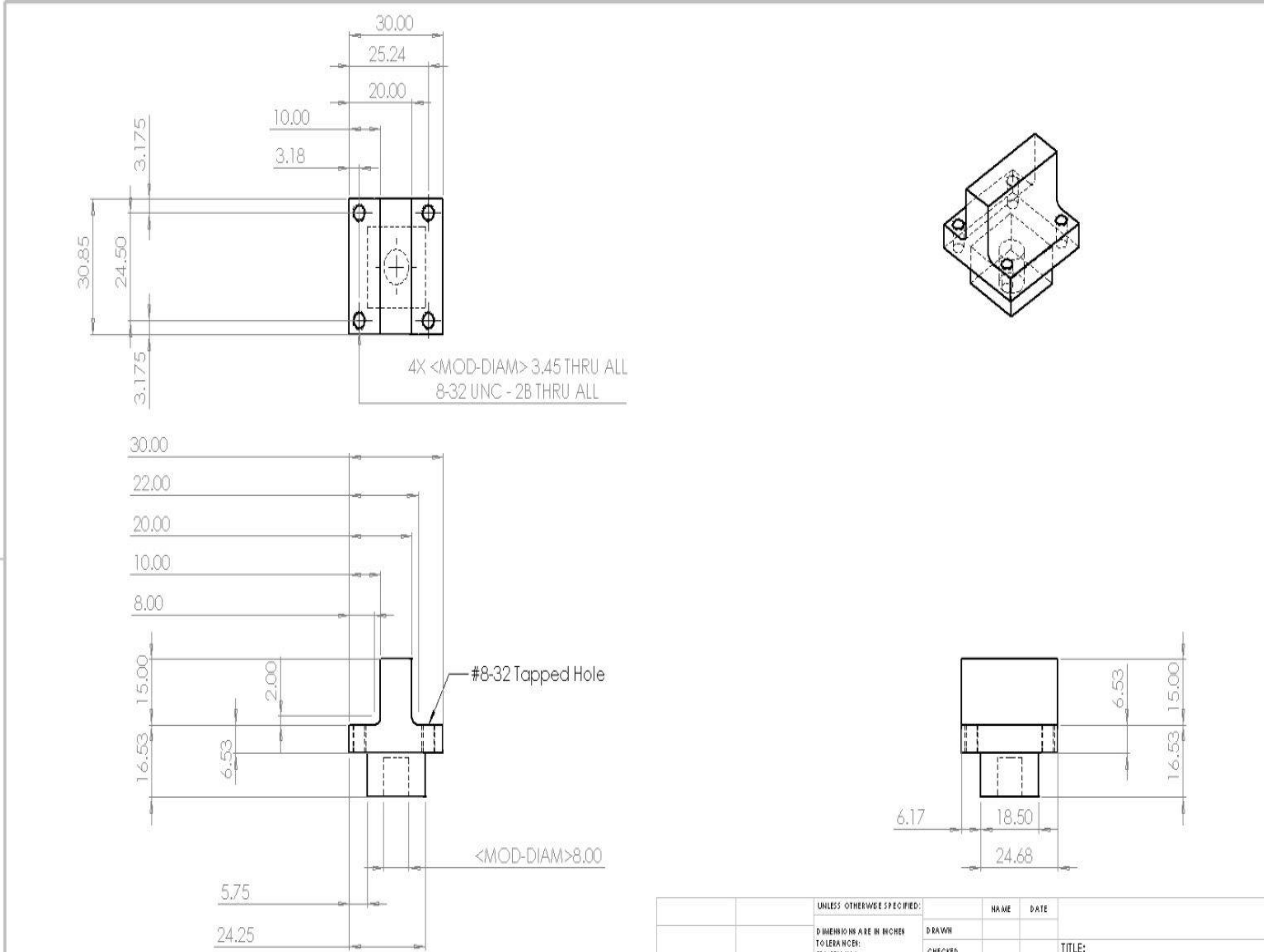

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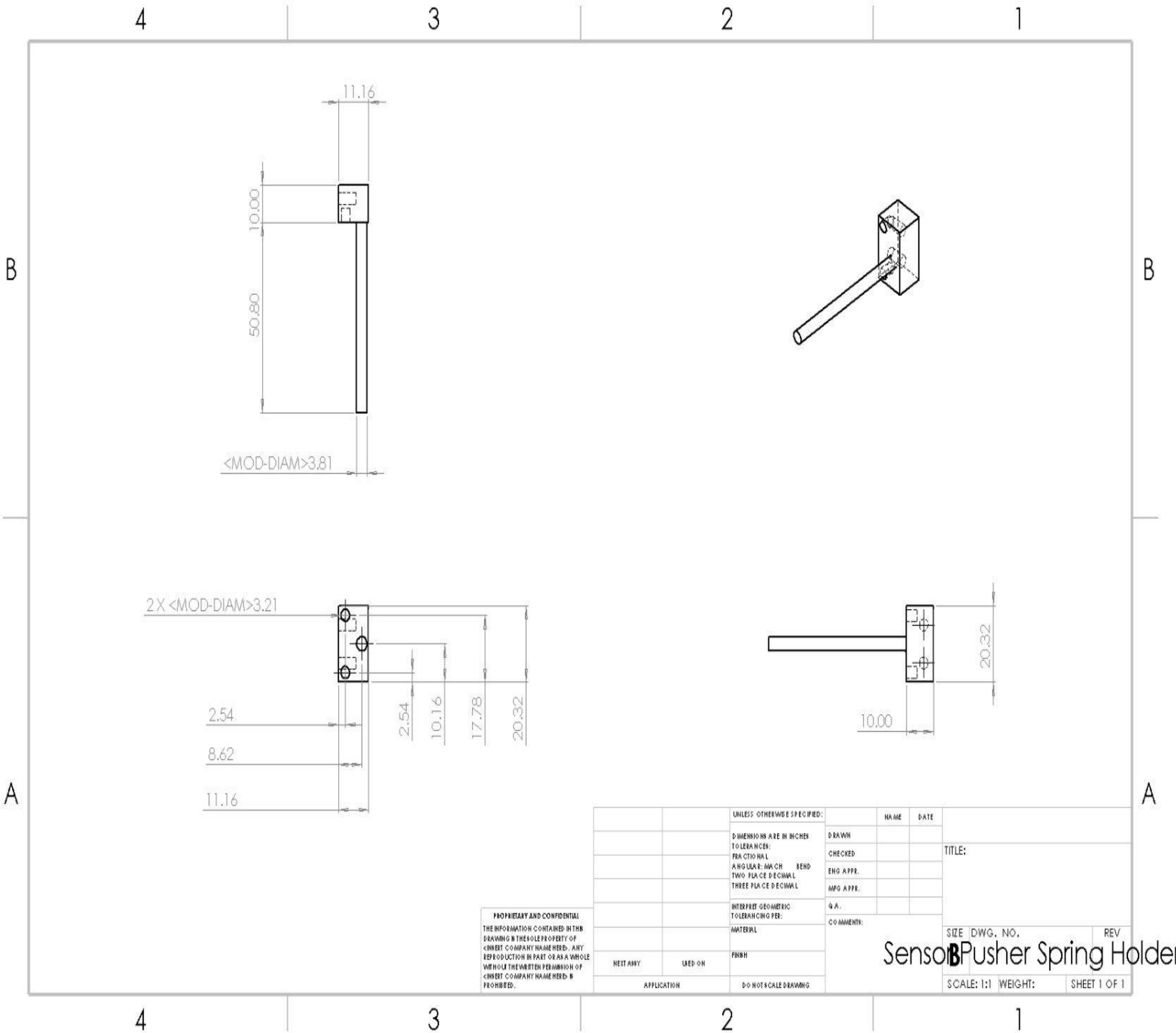
UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ANGULAR: MACH BEND TWO PLACE DECIMAL THREE PLACE DECIMAL	DRAWN			
	CHECKED			TITLE:
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE DWG. NO. REV
FINISH				**B** Storage Cap
DO NOT SCALE DRAWING				SCALE: 1:1 WEIGHT: SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	



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2 X <MOD-DIAM>3.21
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8.62
11.16
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10.16
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20.32
20.32
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UNLESS OTHERWISE SPECIFIED:
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ANGULAR: MACH BEND
TWO PLACE DECIMAL
THREE PLACE DECIMAL
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE DWG. NO.
REV
Sensor Pusher Spring Holder
SCALE: 1:1 WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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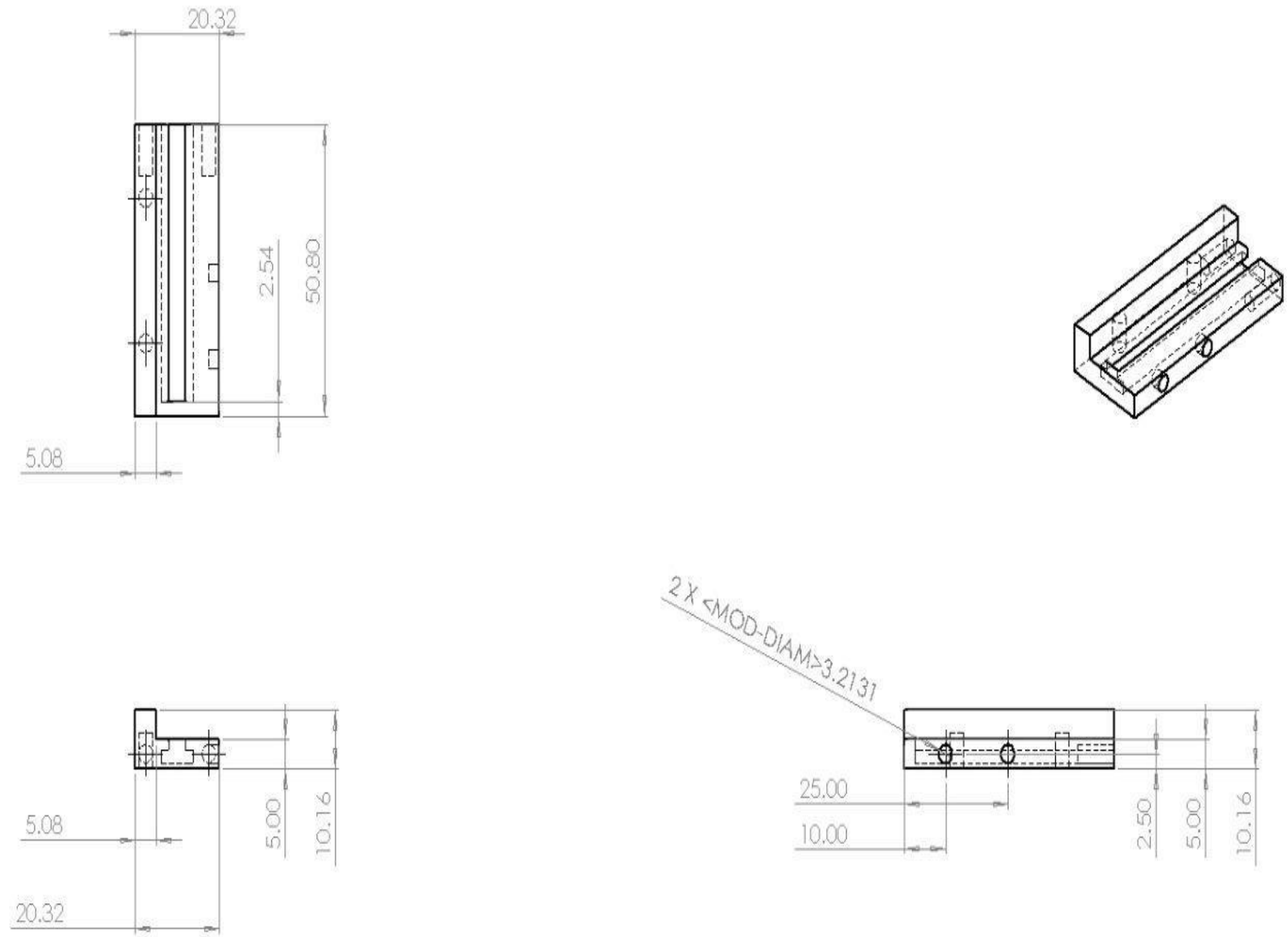

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ANGULAR: MACH BEND
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THREE PLACE DECIMAL

INTERPRET GEOMETRIC
TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

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

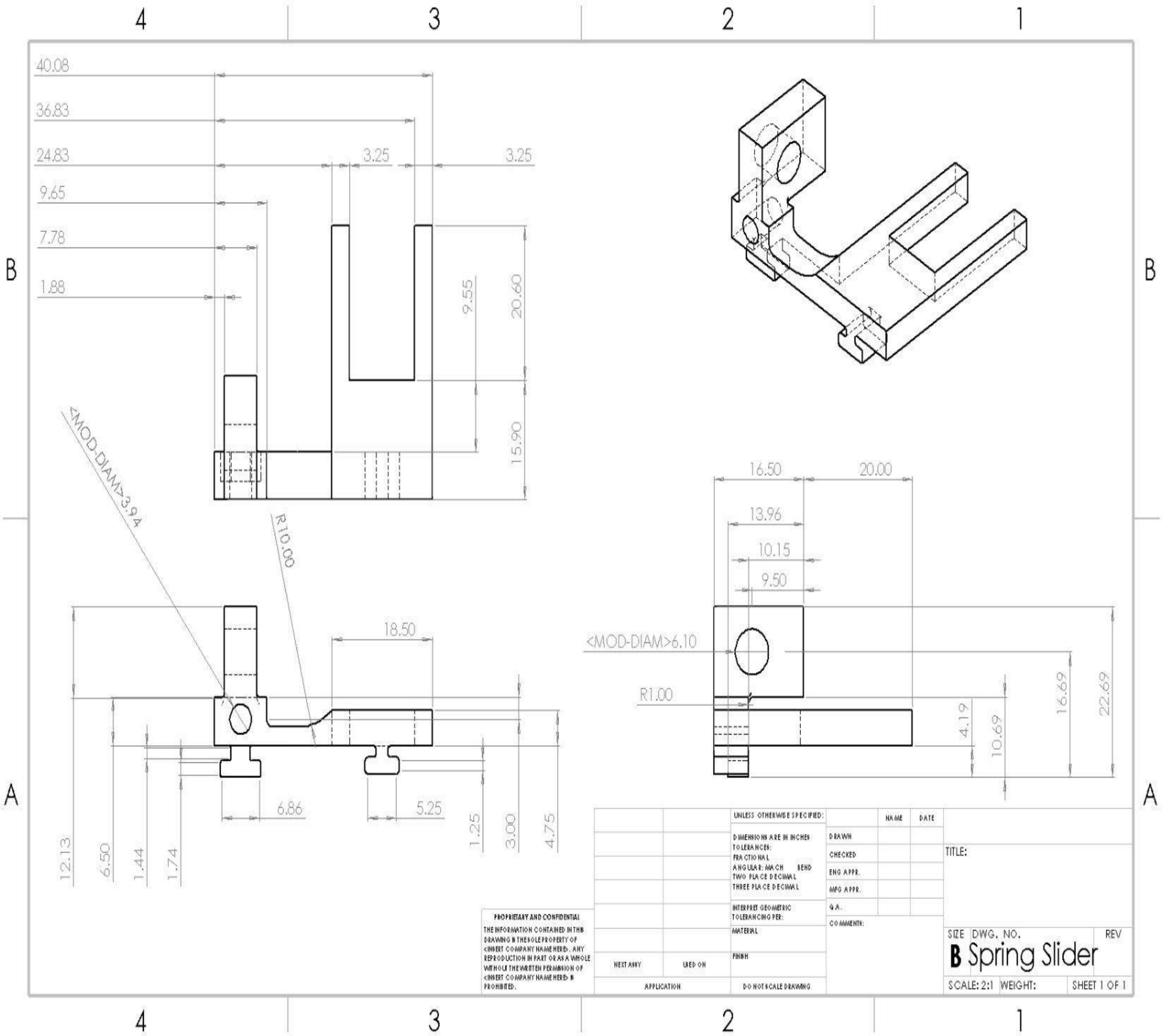
NEXT ASSY	USED ON
APPLICATION	

TITLE:

SIZE B DWG. NO. REV

Bottom of Sensor Pusher

SCALE: 1:1 WEIGHT: SHEET 1 OF 1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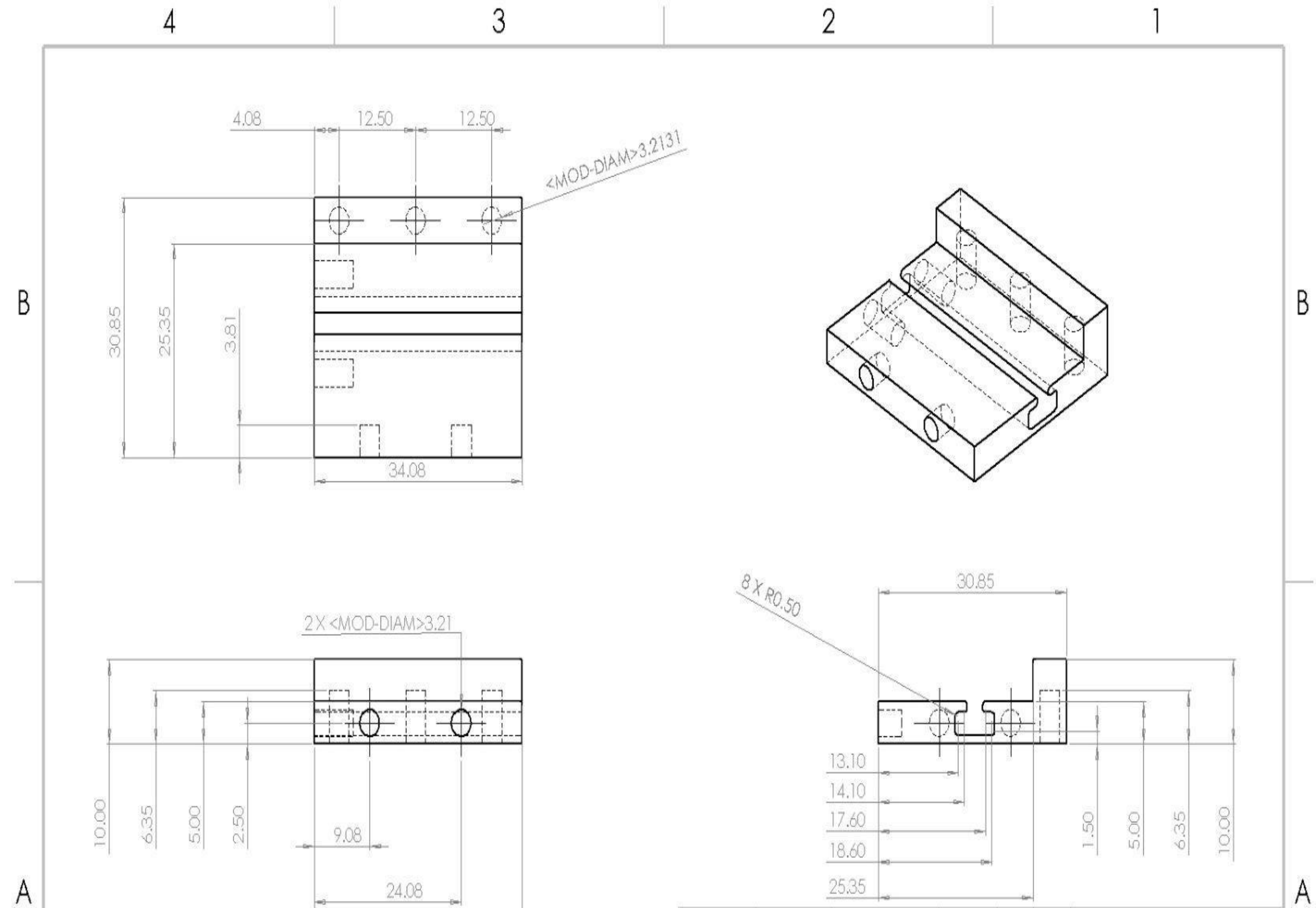
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL
ANGULAR: MACH BEND
TWO PLACE DECIMAL
THREE PLACE DECIMAL
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE DWG. NO.
REV
B Spring Slider
SCALE: 2:1 WEIGHT:
SHEET 1 OF 1



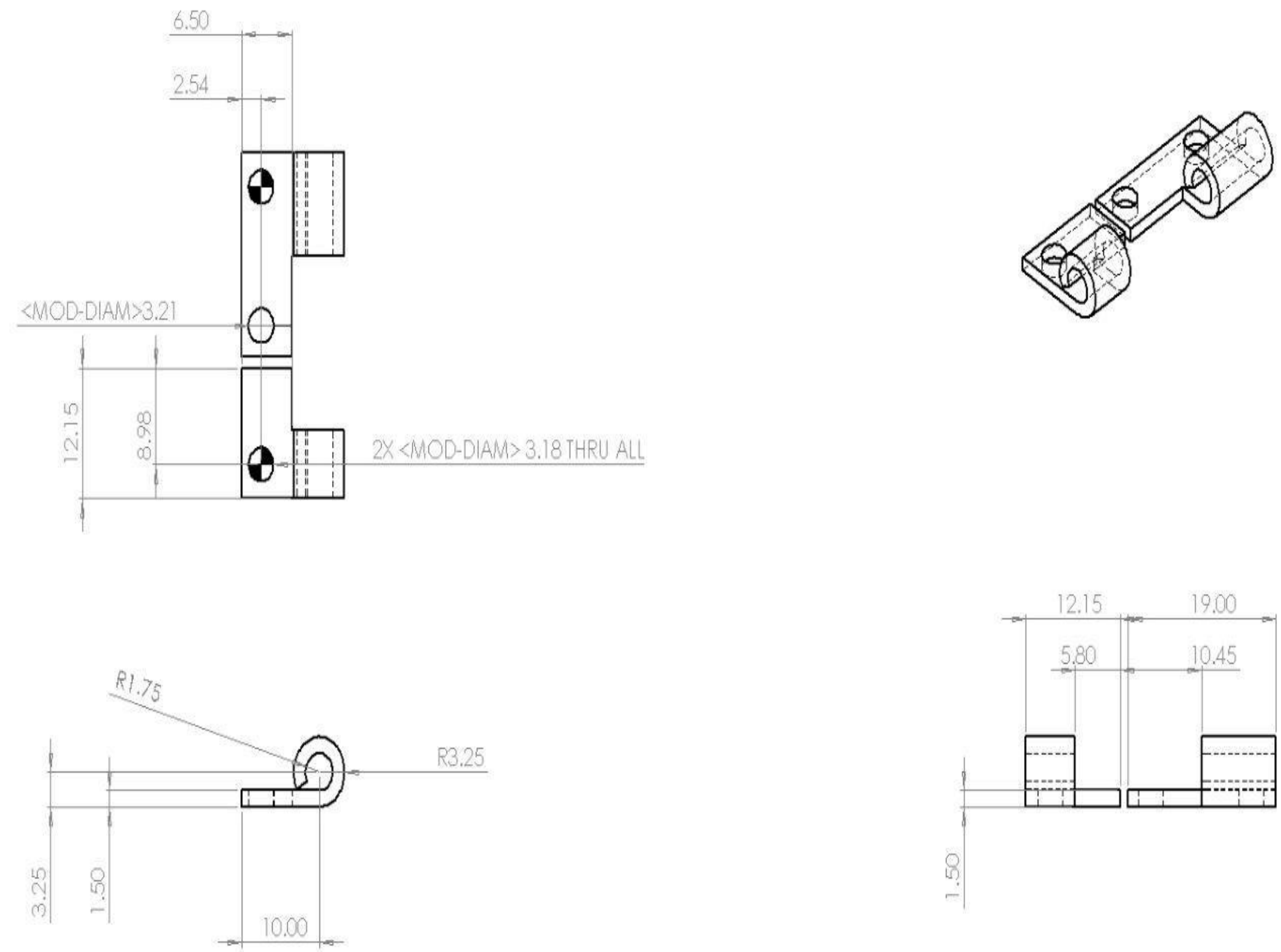
NEXT ASSY	USED ON	UNLESS OTHERWISE SPECIFIED:		NAME	DATE
APPLICATION		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ANGULAR: MACH BEND TWO PLACE DECIMAL THREE PLACE DECIMAL	DRAWN		
		INTERPRET GEOMETRIC TOLERANCING PER:	CHECKED		
		MATERIAL	ENG APPR.		
		FINISH	MFG APPR.		
		DO NOT SCALE DRAWING	Q.A.		
			COMMENTS:		

TITLE:

SIZE DWG. NO. REV

Sensor Pusher Guide

SCALE: 2:1 WEIGHT: SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE		
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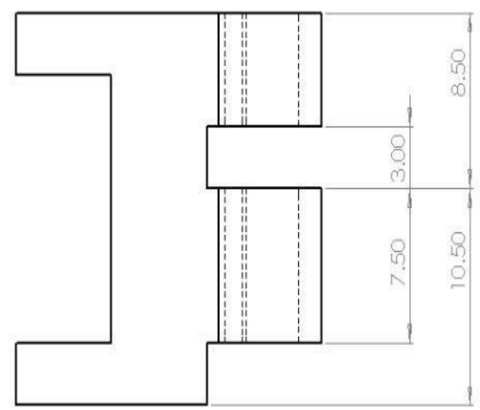
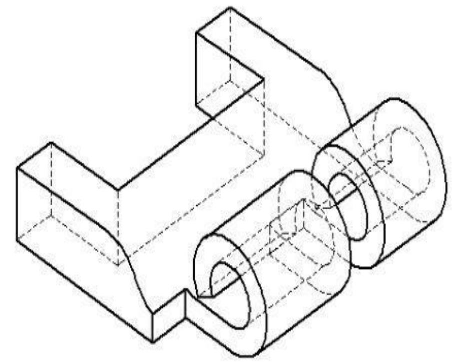
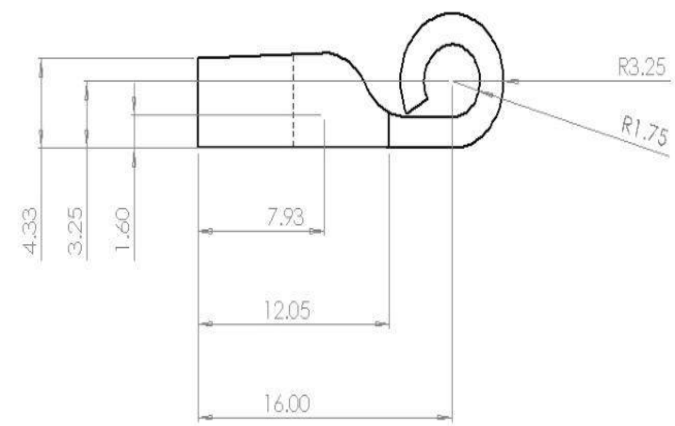
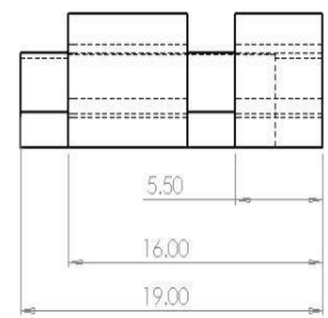
	CHECKED				
	ENG APPR.				
	MFG APPR.				
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.				
MATERIAL PEI	COMMENTS:			SIZE B DWG. NO. Spring Hinge	REV 1
FINISH					
DO NOT SCALE DRAWING				SCALE: 2:1 WEIGHT:	SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	









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		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
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			MFG APPR.			
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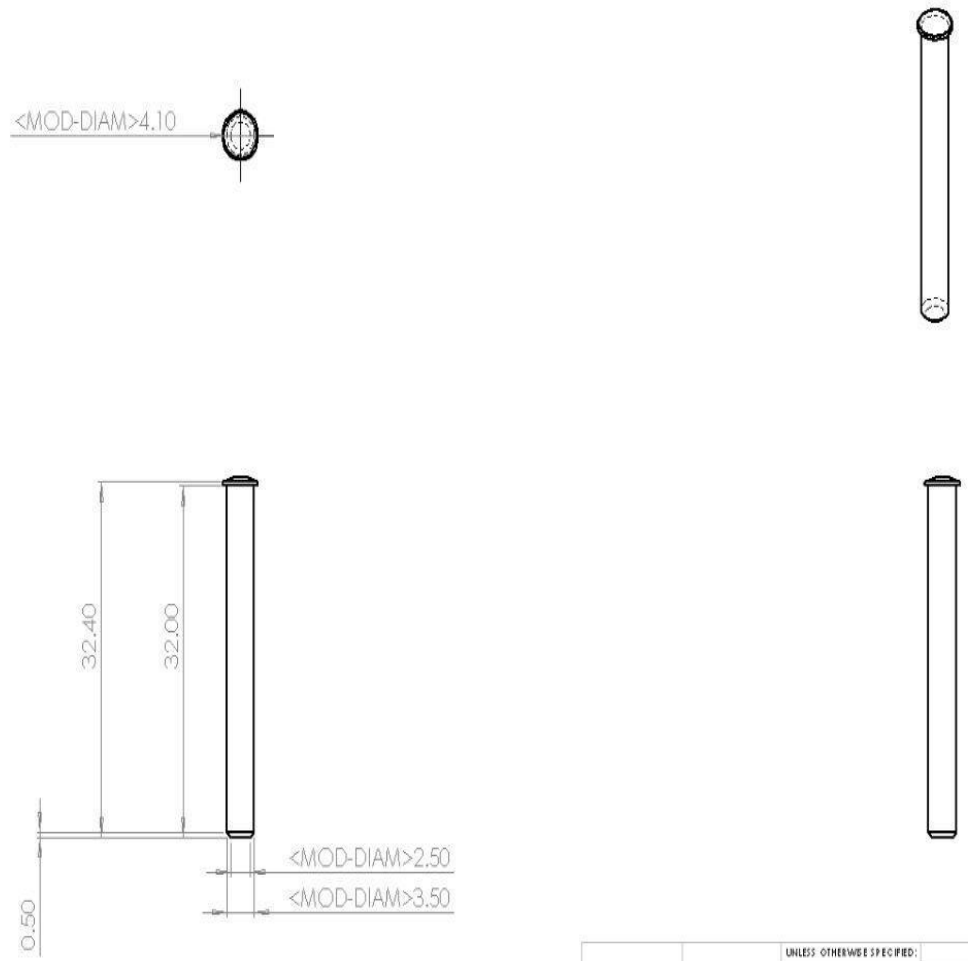
		MATERIAL PEI	COMMENTS:			SIZE B DWG. NO. Spring Hinge 2 REV
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 4:1 WEIGHT: SHEET 1 OF 1



NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

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

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
6061-T4 (SS)

FINISH

DO NOT SCALE DRAWING

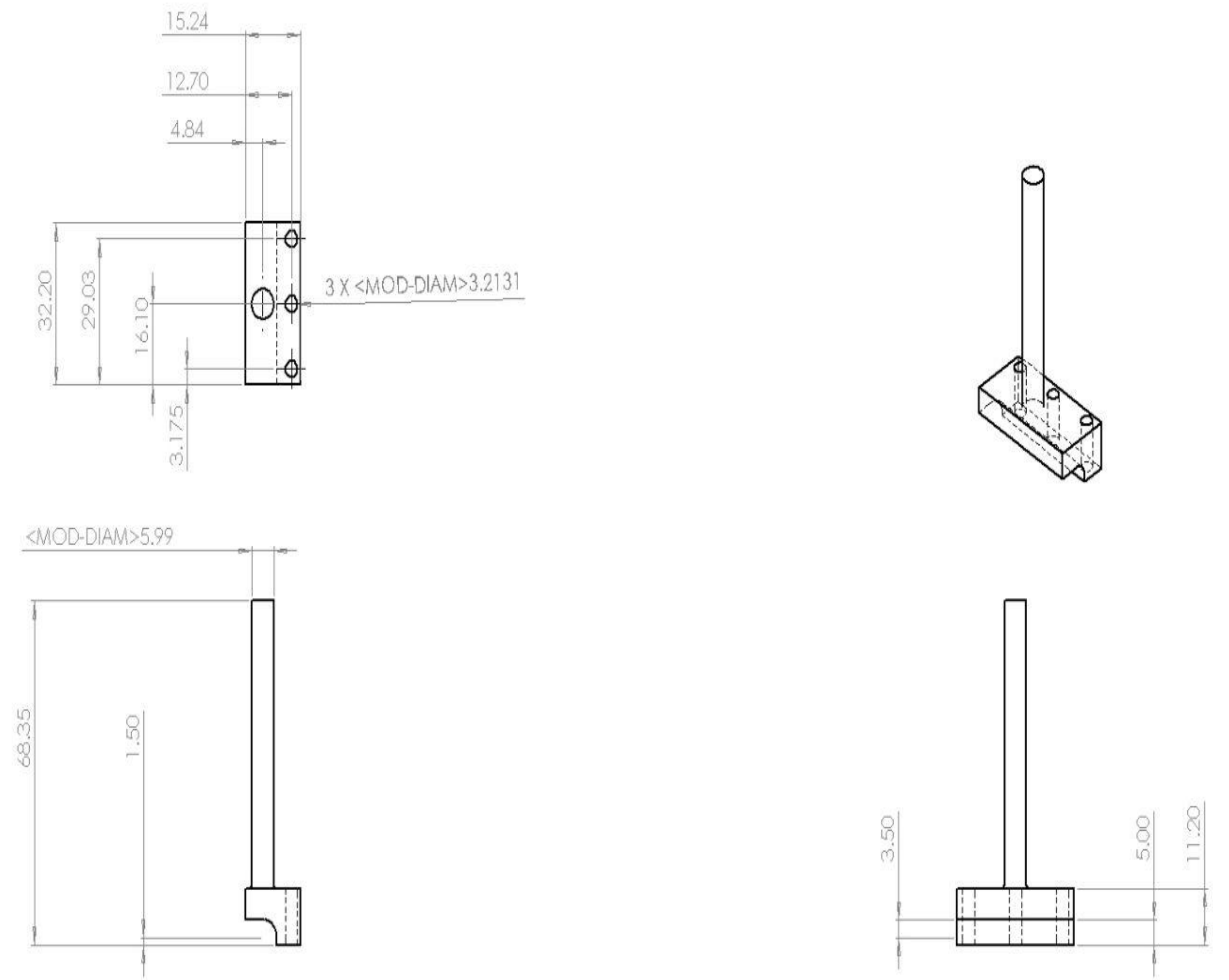
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE B DWG. NO. Hinge Pin REV

SCALE: 2:1 WEIGHT: SHEET 1 OF 1



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	CHECKED			
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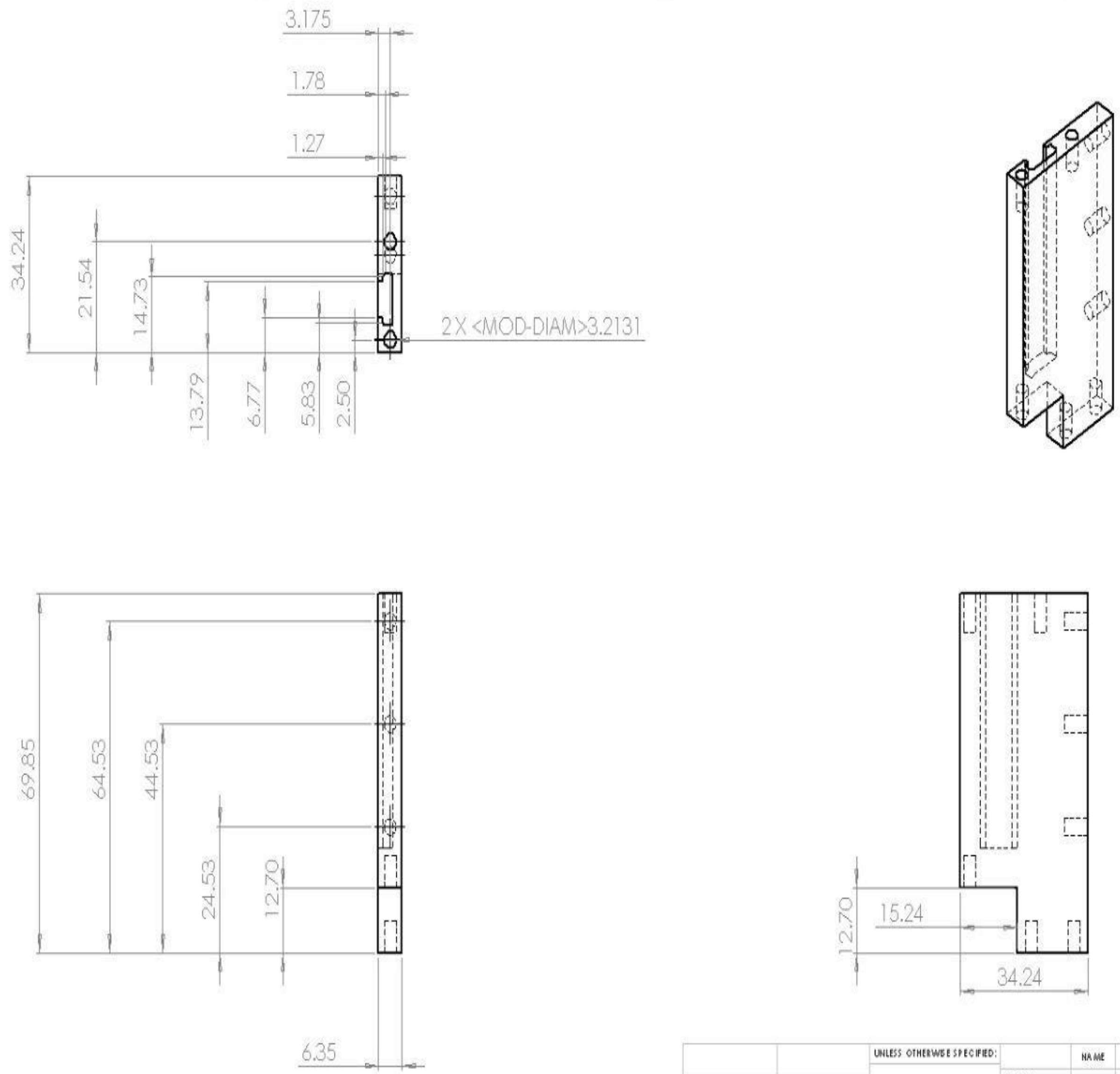
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE B DWG. NO. Stamp Spring Holder REV
FINISH				
NEXT ASSY / USED ON				
APPLICATION / DO NOT SCALE DRAWING				SCALE: 1:1 WEIGHT: SHEET 1 OF 1



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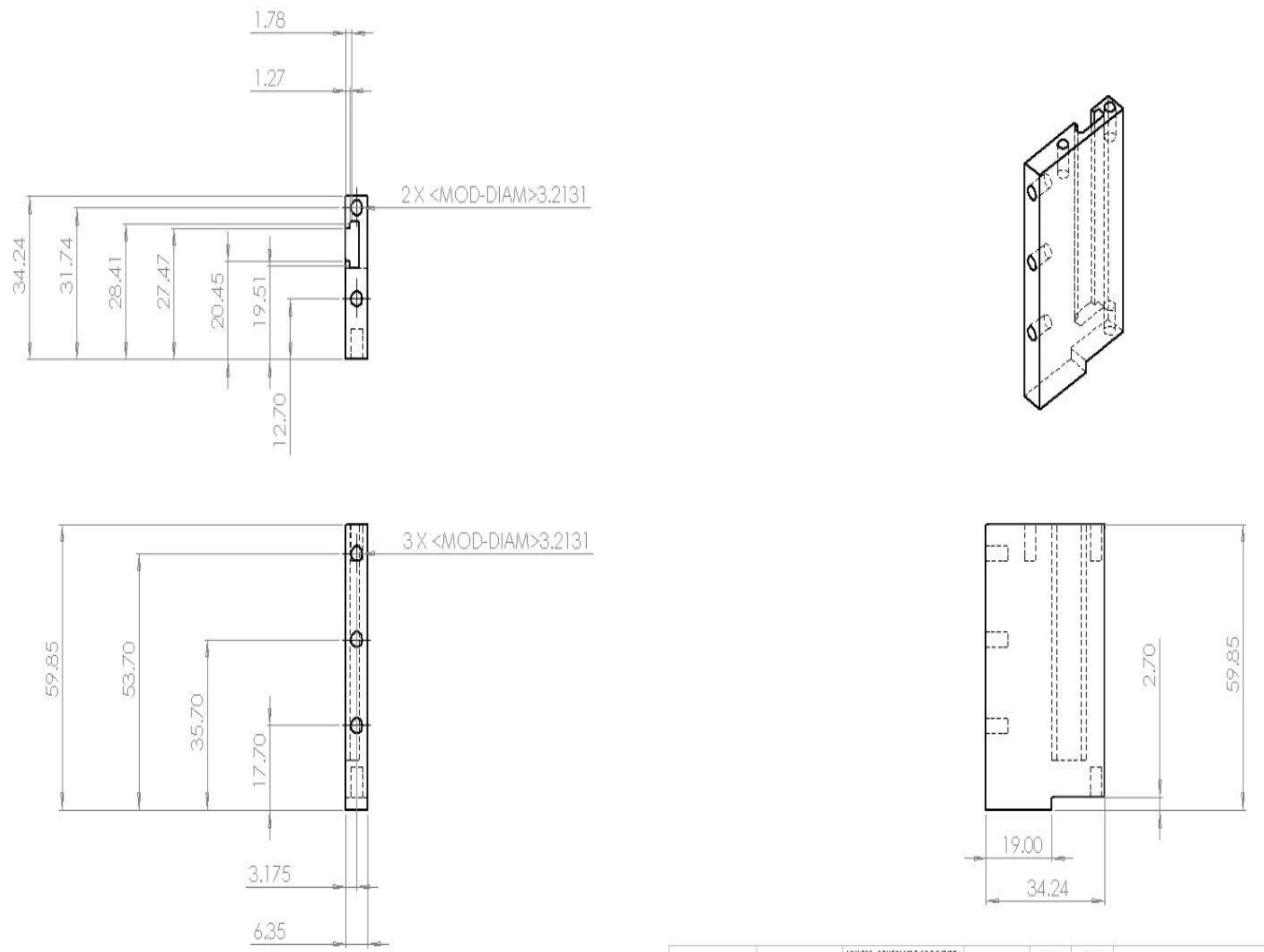
	CHECKED				
	ENG APPR.				
	MFG APPR.				
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.				
MATERIAL	COMMENTS:			SIZE B DWG. NO. Stamp Pin Rail Guide Back	REV
FINISH					
DO NOT SCALE DRAWING				SCALE: 1:1 WEIGHT:	SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	



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NEXT ASSY	USED ON
APPLICATION	

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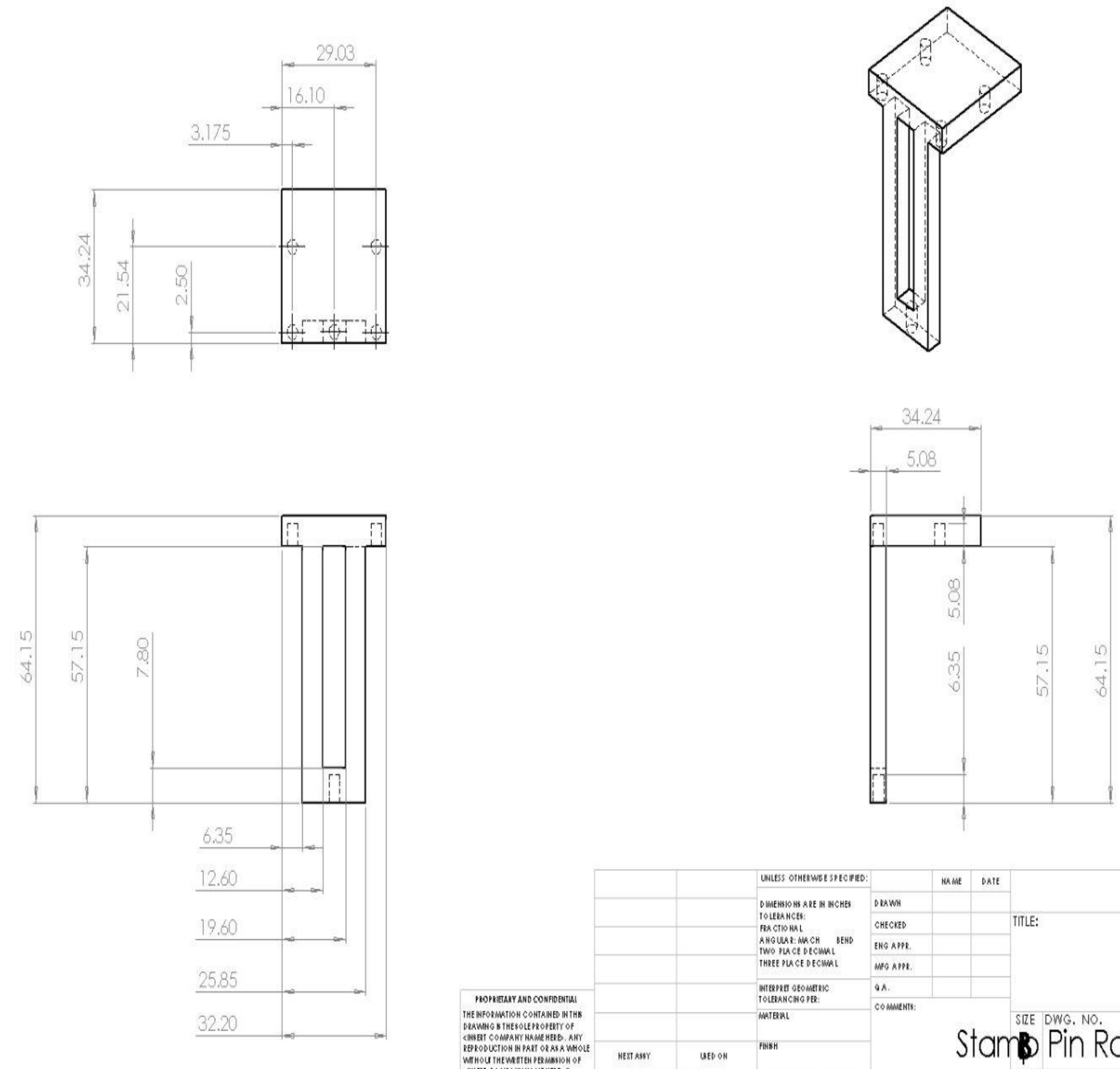
FRACTIONAL
ANGULAR: MACH BEND
TWO PLACE DECIMAL
THREE PLACE DECIMAL
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

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

TITLE:

SIZE B DWG. NO. Stamp Pin Rail Guide Front REV

SCALE: 1:1 WEIGHT: SHEET 1 OF 1



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ANGULAR: MACH BEND
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INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
NEXT ASSY | USED ON
APPLICATION
DO NOT SCALE DRAWING

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

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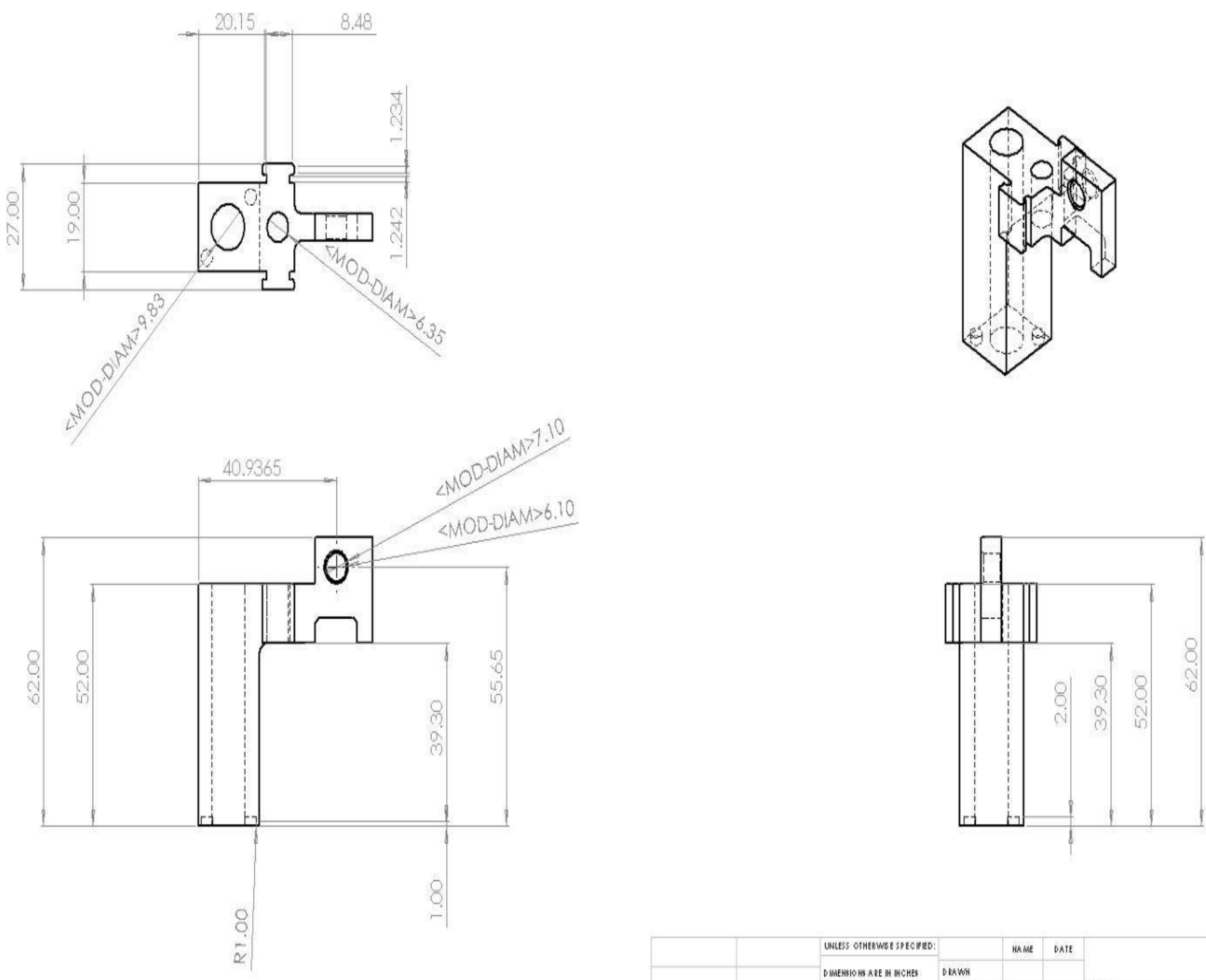
TITLE:

SIZE B DWG. NO. Stamp Pin Rail Guide Slot REV

SCALE: 1:1 WEIGHT: SHEET 1 OF 1



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		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
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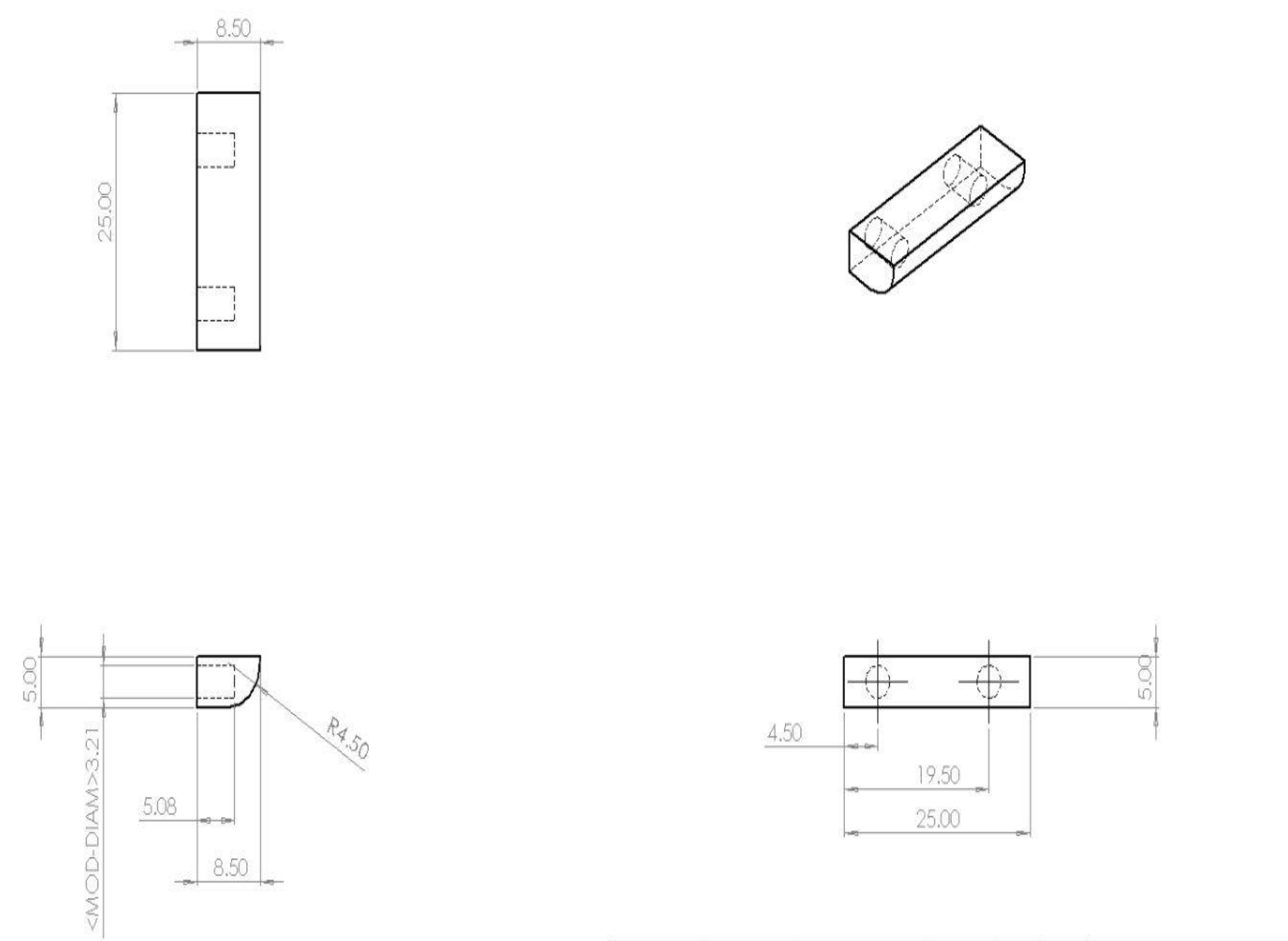
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL	COMMENTS:			SIZE DWG. NO. REV
NEXT ASSY	USED ON	FINISH				**B** Stamp Slider
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:1 WEIGHT: SHEET 1 OF 1



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		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
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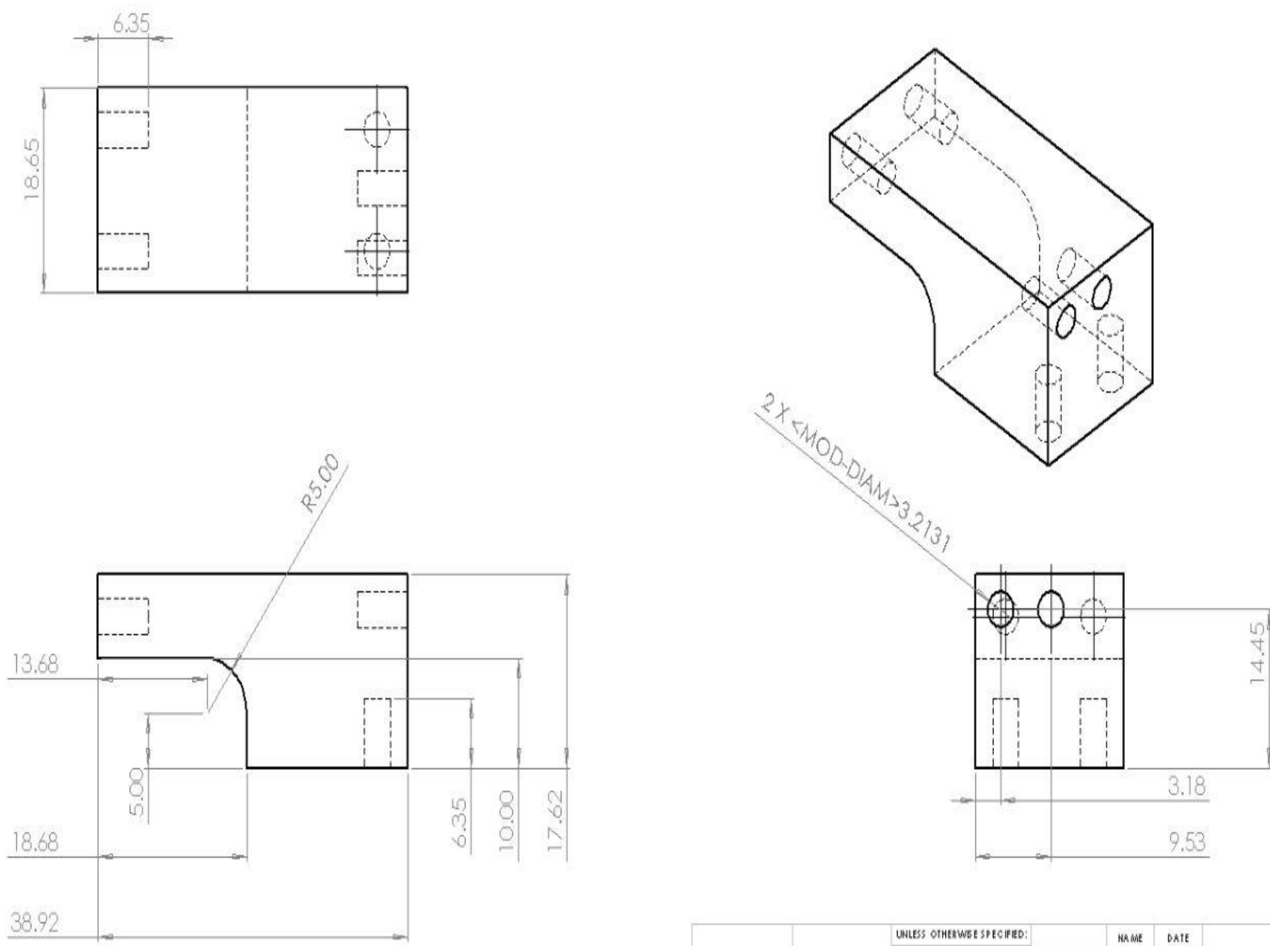
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 2:1 WEIGHT: SHEET 1 OF 1

A 1 2 3 4 B



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			MFG APPR.			
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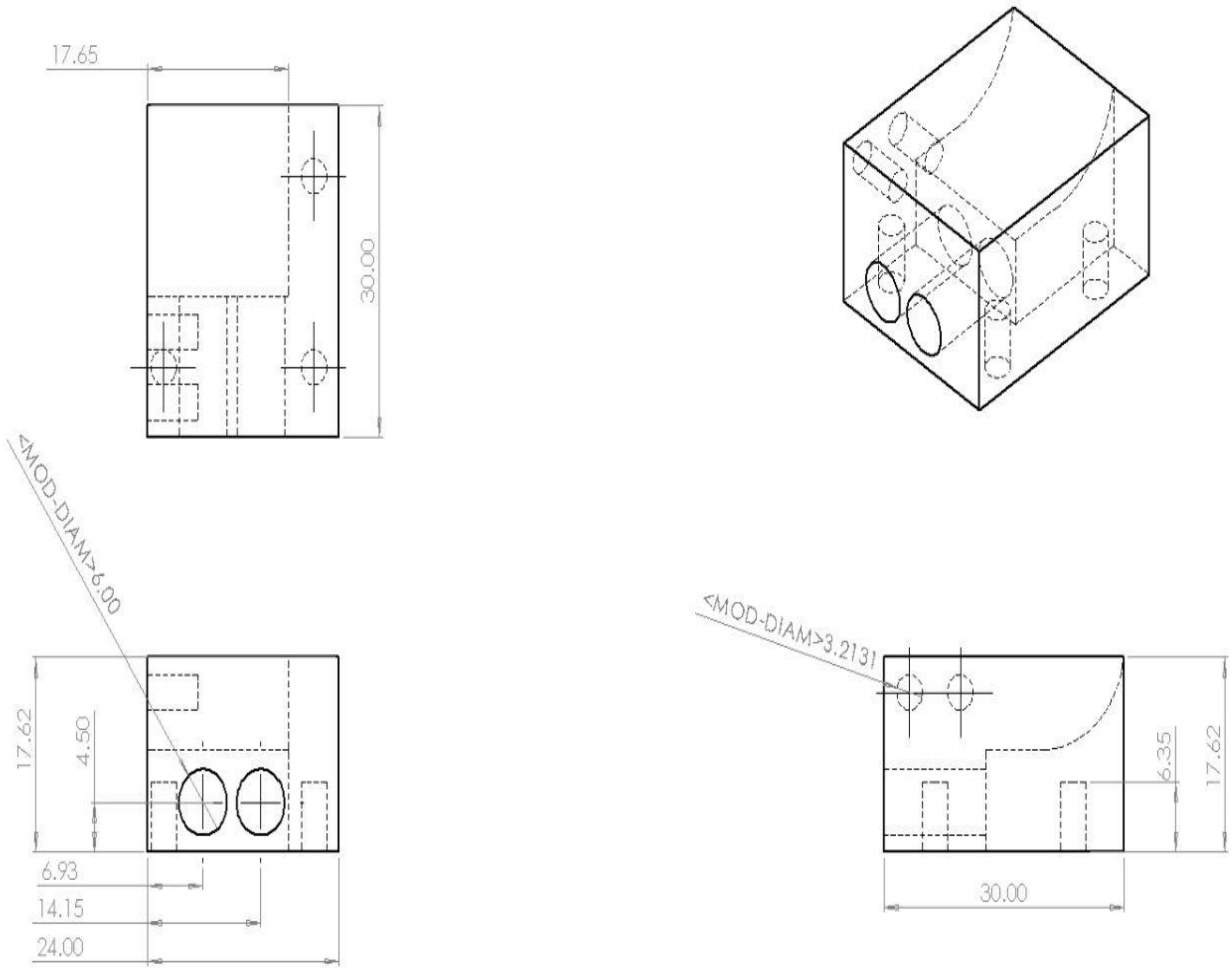
NEXT ASSY	USED ON	FINISH				B Table Top Guide
APPLICATION		DO NOT SCALE DRAWING				SCALE: 2:1 WEIGHT: SHEET 1 OF 1



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			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

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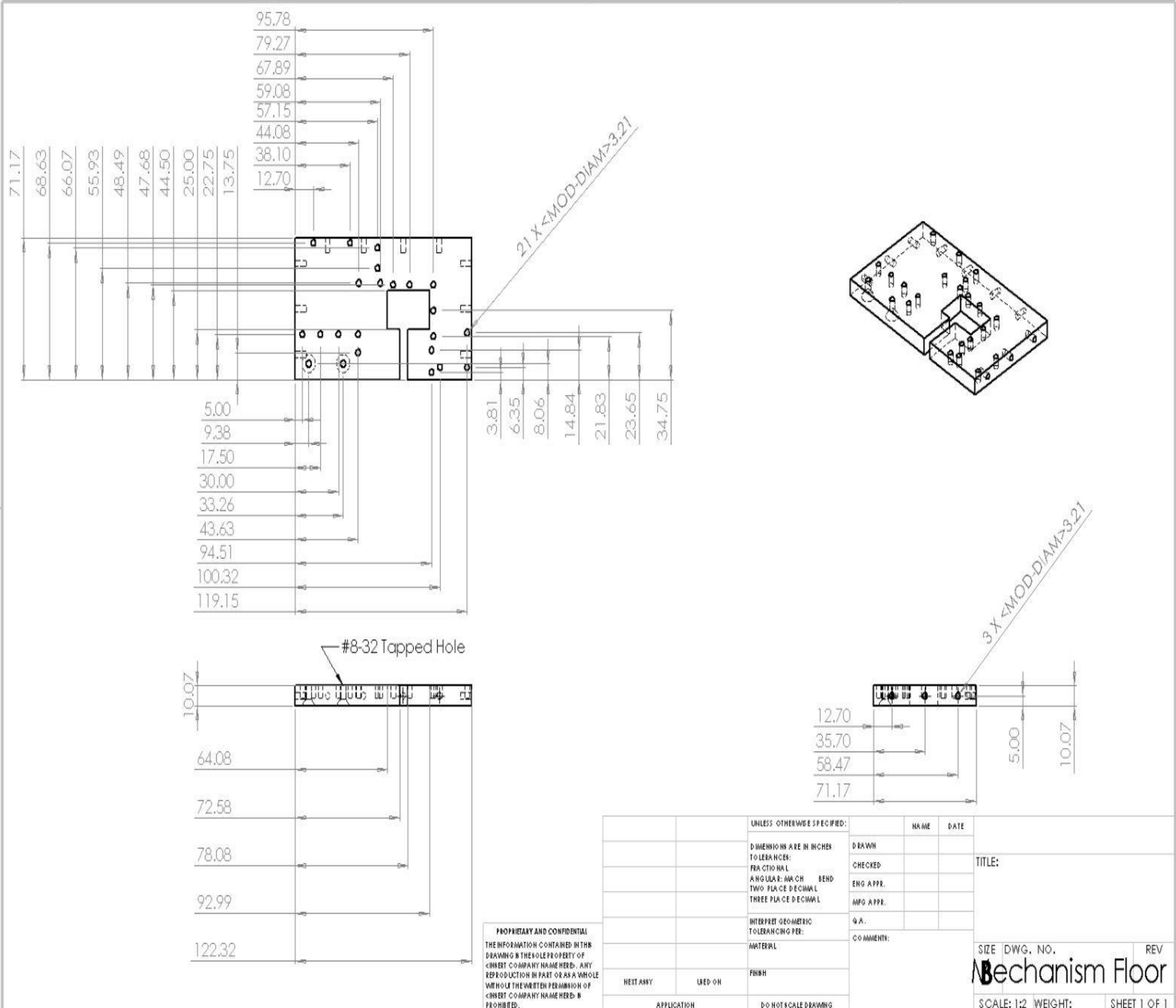
TITLE:

SIZE B DWG. NO. REV

Bowden Cable Guide

SCALE: 2:1 WEIGHT: SHEET 1 OF 1



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23.65
34.75
#8-32 Tapped Hole
10.07
64.08
72.58
78.08
92.99
122.32
3 X <MOD-DIAM>3.21
12.70
35.70
58.47
71.17
5.00
10.07
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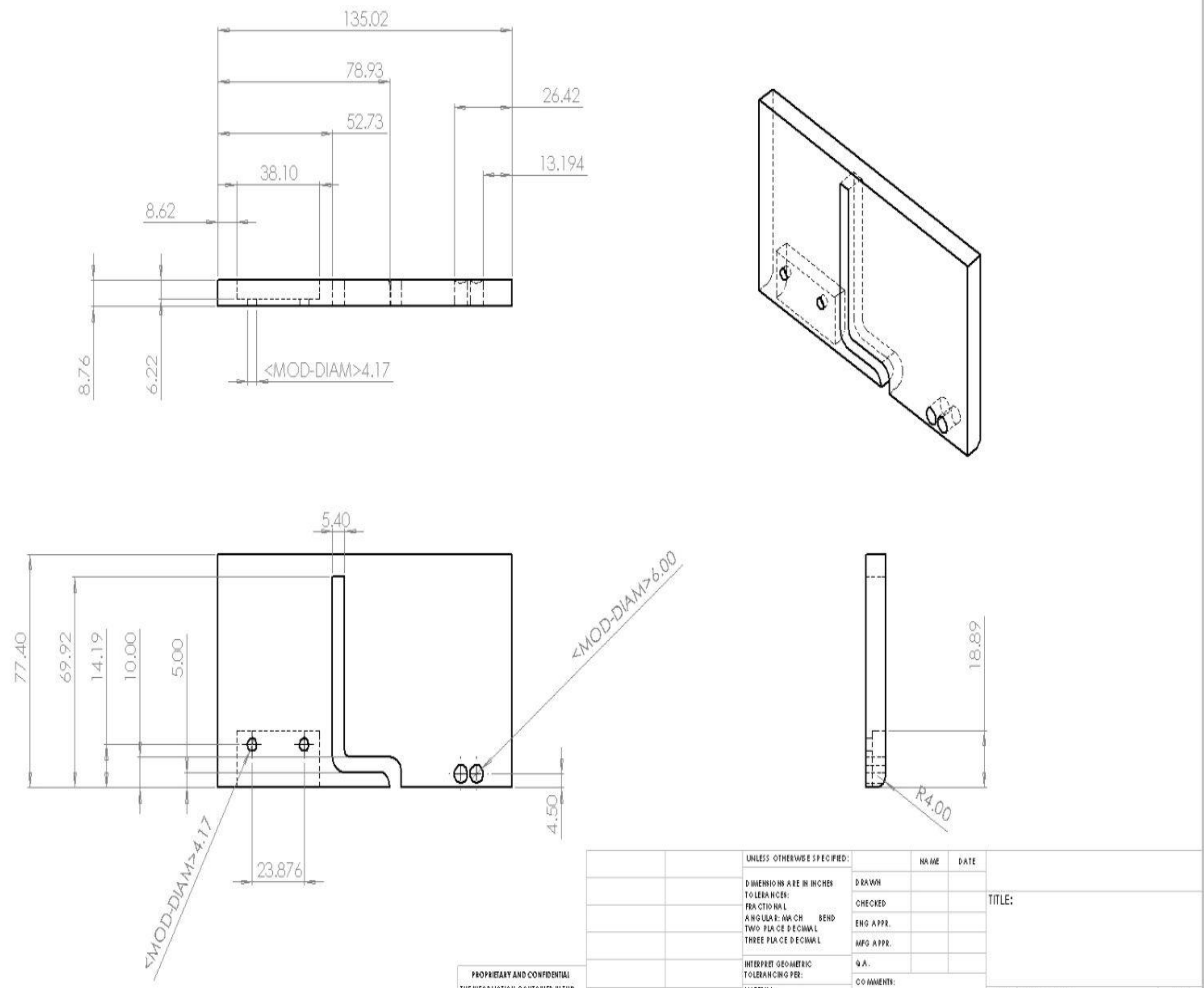
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL
ANGULAR: MACH BEND
TWO PLACE DECIMAL
THREE PLACE DECIMAL
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
DWG. NO.
REV
Mechanism Floor
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1



NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL
ANGULAR: MACH BEND
TWO PLACE DECIMAL
THREE PLACE DECIMAL

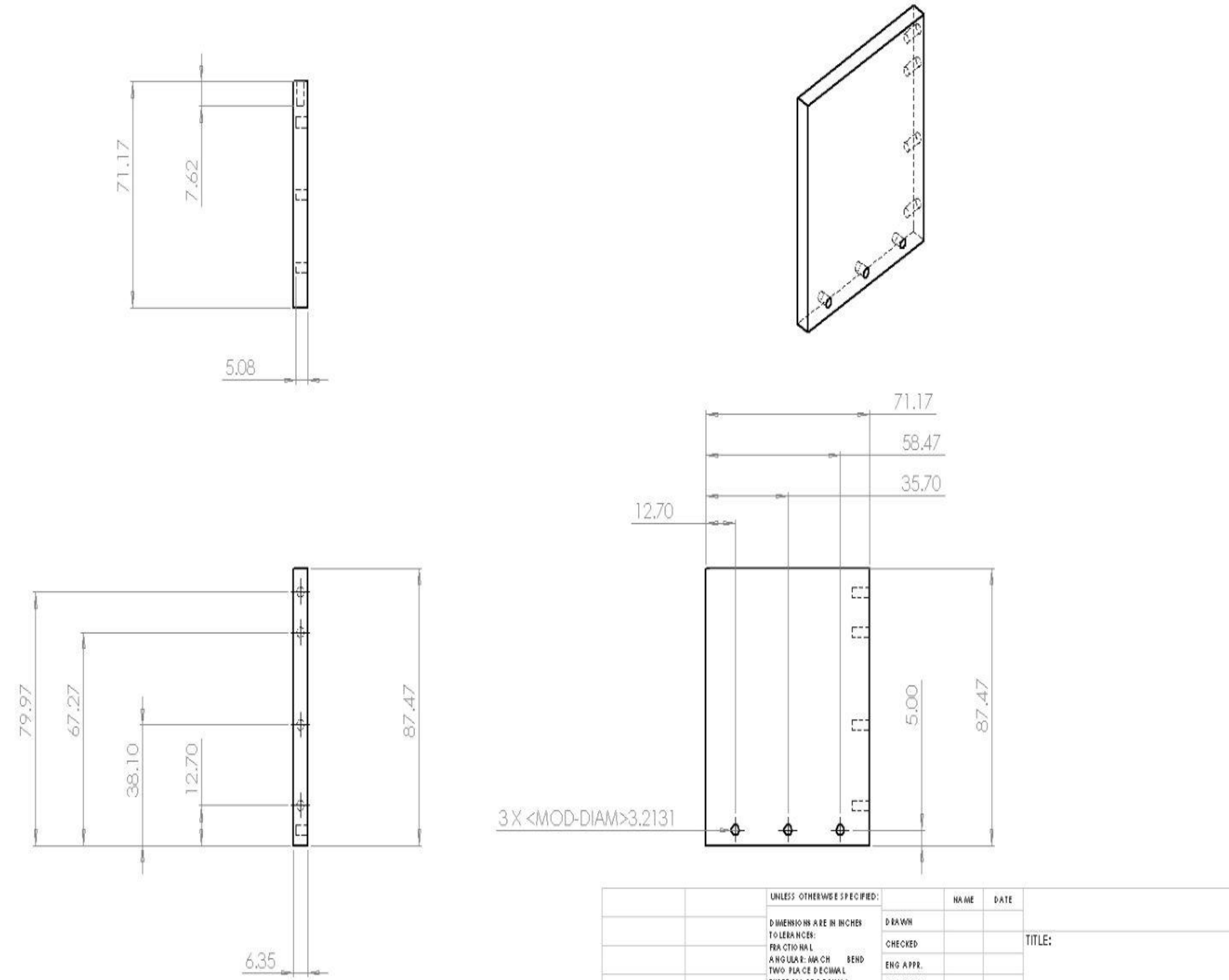
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

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

TITLE:

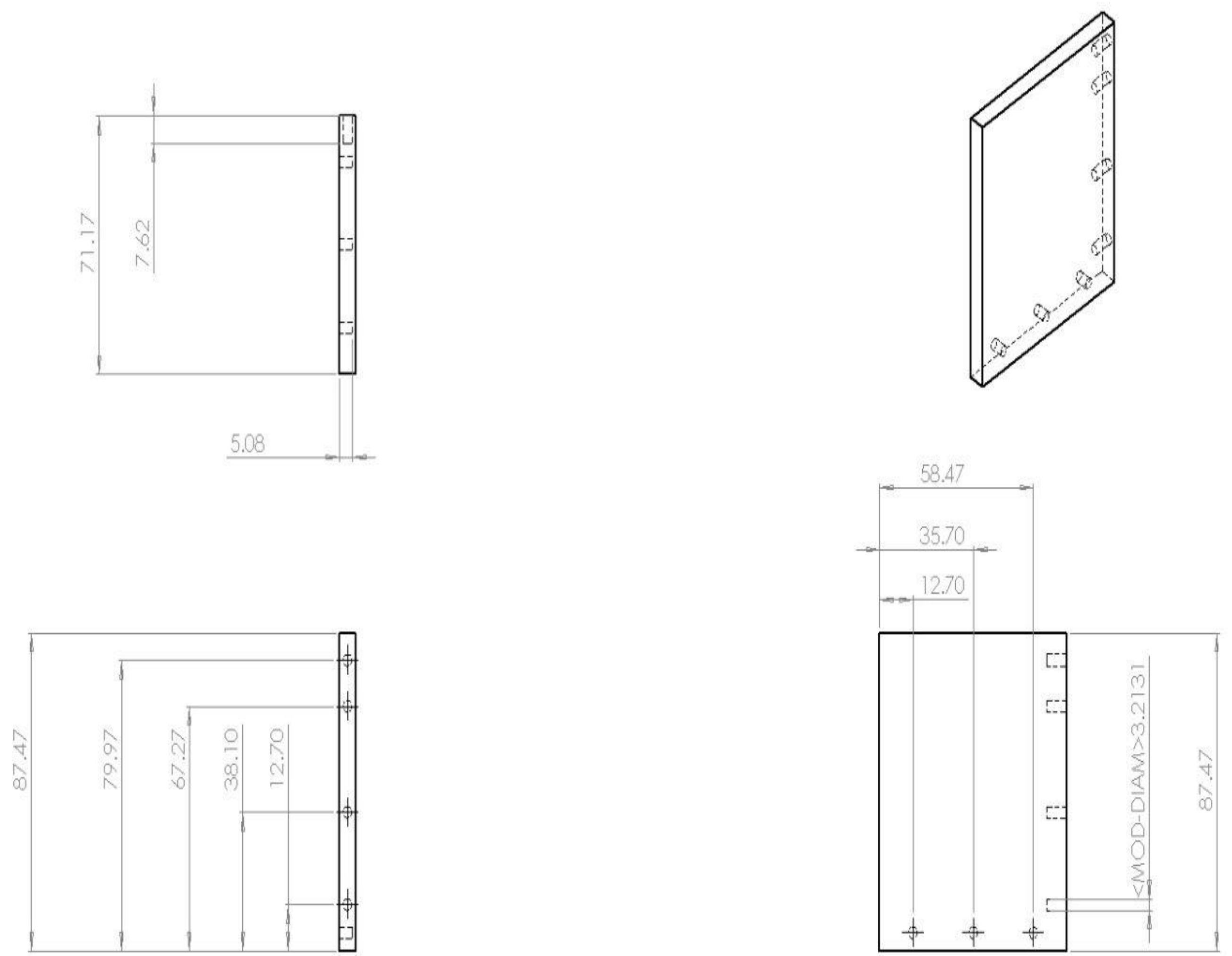
SIZE B DWG. NO. Housing Front REV

SCALE: 1:1 WEIGHT: SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE		
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ANGULAR: MACH BEND TWO PLACE DECIMAL THREE PLACE DECIMAL	DRAWN			TITLE:	
	CHECKED				
	ENG APPR.				
	MFG APPR.				
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.				
MATERIAL	COMMENTS:			SIZE DWG. NO. **B** Housing Left	REV
FINISH					
DO NOT SCALE DRAWING				SCALE: 1:2 WEIGHT:	SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	



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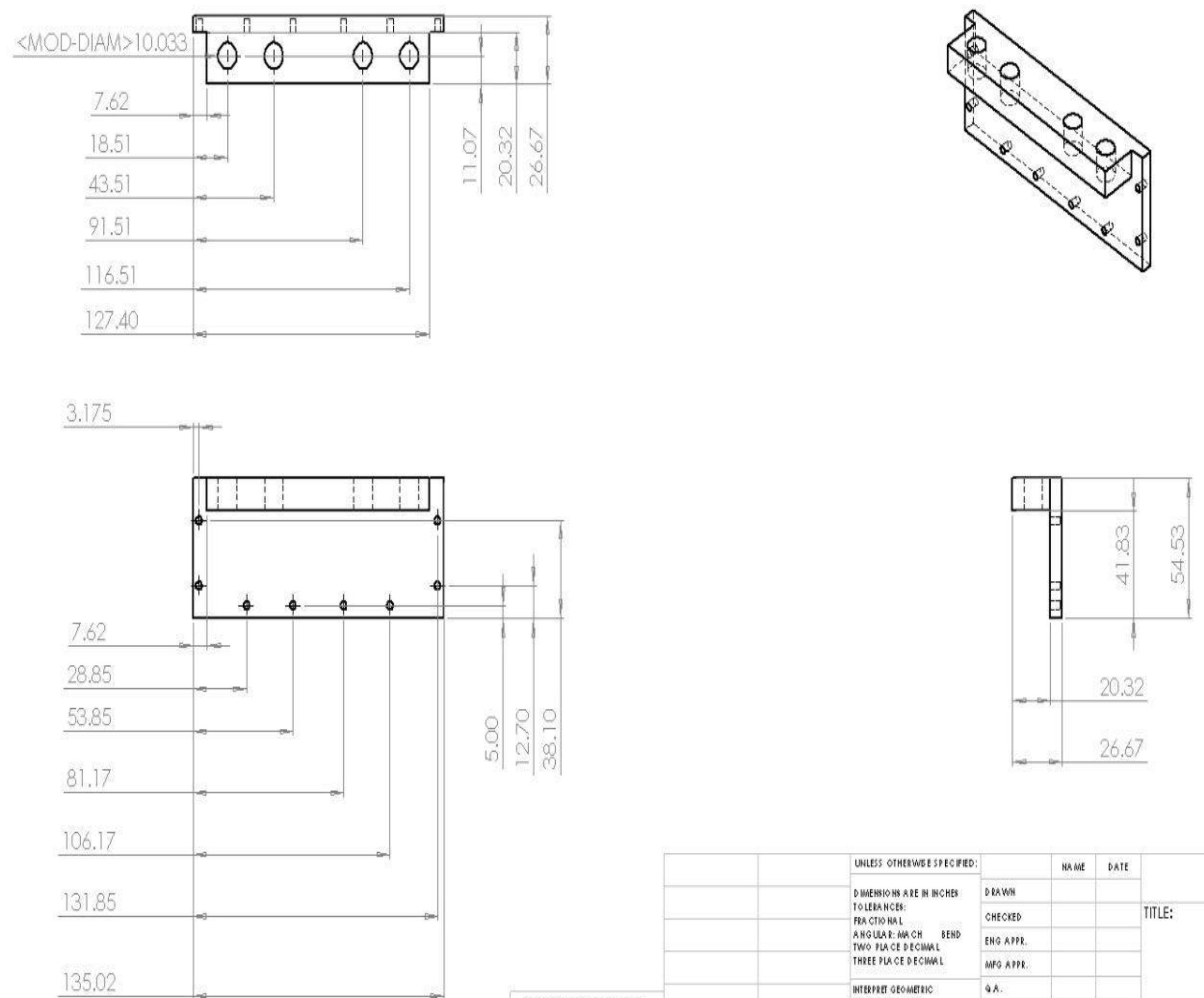
NEXT ASSY	USED ON	UNLESS OTHERWISE SPECIFIED:		NAME	DATE	TITLE:
APPLICATION		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ANGULAR: MACH BEND TWO PLACE DECIMAL THREE PLACE DECIMAL	DRAWN			
		INTERPRET GEOMETRIC TOLERANCING PER:	CHECKED			
		MATERIAL	ENG APPR.			
		FINISH	MFG APPR.			
		DO NOT SCALE DRAWING	Q.A.			
			COMMENTS:			

SIZE B DWG. NO. Housing Right REV

SCALE: 1:2 WEIGHT: SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE		
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ANGULAR: MACH BEND TWO PLACE DECIMAL THREE PLACE DECIMAL	DRAWN			TITLE:	
	CHECKED				
	ENG APPR.				
	MFG APPR.				
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.				
MATERIAL	COMMENTS:				
FINISH				SIZE B DWG. NO. Housing Connection	REV
DO NOT SCALE DRAWING				SCALE: 1:2 WEIGHT:	SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	

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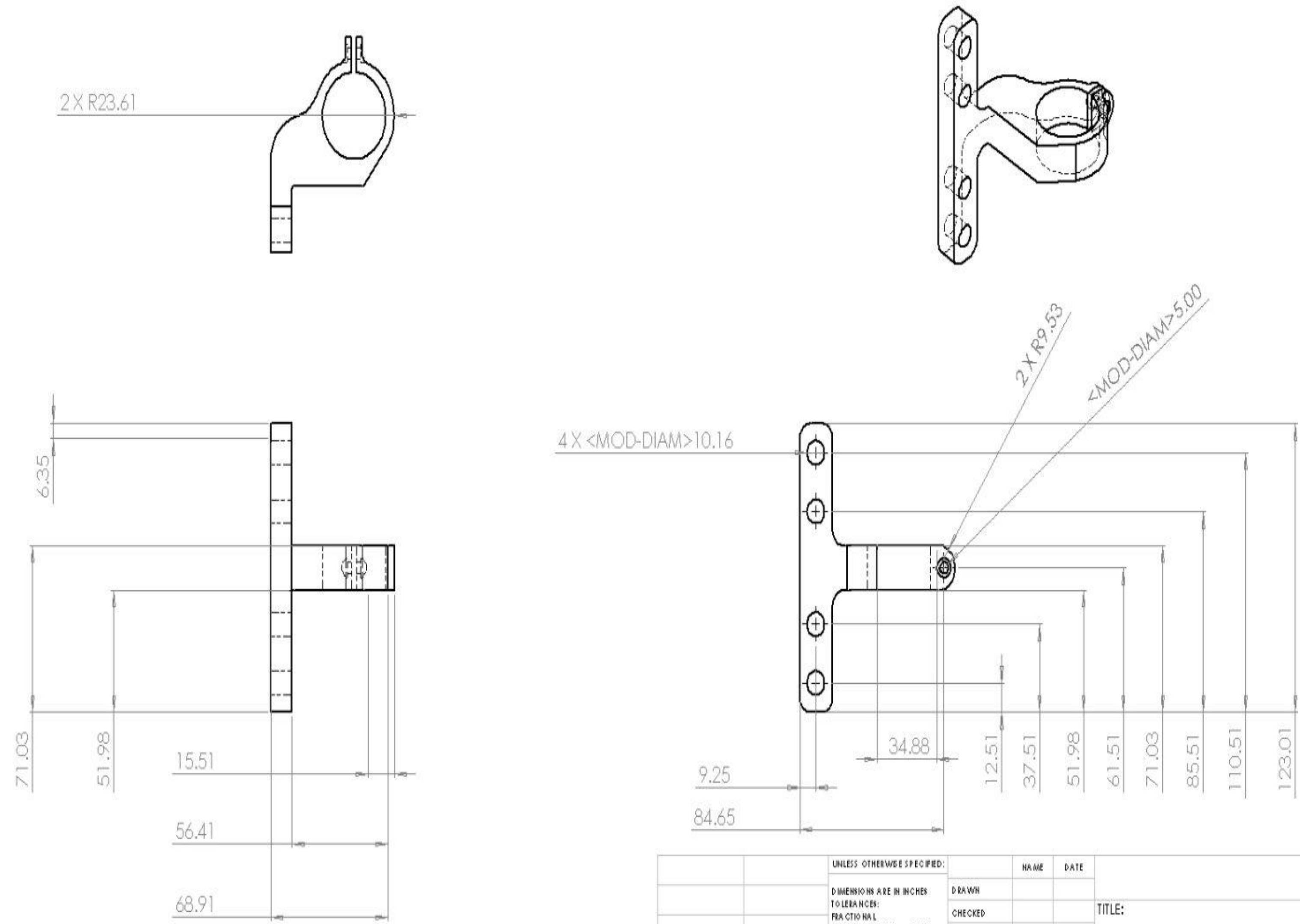

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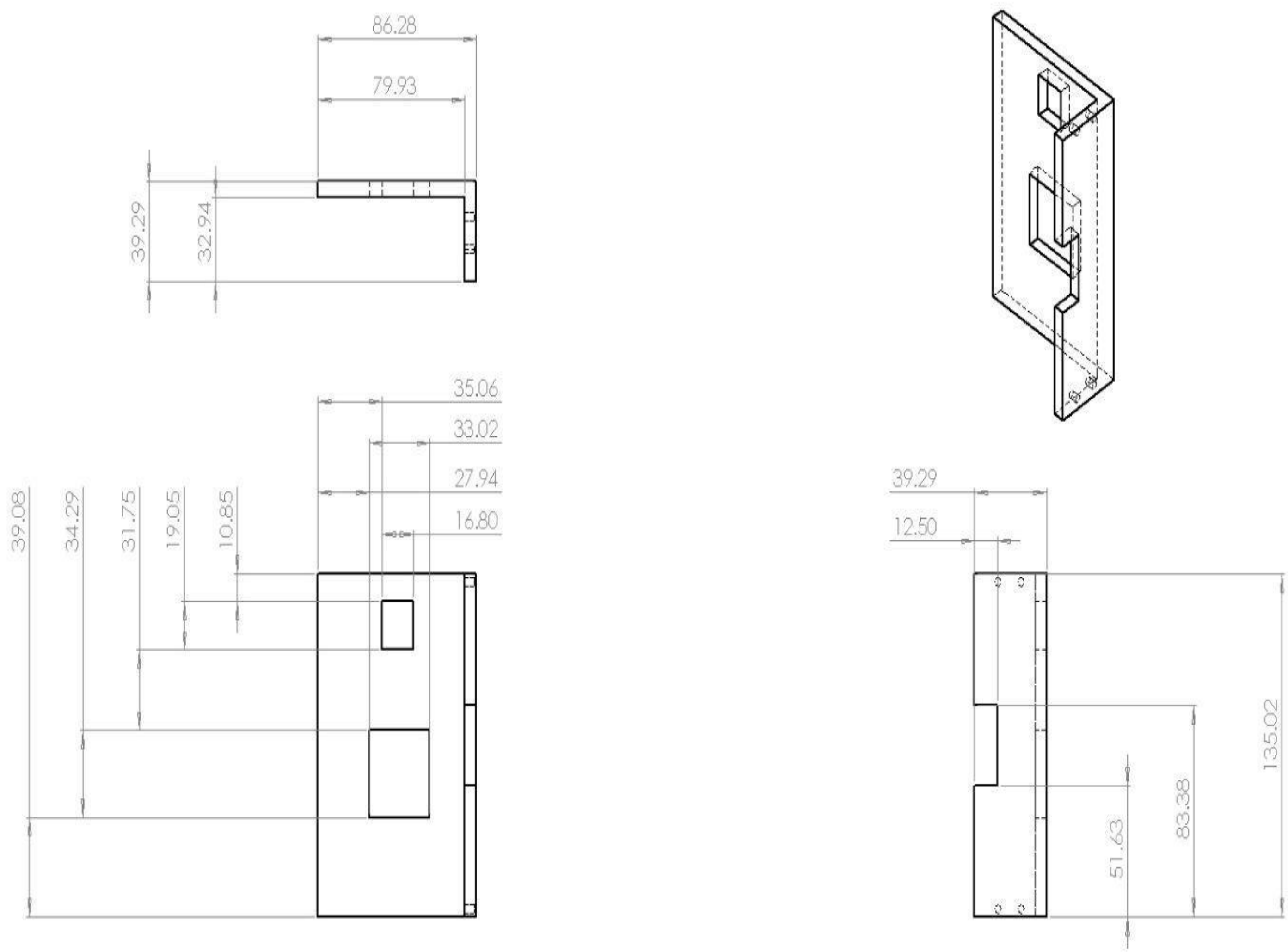
UNLESS OTHERWISE SPECIFIED:		NAME	DATE		
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ANGULAR: MACH BEND TWO PLACE DECIMAL THREE PLACE DECIMAL	DRAWN			TITLE:	
	CHECKED				
	ENG APPR.				
	MFG APPR.				
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.				
MATERIAL SELECT A MATERIAL	COMMENTS:			SIZE B	DWG. NO. SDM Carrier	REV
NEXT ASSY / USED ON / FINISH Deburred					
APPLICATION / DO NOT SCALE DRAWING				SCALE: 1:2 WEIGHT:	SHEET 1 OF 1



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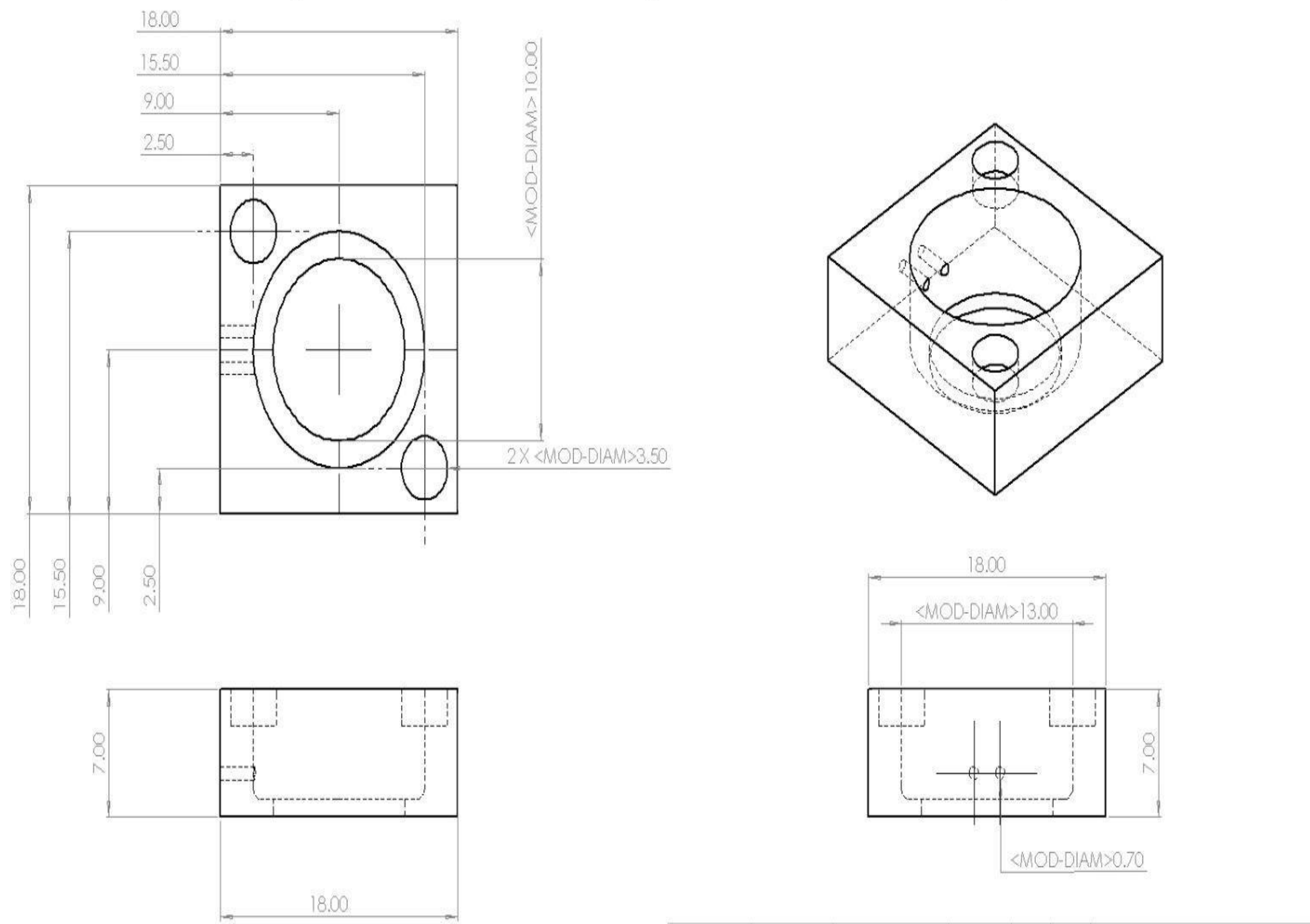
UNLESS OTHERWISE SPECIFIED:		NAME	DATE		
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ANGULAR: MACH BEND TWO PLACE DECIMAL THREE PLACE DECIMAL	DRAWN			TITLE:	
	CHECKED				
	ENG APPR.				
	MFG APPR.				
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.				
MATERIAL	COMMENTS:			SIZE DWG. NO. **B** Housing Top	REV
FINISH					
NEXT ASSY / USED ON APPLICATION	DO NOT SCALE DRAWING			SCALE: 1:2 WEIGHT:	SHEET 1 OF 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL
ANGULAR: MACH BEND
TWO PLACE DECIMAL
THREE PLACE DECIMAL

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

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

TITLE:

SIZE DWG. NO. REV

Sensor Carriage

SCALE: 4:1 WEIGHT: SHEET 1 OF 1