

# Rotor Test Rig



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# Abstract

This paper explains the use and need for a rotor test rig system and how the team produced a design that can experiment with different propellers that can have their pitch angle adjusted. The apparatus is designed to test the various forces that could be applied to propellers in everyday life. Having a small-scale model to work with could drastically help many industries with their testing. The team's design features a straightforward way to change out propellers and adjust the pitch angles of said propellers to perform the required tests.

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Key words: Rotor test rig, Propellers, Pitch

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## Introduction

Rotor test stands play a crucial role in testing and validation of rotating machinery. Two stands were provided to the team that needed an apparatus designed to attach to them. The apparatus includes a motor that mounts to the stand and a hub with propellers that attach to the motor. The first and second design constraints are that the propellers must be able to be manually adjusted to modify the pitch angle and need to be removable to allow for distinct size and shapes of propellers. The third design constraint is speed, the small and medium rotor test rigs need to reach a Mach tip speed of 0.25 and 0.30, respectively. These test rigs could be of immense value to a wide variety of clientele. This clientele includes the aerospace, wind turbine, automotive, teaching, military, and fan industries. Each of these industries could benefit from the rotor test rig, as it is a small-scale device that is easily operated and offers a wide variety of testing capabilities.

## Project Stand

Two test stands were provided to the team by Dr. Li. and were manufactured by Tyto Robotics. These two test stands can be viewed in figures 1 and 2 in the appendix. The test stand in figure 1 is the smaller of the two stands. This stand mounts to the tabletop. The stand shown in figure 2 is self-standing.

## Opportunity Description

The team has been tasked with designing two hubs, one that can attach to the small test stand and one that can attach to the medium. These hubs must be able to accept off the shelf propellers for easy replacement and testing. This hub must also be able to adjust the pitch angle of the propellers to allow for a variety of testing scenarios. The last design constraint is the Mach tip speed of the blades as mentioned before.

## Stakeholders

Stakeholders for this apparatus could include the aerospace industry, automotive industry, renewable energy industry, marine industry, drone industry and educational institutions. These stakeholders could benefit from this rotor rig, as it could make testing propeller designs easier. The apparatus is portable and can be moved from room to room as long as safety procedures are followed i.e., netting around the device. With the blades being removable it allows for a wide variety of propellers that could be tested. That's why these industries could benefit from this product.

# Engineering Principles

Some engineering principles being used during this project include safety, physics, strength in materials, thermodynamics, sustainability, efficiency, manufacturability, reliability and aerodynamics. This project deals with forces so some knowledge of physics is needed, it also uses strength in materials as it is comprised of a few of them. Thermodynamics is being used as we are using the flow of energy and aerodynamics is being used as it affects the overall performance of the system. Sustainability, efficiency, manufacturability and reliability have to do with all products being made, the product being produced needs to be as good as it can be.

## Job Hazard Analysis

Assessing the hazards of a job can play a huge role in reducing the number of injuries that can occur. Even simple things people don't think about can cause a serious injury. It is imperative that each job has a job hazard analysis. Refer to tables 1 and 2 below for the team's analysis.

Table 1: Grading criteria for job hazard analysis

Severity			Probability		
Score	Classification	Description	Score	Classification	Description
1	Catastrophic	May cause death	A	Very Likely	Very likely to occur frequently
2	Critical	May cause severe injury or illness	B	Probable	Probably will occur at some time
3	Marginal	May cause minor injury or illness	C	Occasional	May occur infrequently
4	Negligible	Will not cause injury or illness	D	Remote	Unlikely, but possible
			E	Improbable	Very unlikely. Can be assumed to never occur

Table 2: Rotor test rig job hazard analysis

Hazard	Description	Severity	Probability	Mitigation Strategies
Electrical Shock	Getting shocked by electrical connections	3	D	Inspect connections and wiring, wear gloves and eye protection
Falling Objects	Objects falling from elevated surfaces may cause injury	3	E	Secure all tools and parts, wear closed toe shoes
Pinching	Moving parts could potentially pinch you	3	C	Wear gloves while handling

Motor failure or malfunction	Motors may overheat	2	E	Allow sufficient time for cooling after motor is shut off, wear gloves
Rotational injury	Fast spinning propellers could cause serious injury	2	D	Netting will be put up between people and testing rig
Sharp objects	Machined metal parts could have sharp edges	3	C	Wear gloves while handling
Flying Debris	While testing parts may come loose and cause injury	1	D	Netting will be put up between people and testing rig

## EHS

To ensure the safety and health of operators, it is recommended to use personal protective equipment (PPE), such as earplugs, to mitigate noise exposure during operation. Additionally, an emergency stop mechanism will be incorporated to immediately cut power in case of any malfunction. Areas with rotating parts will be clearly marked, and safety barriers will be constructed to prevent accidental contact.

Efficient fabrication processes are essential for sustainability. Minimizing material waste during manufacturing can be achieved through the use of CNC machining or additive manufacturing (3D printing) with optimized designs. These methods not only reduce any waste but also help to improve the overall efficiency of the fabrication process.

Usability is a key factor in the design of the rig, ensuring it is intuitive and user-friendly. It is also crucial to ensure that the rig complies with international standards for safety and performance.

## Codes and Standards

The Engineering Codes and Standards provided in this section are applicable and instrumental in providing guidance to the total scope of the engineering design process. As progression is made, the codes and standards will go through a filtration process to see what codes and standards are applicable and imperative. As of now, the current phase of the design process is the fabrication phase and experimentation. There will be codes that are applicable to fabrication and experimentation. The formatting of the of the codes and standards are based upon the classifications of the materials, subassemblies and individual components, electrical circuitry, electronics, flight worthiness, testing and functionality.

### **Load Cell:**

*ASTM E4-24 Standard Practices for Force Calibration and Verification of Testing Machines:*

This standard addresses the calibration and verification of force-measuring systems ensuring the accuracy and reliability of load measurement on test stands.

**Propeller Design:**

CFR 73 FR 63339 - Airworthiness Standards; Propellers: This regulation outlines the propeller design, including safety, performance, and testing requirements for propellers used in aircraft. It establishes the minimum criteria for certification and approval of propellers to ensure they meet airworthiness standards.

ASTM F3065/F3065M-21a Standard Specification for Aircraft Propeller System Installation: This standard specifies the requirements for the installation of aircraft propeller systems, including both fixed-pitch and variable-pitch propellers. It covers considerations such as mounting, vibration, power absorption, and alignment to ensure proper integration into the aircraft.

**Variable Pitch Propellers:**

14 CFR § 35.21 - Variable and reversible pitch propellers: This code specifies the requirements for variable-pitch and reversible-pitch propellers. These propellers can adjust blade angle in flight to optimize performance, and the regulation outlines the criteria for their design, testing, and certification.

**Propeller Control Systems:**

14 CFR § 35.23 - Propeller control system: This CFR outlines the standards for the design and testing of propeller control systems, which are responsible for adjusting the pitch of the propeller blades. The system must ensure reliability, safety, and functionality under normal and emergency conditions.

14 CFR § 35.42 - Components of the propeller control system: This section defines the components that make up the propeller control system, such as governors, actuators, and feedback devices, and sets performance and safety criteria for their operation in variable-pitch and reversible-pitch propeller systems.

**Motor:**

CFR 14 CFR § 91.407 - Operation after maintenance, preventive maintenance, rebuilding, or alteration: This regulation provides guidelines for the safe operation of an aircraft after maintenance, repair, or modification, including the motor and propeller systems. It ensures that maintenance work is properly documented, and that inspections are performed to ensure continued airworthiness.

IEC 60034 Standards for rotating electrical machinery, performance, safety and efficiency standards: It covers the design, performance, safety, and efficiency requirements for rotating electrical machinery, including motors. It sets standards for electrical performance, vibration limits, and insulation to ensure the proper functioning of motors, such as those driving propellers, in a safe and efficient manner.

**Material:**

ASTM E8/E8M-24 Standard Test Methods for Tension Testing of Metallic Materials: This standard specifies methods for testing metallic materials under tension. It provides guidelines for determining the mechanical properties of materials used in propellers and other critical

components, such as tensile strength, yield strength, and elongation, which are crucial for evaluating material performance under operational stresses.

### **Functionality/Testing:**

ASTM F2590-06(2022) Standard Specification for Bearing, Roller, Thrust, Two Channeled Race Surface, Rigid or Flat Seat Type: This standard specifies the requirements for roller and thrust bearings used in propeller systems. Bearings are critical components in variable-pitch propeller assemblies and need to be designed and tested for durability, load handling, and performance under various operating conditions.

ASTM E2428-22 Standard Practice for Calibration and Verification of Elastic Torque Measurement Standards- Flight stand calibration: This standard addresses the calibration and verification of torque measurement systems used in flight stand testing. It ensures that torque measurements, which are essential for evaluating propeller performance, are accurate and reliable.

ASTM F2506-22 Standard Specification for Design and Testing of Light Sport Aircraft Propellers: This standard is focused on the design and testing of propellers for light sport aircraft. It outlines performance criteria, including testing on flight stands, to ensure that the propellers meet safety and efficiency standards.

ASTM E74-18e1 Standard Practices for Calibration and Verification for Force-Measuring Instruments: This standard provides guidelines for the calibration and verification of force-measuring instruments, such as load cells used in propeller assembly testing. Accurate force measurement is crucial for determining propeller thrust and efficiency during testing.

### **Electrical/Electronic Codes:**

IEC 61010 - Safety Requirements for Electrical Equipment for Measurement, Control, and Laboratory Use: It specifies safety standards for electrical equipment used in measurement and control applications. This includes any electrical systems or instruments used in propeller test stands (such as motor controllers, measurement instruments, and load cells) to ensure they operate safely and minimize electrical hazards.

IEC 60204 - Safety of Machinery - Electrical Equipment of Machines: This standard provides safety requirements for the electrical equipment used in machinery, including motors and electrical controls. It ensures that electrical systems are designed and maintained with adequate safety features to protect operators and prevent accidents during propeller assembly testing.

## Wiring Diagram

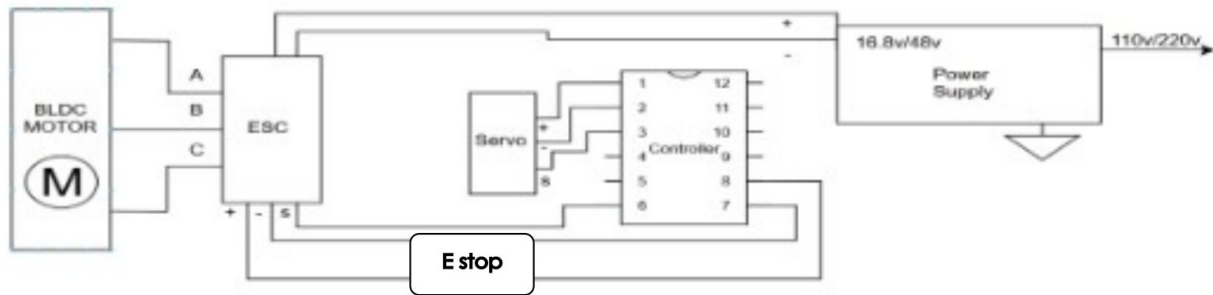


Diagram 1: Wiring Diagram

The wiring diagram shows the overall connections needed to be made at a system level to operate the motor and subsequent propeller hub system. This system incorporates the motor speed controller, the PWM generator, power supply and one of the projected two servo motors in the system needed to allow the angle of attack of the blades to be changed while the Brushless Direct Current Motor (BLDC) is in operation. The system remains the same in connection quantity and placement regardless of which size of motor is in operation. The major system differences are the voltage supplied to the Electronic Speed Controller (ESC) based on the requirements of the motor. The ESC auxiliary power allows power to be sent to the STM32 or PWM generator for operation. This eliminates the need to additional power to be run to the system outside of the main 16.8 or 48 voltages.

## Design Supporting Analysis

While the project objectives did not require the ability to alter the pitch of the propellers while the hub is in use, our team wanted to go above and beyond to challenge ourselves.

To enhance the ease of assembly for our hub, a split hub case design has been selected. The internal mechanical assembly is constructed separately and subsequently positioned between the hub cases before the two halves are conjoined. Utilizing standard-sized fasteners and bearings allows us to efficiently order the parts and ensure timely delivery.

The nose cone serves as both a cover for the hub case assembly and a mechanical linkage that connects the actuation ring to the plunger. The plunger, in turn, connects to the cams that drive the pitch via small linkage arms. The propellor clamps function as their own axle, passing through the bearing and the cam. The cam is secured to the propellor clamp by a small screw, ensuring proper leveling of the propeller and preventing the arm from sliding through the bearing and becoming a projectile. The bearing is clamped in place between the two halves of the hub case, facilitating easy installation and secure positioning. Before clamping the halves together, a nut is placed in the cutout so that the threaded collet can be inserted into the hole on the bottom and the entire assembly can be rotated, tightening the threaded collet to the motor.

The design of the propellor clamps were made to be simple to operate while maintaining a secure connection with the propellers that are being tested. The design allows a range of propellers to be used with very little modification to the propellers due to the clamping design.

The hub as a whole was designed to have an extended lifespan and last indefinitely provided maintenance and cleaning are conducted on a regular basis. This allows for the use of our design by students and the faculty of Oklahoma State University for years to come.

### Maintenance:

Before a testing session using the hub it is recommended to inspect the hub for wear and damage, and ensure all fasteners are tightened.

It is recommended that every 6 months or 10 testing sessions (whichever comes first) that the hub is disassembled and inspected for wear and damage, and the bearings are relubricated before reassembly.

## Detailed Drawings

As a keynote, in this section only the drawings provided below are the final steps of the small scale and medium scale Testing Rotor Rig in conjunction with their perspective subassemblies. The figures are duplications, and all the detailed drawings are in the Appendix. The figures in this section do not appear in an increasing numeric order, but rather as subassemblies to assemblies.

The details of the drawing are the final drawings of the critical design review but are subject to change. These drawings components, dimensions and threshold of complexity may vary as the fabrication phase initializes especially during the experimentation and functionality assessment phases. The drawings will be updated in accordance with the necessitated adjustments and annotations will be reflected on the drawings. Some of the drawings have threaded ends, but are not depicted in the drawings, but it is referenced in the assembly drawings. The drawings in the appendix display both the small and medium scaled detailed drawing of the flight stands, fabrication drawings and the assembly drawings.

The major distinction between the small and medium scale designs is primarily the dimensions with additional configurations designed for operation and bracing/reinforcement. There are many minor configurations made to the medium scale design as in Figure 43 below illustrates there being a motor shaft extension, it will connect the motor and will be threaded into hub assembly. The small assembly (Figure 34), motor shaft will be directly threaded into the hub assembly. The small assembly only contains two spring sub-assemblies, its function is to control and change the Angle of Attack on for the propellor blades, and the platform only has two holes for the spring assemblies to be mounted onto. The medium scale has three spring assemblies to help with weight distribution and to mitigate any vibrations. There are four holes in the platform for the medium scale, the fourth hole is marginal and maybe used for other purposes but may provide another structural support to stabilize the rotor rig.

There were many configurations and a last-minute adjustment that were being considered and some of the considerations are mentioned but are not visual. One consideration was the plunger cover will be secured to the actuator ring by applying a compressional force to the plunger cover to lock it into the actuator ring. This consideration is imperative because it must be properly secured and able to withstand coming loss due to change in angular velocity. In figure 38, the grooves in the plunger cover are not visually, but are annotated. For the spring assembly in Figure 45 below, the slot pin (Appendix Figure 19) will be threaded into the stopper and will be locked into place with a cotter pin. This modification is referenced, but not visually shown within the figure.

The hub assembly has many different components and will be the most intricate assembly in totality due to dual axial rotations (the hub rotating and the change in pitch). The propellor blades will be primarily locked by compressive spring connection in the propellor clamp arm, it will be secured with a screw going through it being secured into the internal cam. There will be a pin connection added into the propellor clamp arm as a secondary security feature for the propellor blade. The plunger arm (Appendix Figure 29) will be connected to the plunger (Appendix Figure 23). The functionality of the internal components for this hub assembly is to create the variable pitch for the propellor blades as shown in Figure 38. The hub case will hold all of the internals together and will have the hex nut and collet inside to be mounted onto the motor, in conjunction to the plunger cover and actuator ring being connected.

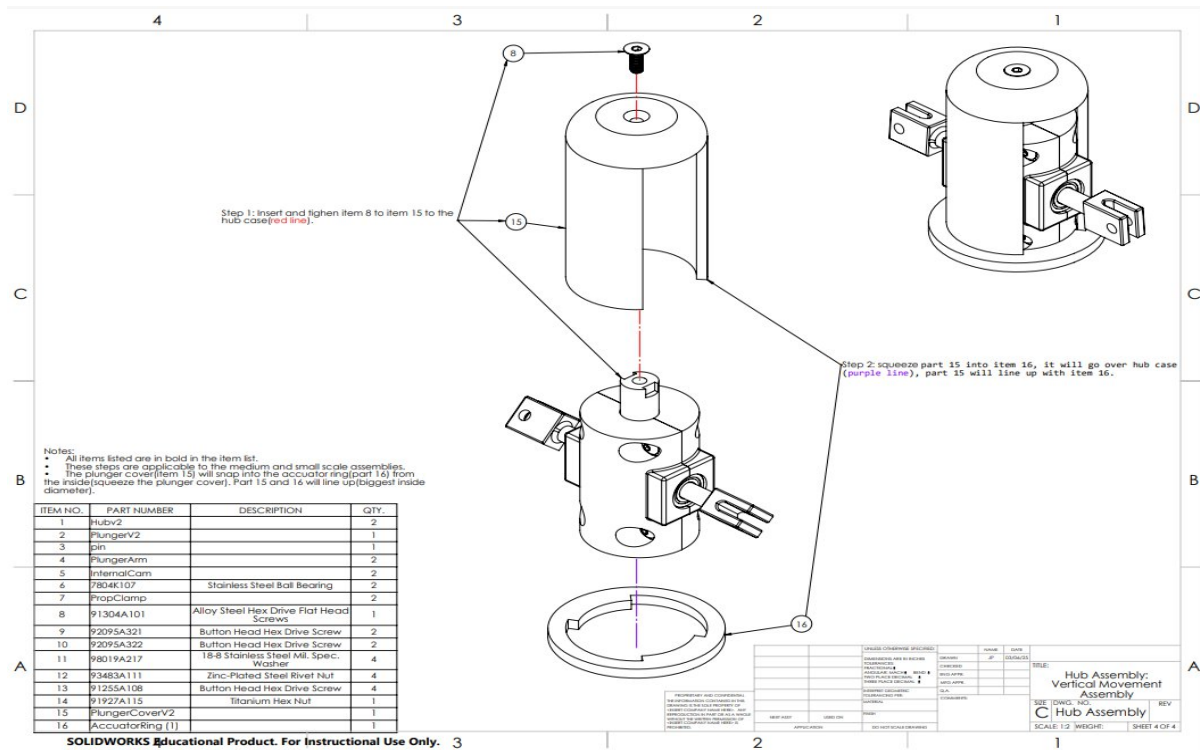


Figure 38: Hub assembly: Vertical movement assembly

The spring assembly is a simple assembly with only five components as shown in figure 45 below. The stopper will be inserted into the damper shell that will have spring and be locked

in with the slot pin. The slot pin is responsible for locking in everything and allowing to move within the slot in the damper shell. This controls the movement of the stopper which will cause motion in the platform and be translated in changing the pitch angle. The spring was implemented as a mechanical control device by providing resistance in the range of motion.

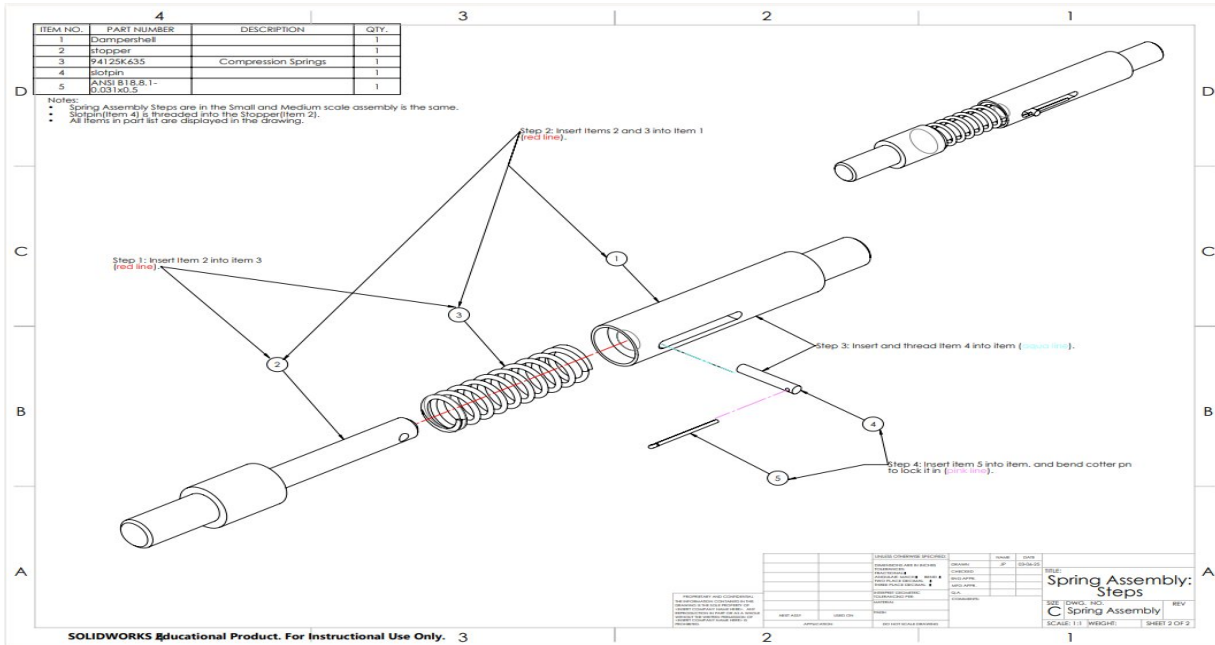


Figure 45: Spring assembly steps

In figures 34 and 38 shown below are the last steps of the assemblies. The motor is secured to a support bracket and secured to the flight stand. The spring assemblies are secured directly to the flight stand in the small assembly, but it in the medium assembly it is secured to the support bracket because dimensional issues with the medium scale flight stand.

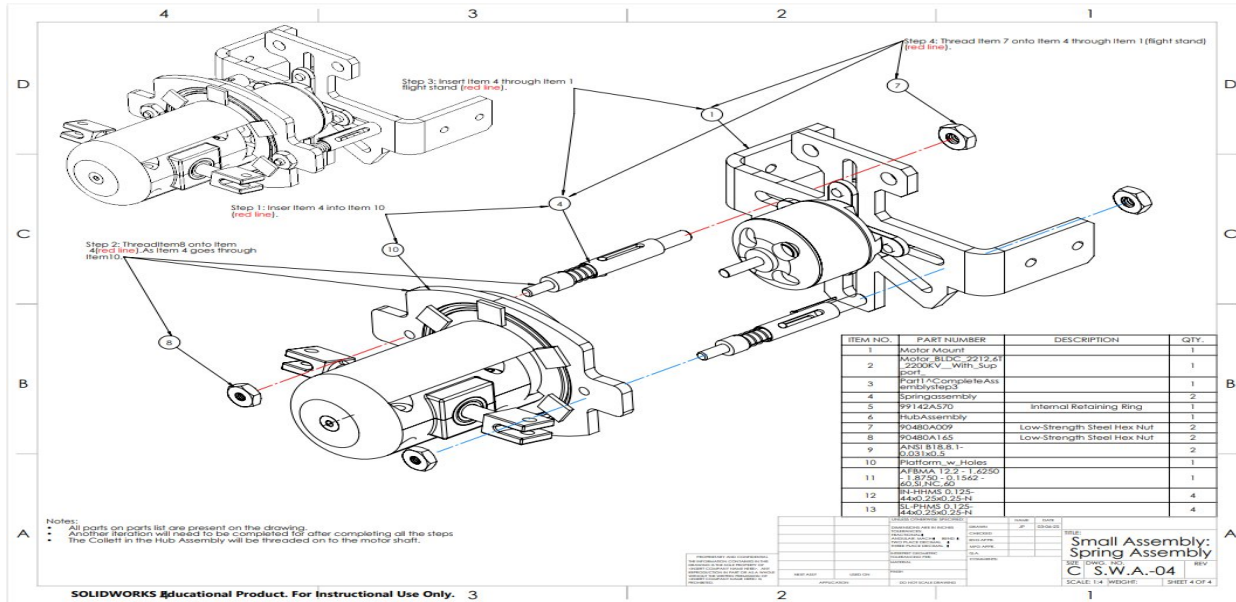


Figure 34: Small assembly: Spring assembly

The motor shaft extension will be threaded onto the motor directly followed by the hub assembly being secured to the extension component. The Platform will have multiple components within it such as a bearing to allow rotation, the actuator ring, and the internal retaining ring to properly secure everything.

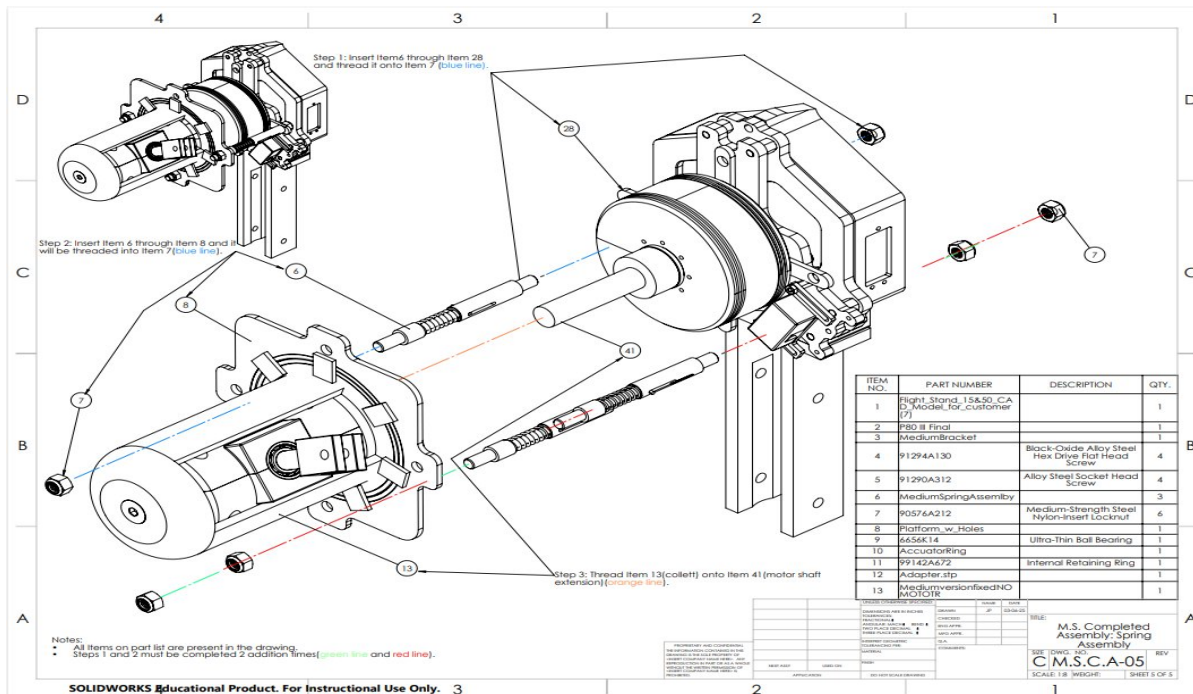


Figure 43: Medium assembly: Spring assembly

## Motor Specifications & Calculations

$$K_v = 100$$

$$I = 80_{run} 105_{peak}$$

$$K_T = \frac{60}{2\pi K_v} = 0.0955 \frac{N \cdot m}{A}$$

$$T_{stall} = K_T I_{run} = 7.64 ft \cdot lb$$

$$T_{peak} = K_T I_{peak} = 10.03 ft \cdot lb$$

$$T_{motor} = K_T I_{motor} = 5.59 ft \cdot lb$$

$$RPM_{max} = K_v 48v = 4800RPM$$

$$P_{low} = VI = 48v \cdot 58.5A = 2808W \rightarrow 3.76HP$$

$$P_{high} = VI = 50.4v \cdot 58.5A = 2948W \rightarrow 3.95HP$$

$$Max\ ESC\ Power = VI = 48v \cdot 105A = 5040W \rightarrow 6.76HP$$

$$T_{reported} = 102.9N$$

$$\rho_{air} = 1.225 \frac{kg}{m^3}$$

$$d = 1.016m$$

$$N = \frac{RPM}{60} = 32.24RPS$$

$$RPM = \frac{T_{reported}}{\pi d} = 32.24RPS \rightarrow 1934.30RPM$$

$$C_T = \frac{T_{reported}}{\rho N^2 d^4} = 0.0758$$

$$Assumed\ C_p = 0.05 \& 0.06$$

$$T = C_p \cdot \rho \cdot N^2 \cdot d^4 = 102.84N$$

$$P_{low} = C_p \cdot \rho \cdot N^3 \cdot d^5 = 2222.08W$$

$$P_{high} = C_p \cdot \rho \cdot N^3 \cdot d^5 = 2666.50W$$

## Hazard Analysis

The Hazard Analysis Table for the rotor test rig systematically breaks down potential issues in the different systems (test rig, electrical system) and then into specific subsystems (rotor, mounting plate, fastening system) to identify failures, their causes, and mitigations. Under the system “Test Rig” and subsystem “Rotor”, for instance, a failure is “shaft failure” from overload due to excess torque or misalignment, and this can be mitigated with regular inspections and alignment before test runs. Under the system “Mounting Plate”, “loose bolts” can be due to under tightening or vibration in operations and the mitigation for that is using thread-locking material and the proper torque specification. Other systems such as “Electrical Wiring” or “Software” cover a variety of problems such as short circuits to incorrect automation sequences. Every entry in the chart provides a concise, cause and effect overview, and enables the team to find a mitigate hazards through design, operation procedures, and maintenance.

## Testing Objectives

The primary testing goals for the rotor test rig are to confirm system performance with a Mach tip speed  $\geq 0.3$ , ensure the safety and reliability of the system, and ensure proper pitch change during operation. This will be accomplished through thrust, torque, and RPM measurement over a variety of tests to confirm that all the different systems such as the rotor hub, mounting plate, and electrical controls are in their respective tolerances. Detailed structural stability tests and accuracy tests help to determine whether or not the design can withstand expected operating conditions without failure. These tests are also used to confirm proper vibration control and confirm alignment between critical components. The test process will ensure that the rig meets project goals and provides consistent, reproducible results for further development.

## Testing Workflow

The process of testing begins with a full pre-test mounting in which all sensory components are mounted and aligned properly. Electrical connections are then verified along with grounding procedures. A protective enclosure is installed to protect the team against a catastrophic failure of the system. Once powered, the system is tested with incremental RPM steps with thrust, torque, and vibration measured in real-time. This incremental RPM step allows mechanical or electrical faults to be identified in advance. A pitch rotation of  $5^\circ$  will be done every RPM step to ensure the pitch hub system is working properly and can maneuver despite increased RPM. Post-test evaluation is carried out after each test run whereby measurements are references against design limits and recorded.

## Quality Control

Quality control processes ensure consistent and reliable test results throughout multiple test cycles. This includes visual inspections for faults or misalignment on mechanical components such as the propellers, bearings, and fasteners. Periodic recalibration for sensors is done is also included in the quality control to obtain accurate thrust and torque readings. All tests, calibration checks, and maintenance are thoroughly documented to ensure a detailed performance history that will allow easy traceability.

## Acceptance Criteria

The acceptance criteria for the rotor test rig are performance, reliability, safety, and accuracy in data. Crucial factors such as thrust, torque, and RPM should remain within  $\pm 0.5\%$  of their measured values to confirm accuracy in the rig and sensors. All hardware is to be visually and functionally tested as well as measured to confirm drawing specifications which will confirm hardware integrity. The system should then demonstrate continuous operation for 30-minute test cycles to confirm reliability in real use. Accurate data logging and documentation should be carried out to confirm that all results obtained match original design specifications.

## Final Validation Plan

The final validation plan consists of rigorous tests to confirm that the rotor test rig is field ready. Stress testing is performed by pushing the system to 110% of the maximum design specifications, with emphasis on how pitch angles affect system durability and component performance as well as the overall integrity of the system. Environmental testing consists of exposing the rig to extremes in temperature and humidity to confirm ruggedness in different atmospheric conditions to obtain its operating limits. Operational training may be provided to introduce users to safe procedures, proper equipment handling, and effective troubleshooting.

## Testing Results

After tracking the rotations per frame on the small and medium testing rigs we were able to find out that they did exceed the required mach tip numbers. Below is a table of the data that was recorded.

Table 3: Small assembly testing results

<b>Metric</b>	<b>Value</b>
RPM (Measured)	14,400 RPM
Tip Speed	191.4 m/s
Tip Mach Number	0.558
Prop Diameter	10

Table 4: Medium assembly testing results

Metric	Value
RPM (Measured)	2063 RPM
Tip Speed	109.8 m/s
Tip Mach Number	0.32
Prop Diameter	40

## Costs (BOM)

Below is an updated list of materials and their associated cost. Since much of the system in being manufactured as new components the raw materials were the only cost associated with the individually listed parts listed. There are additional services listed in the event that there is not a realistic way to manufacture certain parts with the tooling available to the team.

Small/Medium Rotor & Additional Considerations				
Description	Quantity	Per	all Units	
Small Brushless Motor	1	20	\$20.00	
Mounting Plate	1	0	\$0.00	
Machined/Bent Steel Plate	1	15	\$15.00	
Brass or Delryn Upper Plunger Comp	1	15	\$15.00	
Carbonfiber-Nylon 3D Print	1	65	\$65.00	
Machined Brass Cam	2	15	\$30.00	
Bearing for mounting prop on housing	4	7.26	\$29.04	
Large ID Bearing for platform	1	40	\$40.00	
CF-Nylon 3D printed moveable platform	1	15	\$15.00	
ID Mounting Ring for nosecone/Control Arms	1	5	\$5.00	
Machined Brass Control Arms for Cam control	2	35	\$70.00	
Propeller Through-hole Spring Clamps	2	45	\$90.00	
Modified Off-The-Shelf Propellers	2	25	\$50.00	
Hardware Kit	2	50	\$100.00	
3D Printed Nose snap-on Nose Cone	1	2	\$2.00	
High Current Speed Controller	1	415	\$415.00	
MISC	1	80	\$80.00	
Internal Retaining Ring	1	7.47	\$7.47	
Cotter Pins	1	20.94	\$20.94	
Steel Hex Nut 5-44 Thread Size	1	3.89	\$3.89	
Steel Hex Nut 8-32 Thread Size	1	2.02	\$2.02	
Compression Springs	1	11.6	\$11.60	
Rivet nut	8	4.14	\$33.12	
Hex Drive Screw	1	16.53	\$16.53	
Washers	1	7.68	\$7.68	
Hex Drive Screw	1	4.99	\$4.99	
Hex Drive Screw	1	7.14	\$7.14	
Titanium Hex Nut	2	7.19	\$14.38	
Hex Drive Flat Head Screw	1	9.1	\$9.10	
Slotted Spring Pin	1	11.14	\$11.14	
Drill Bits	1	4.99	\$4.99	

Description	Quantity	Per	all Units
6s-12s BLDC motor	1	249.99	\$249.99
Mounting Plate	1	189	\$189.00
Machined/Bent Steel Plate	1	0	\$0.00
Brass or Delryn Upper Plunger Comp	1	18	\$18.00
Carbonfiber-Nylon 3D Print	1	18	\$18.00
Machined Brass Cam	1	78	\$78.00
Bearing for mounting prop on housing	4	8.75	\$35.00
Large ID Bearing for platform	1	59.99	\$59.99
CF-Nylon 3D printed moveable platform	1	48	\$48.00
ID Mounting Ring for nosecone/Control Arms	1	18	\$18.00
Machined Brass Control Arms for Cam control	1	6	\$6.00
Propeller Through-hole Spring Clamps	2	42	\$84.00
Modified Off-The-Shelf Propellers	2	54	\$108.00
Hardware Kit	2	30	\$60.00
3D Printed Nose snap-on Nose Cone	2	60	\$120.00
120A ESC	1	0	\$0.00
Rivet Nuts	2	8.07	\$16.14
Hex Drive Screw	1	14.41	\$14.41
Black-Oxide Steel Oversized Washer	1	7.12	\$7.12
Button Head Hex Drive Screw	1	8.64	\$8.64
Button Head Hex Drive Screw	1	9.44	\$9.44
Hex Drive Flat Head Screw	1	17.65	\$17.65
Steel Nylon-Insert Locknut	1	23.41	\$23.41
Retaining Ring	2	5.43	\$10.86
Compression Springs	1	11.6	\$11.60
Hex Drive Flat Head Screw	1	6.36	\$6.36
Socket Head Screw	1	12.48	\$12.48
Servo Motor	2	13.59	\$27.18
Arduino Uno	1	27.99	\$27.99
Potentiometer	1	13.99	\$13.99
4 Gauge Wire	1	39.99	\$39.99
12 Gauge Wire	1	29.99	\$29.99

Total ~ 2027.63

## Project Risk Management

The project risk management plan includes a color-coded matrix to prioritize risks in terms of likelihood and ability to influence schedule time and cost. Small problems like small alignment rework is at the low end and will result in a delay of less than a day and minimal cost overruns. Mid-level risks include imprecise tolerances or small machining errors requiring redesign or additional machining time, with a potential for up to five days' delay and additional cost. Large and serious risks such as large machining rework or catastrophic material failure have extensive downtime and high budget overruns. To mitigate these problems, strategies such as early tolerance analysis, prescheduling machining operations, thoroughly testing materials prior to machining, and using 3D-printed prototypes for early fit and verification will be employed. These processes ensure risks are tracked, responded to in a timely fashion, and minimized.

## Project Plan

Effective project planning and management have been essential in ensuring the success of our rotor test rig project. To facilitate this, we utilized Smartsheet Gantt charts, allowing for detailed scheduling, dependency tracking, and progress monitoring. The Gantt chart provided a

clear visualization of our project timeline, highlighting critical design phase milestones, task assignments, and potential bottlenecks.

During the Critical Design Phase, our focus was on finalizing technical details and validating the feasibility of our design choices. The Gantt chart played a crucial role in keeping our project on track by clearly defining task dependencies and ensuring proper sequencing of activities.

- Defining clear dependencies early helped prevent timeline misalignment and delays in critical tasks.
- Gantt chart tools provided structured project tracking, allowing the team to monitor progress and adjust plans as needed.
- Baseline tracking was implemented to compare actual progress against planned objectives, helping us mitigate potential risks and scope changes.

By leveraging these project management strategies, we maintained a structured approach to design execution, minimizing inefficiencies and optimizing resource utilization.

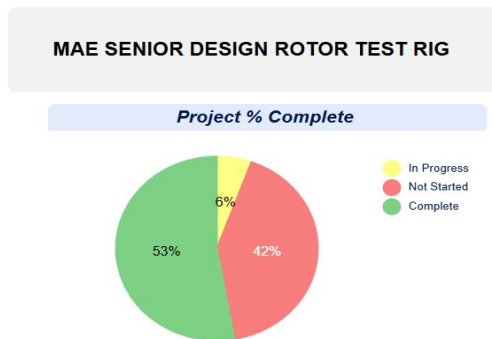
Health	Status	Task	Assigned To	Allocation Percent	Begin Date	End Date	% Complete
●	Complete	- Detailed Design			02/03/25	03/07/25	
●	Complete	Begin Formulating SOP	A andrew.pace@okstate.edu	20%	02/03/25	02/13/25	1
●	In Progress	Machine Training (in Stillwater)	I jordan.pascoe@okstate.edu	20%	02/14/25	02/14/25	
●	Complete	Standard Operating Procedure (SOP) Submitted to Project Mentors	A andrew.pace@okstate.edu	20%	02/14/25	02/14/25	1
●	In Progress	Standard Operating Procedure (SOP) Submitted to Safety Review Board (SRB)	I jordan.pascoe@okstate.edu	20%	02/21/25	02/21/25	1
●	Complete	Conduct Detailed Engineering Analysis of all Components	E ethan.w.brown@okstate.edu	20%	02/03/25	02/04/25	1
●	Complete	Lead on Build-Ready Engineering Drawings	I jordan.pascoe@okstate.edu	20%	02/05/25	02/05/25	1
●	Complete	Prepare Detailed Bill of Materials	J jesse.brownfield@okstate.edu	20%	02/06/25	02/06/25	1
●	Complete	Update Project Plan to include Fabrication and Testing	B brandon.bradshaw@okstate.edu	20%	02/07/25	02/07/25	1
●	Complete	Design Advice Appointment	B brandon.bradshaw@okstate.edu	20%	02/10/25	02/10/25	1
●	Complete	Platform Actuation Design	I jordan.pascoe@okstate.edu	20%	02/11/25	02/14/25	1
●	Complete	Spring Clamp Bearings/Cam Assembly	A andrew.pace@okstate.edu	20%	02/17/25	02/17/25	1
●	Complete	Begin Preparing Presentation for Detailed Design	Team		02/17/25	02/20/25	1
●	Complete	Problem or Opportunity Description	A andrew.pace@okstate.edu	20%	02/17/25	02/20/25	1
●	Complete	Detailed Design	I jordan.pascoe@okstate.edu	20%	02/17/25	02/20/25	1
●	Complete	Testing and Quality Plan	B brandon.bradshaw@okstate.edu	20%	02/17/25	02/20/25	1
●	Complete	Costs	J jesse.brownfield@okstate.edu	20%	02/17/25	02/20/25	1
●	Complete	Work Breakdown Overview	A andrew.pace@okstate.edu	20%	02/17/25	02/20/25	1
●	Complete	Project Plan	GG Gonzalo Garcia Garcia	20%	02/17/25	02/20/25	1
●	Complete	Design Advice Appointment	B brandon.bradshaw@okstate.edu	20%	02/20/25	02/20/25	1

Chart 1: Gantt chart of detailed design phase

## Project Dashboard

Additionally, a project dashboard was created to centralize key project metrics and progress indicators. This dashboard enabled the team to track deliverables in real time, ensuring alignment

with deadlines and improving overall project visibility. By incorporating these tools, we were able to maintain organization, anticipate potential risks, and allocate resources efficiently.



Graph 1: Pie chart of progress

## Lessons Learned

Reflecting on our project execution so far, we identified several key lessons learned that will inform our approach moving forward:

- Defining clear dependencies early is crucial to preventing scheduling conflicts and ensuring seamless task execution.
- Using Gantt chart tools significantly improved visibility, making it easier to track progress and adjust timelines as necessary.
- Baseline tracking was an effective way to monitor scope changes and mitigate risks proactively.

Moving forward, we will implement the following:

1. Continue refining resource allocation to balance team workload efficiently and maximize productivity.
2. Ensure all project dependencies are well-defined before implementation to minimize delays and streamline execution.
3. Maintain an adaptive approach to design changes, ensuring flexibility while adhering to project constraints.

By incorporating these lessons into our project management practices, we aim to enhance efficiency and maintain progress toward successful project completion.

## Work Breakdown Overview

Brandon Bradshaw – cover page, abstract, table of contents, introduction, project stand, opportunity description, stakeholders, engineering principles, job hazard analysis, list of figures and figures in appendix

Gonzalo Garcia - project plan, project dashboard, lessons learned

Jesse Brownfield – Costing, Bill of Materials, Wiring Diagram, Original Design Concept, Electronics Specifications, Rotor/Power Calculations, Manufacturing Drawings, motor specifications & calculations

Andrew Pace - EHS, Design supporting analysis, modified pitch hub

Ethan Brown – hazard analysis, testing objectives, testing workflow, quality control, acceptance criteria, final validation plan, and project risk management

Jordan Pascoe - Engineering Codes & Standards, Detailed Drawings, Assembly Drawings, Exploded View Drawings, Spring Assembly drawings, Bill of Materials - lower rotor, Modified the Platform and Spring assembly

Formatting - Team

## Works Cited

Tyto Robotics, 'Series 1585 Thrust Stand Datasheet', V2.4, 2024-08-01

Tyto Robotics, 'Flight Stand 50', V4.1, 2023-06-16

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Leishman, J. G. (2006). Principles of helicopter aerodynamics. Cambridge University Press.

Johnson, W. (1994). Helicopter theory. Courier Corporation.

### Motor Performance and Design

Chapman, S. J. (2011). Electric machinery fundamentals (5th ed.). McGraw-Hill Education.

Boldea, I., & Nasar, S. A. (2006). Electric drives. CRC Press.

### Electronics

#### Pulse-Width Modulation (PWM)

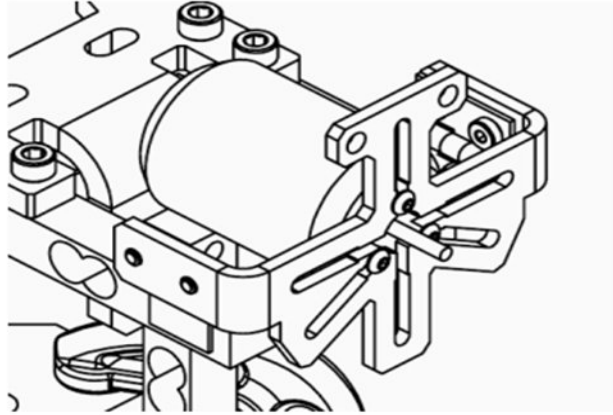
Texas Instruments. (2016). Understanding pulse width modulation (PWM) for motor control [Application note]. Retrieved from <https://www.ti.com/lit/an/slyt209/slyt209.pdf>

### ESP32 Microcontroller

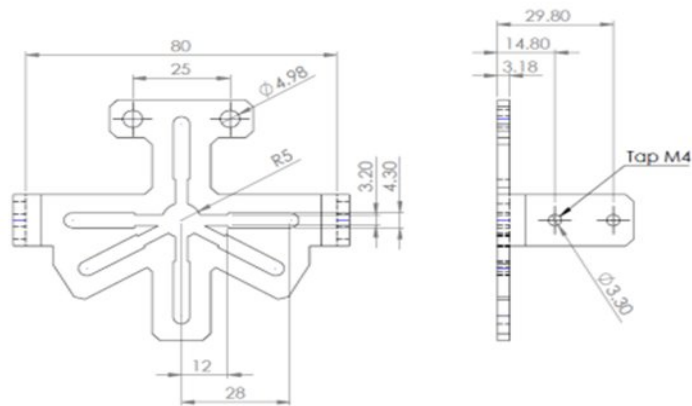
Espressif Systems. (2020). ESP32 technical reference manual. Retrieved from [https://www.espressif.com/sites/default/files/documentation/esp32\\_technical\\_reference\\_manual\\_en.pdf](https://www.espressif.com/sites/default/files/documentation/esp32_technical_reference_manual_en.pdf)

## Appendix

# Flight stands



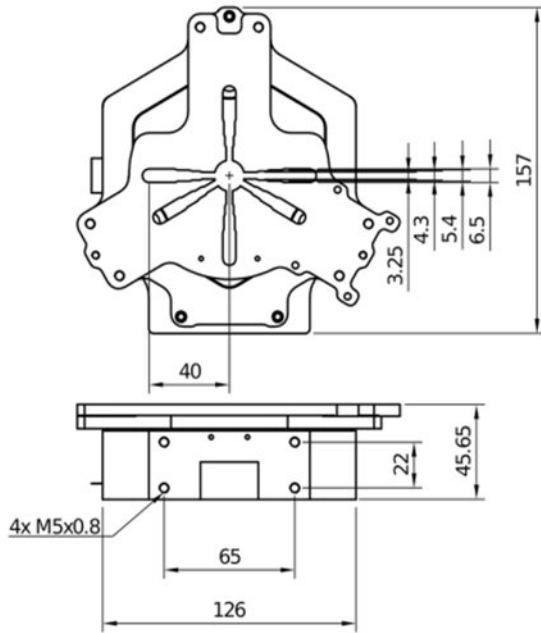
**Fig. 2:** Mounting shown with 36 mm  $\varnothing$  and 53 mm length inrunner motor.



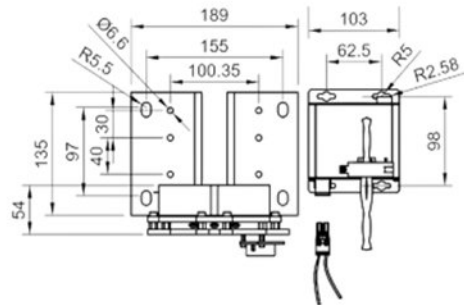
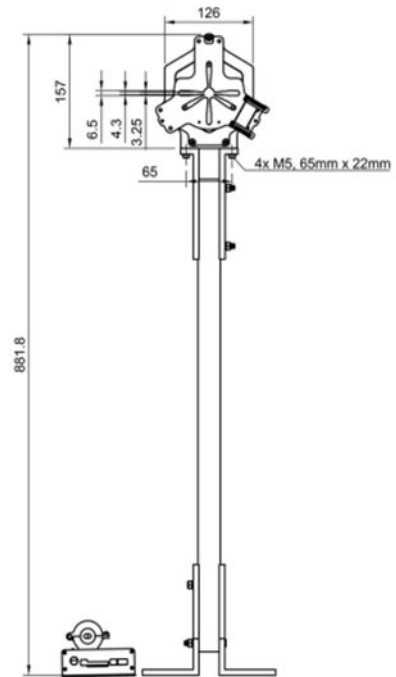
**Fig. 3:** Motor mounting part dimensions

Figure 1: Small test stand

**Force Measurement Unit:**



**Stand Components:**



**Electrical Measurement Unit**

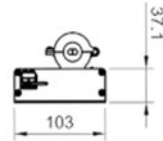


Figure 2: Medium test stand

# Fabrication Drawings

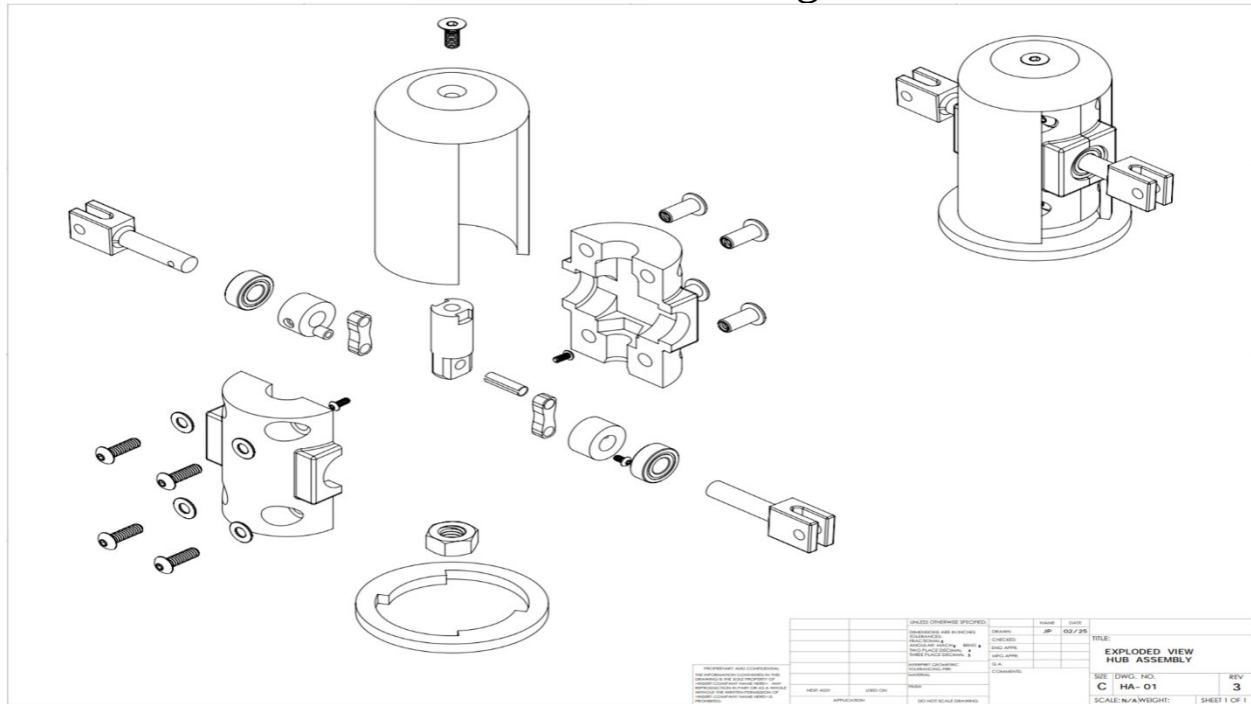


Figure 3: Exploded view hub assembly

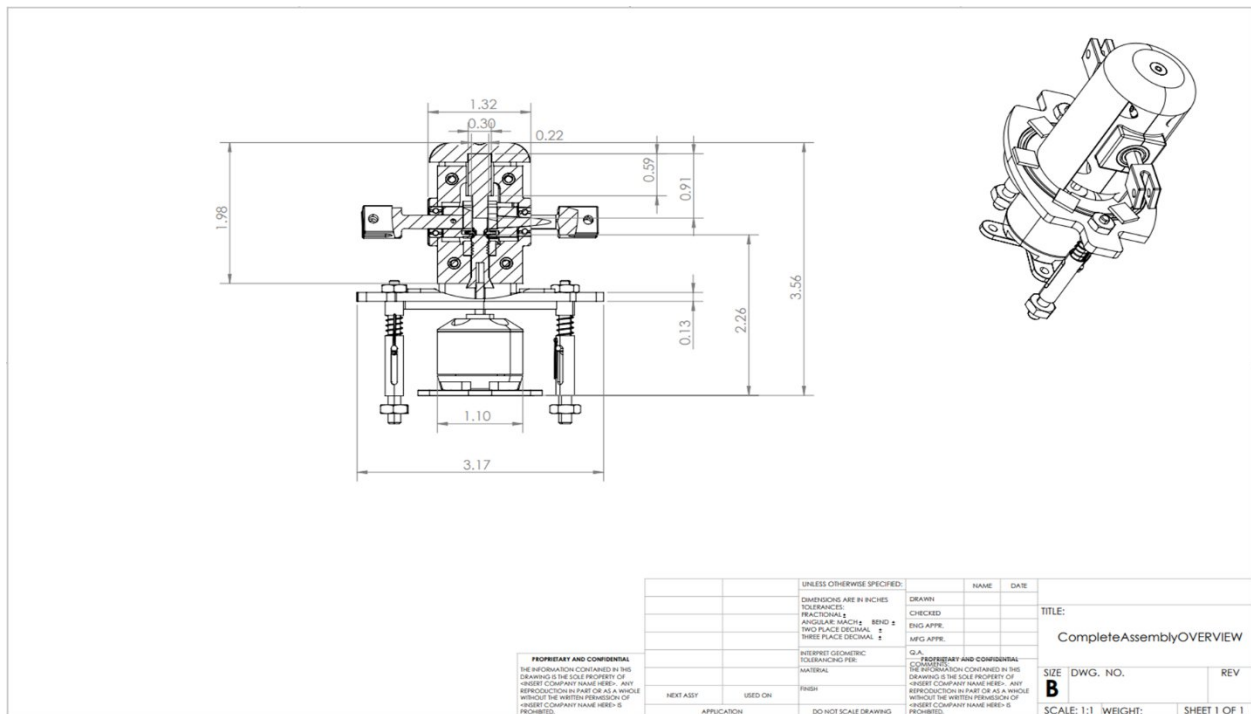


Figure 4: Complete assembly overview

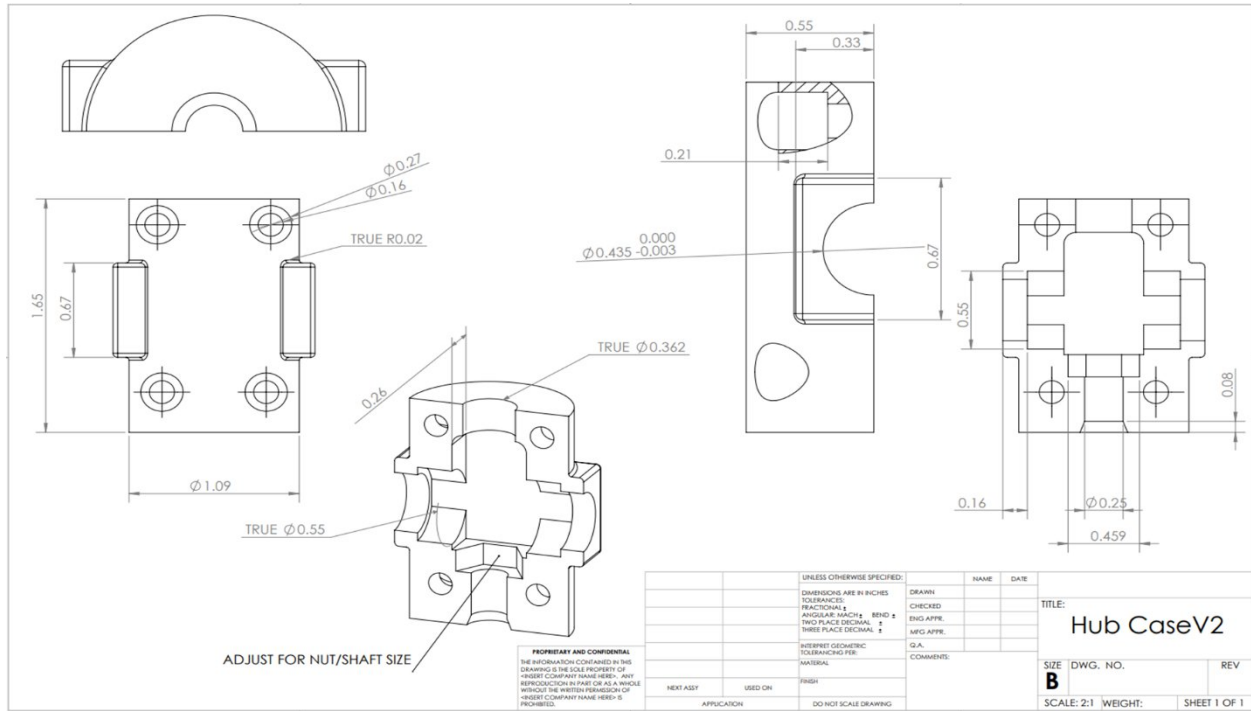


Figure 5: Hub case

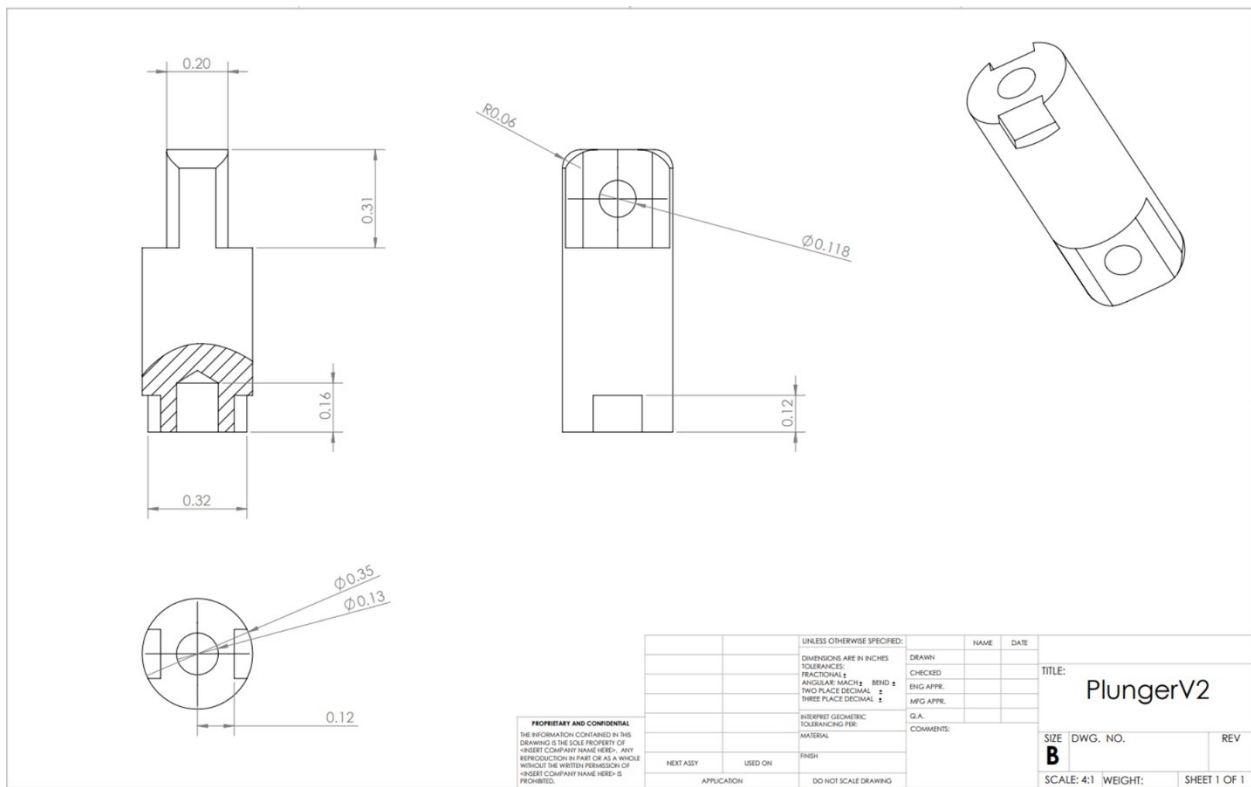


Figure 6: Plunger

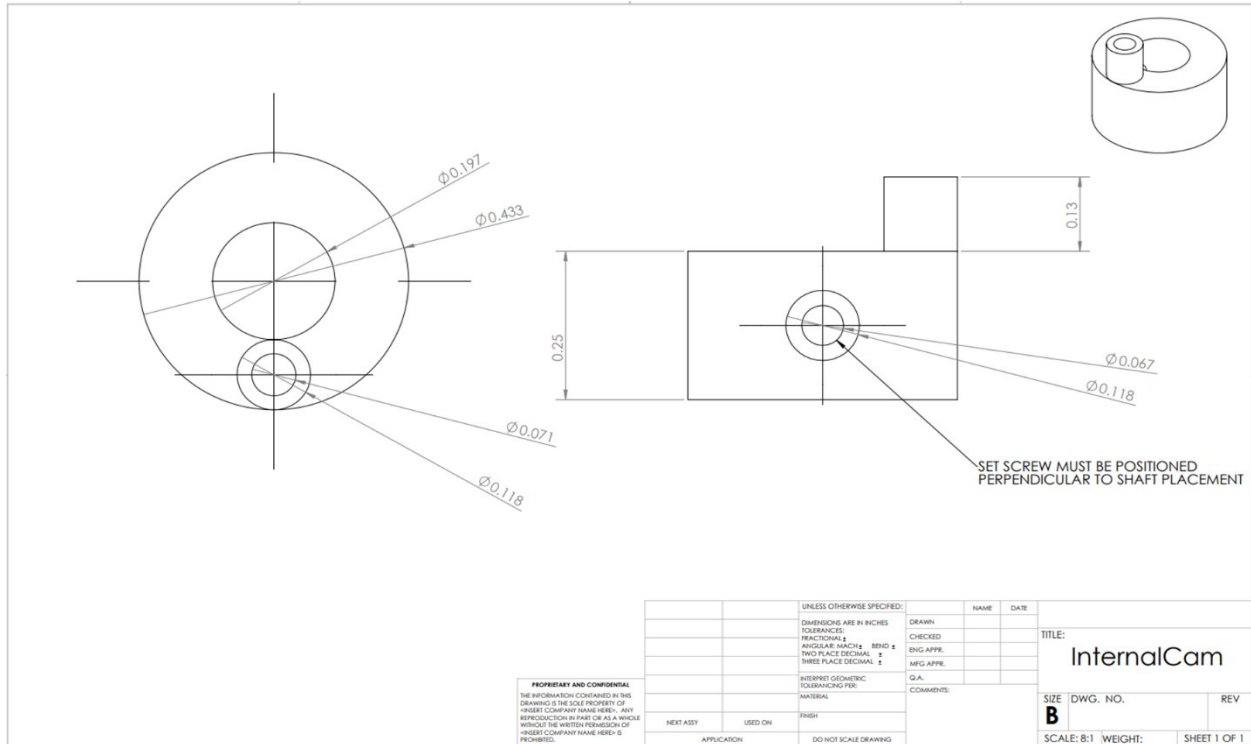


Figure 7: Internal cam

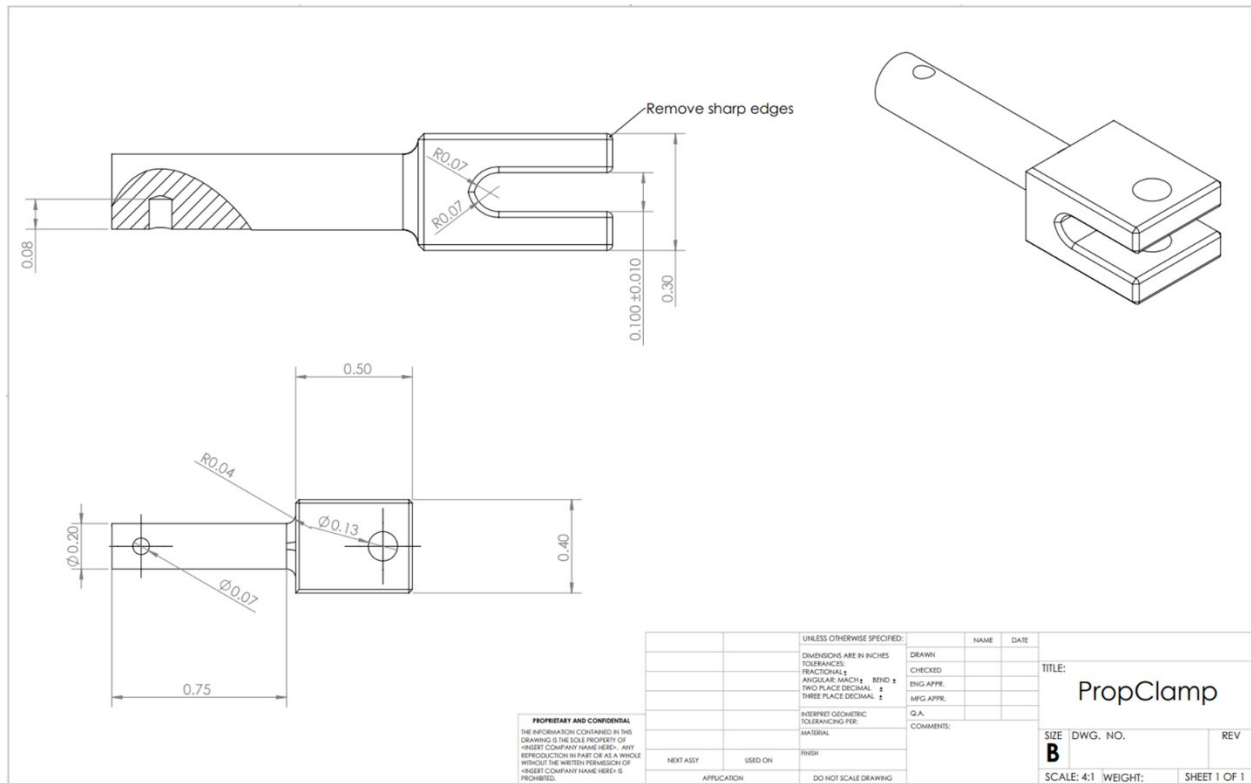


Figure 8: Prop clamp

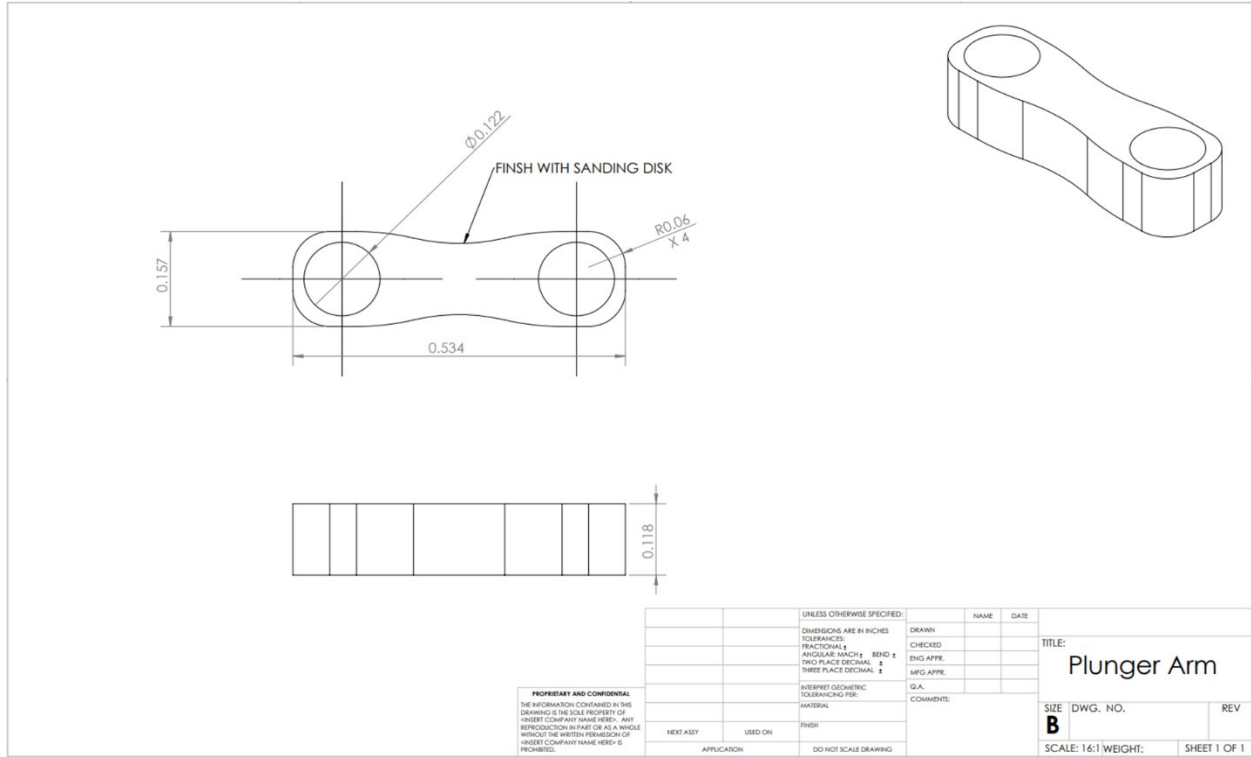


Figure 9: Plunger arm

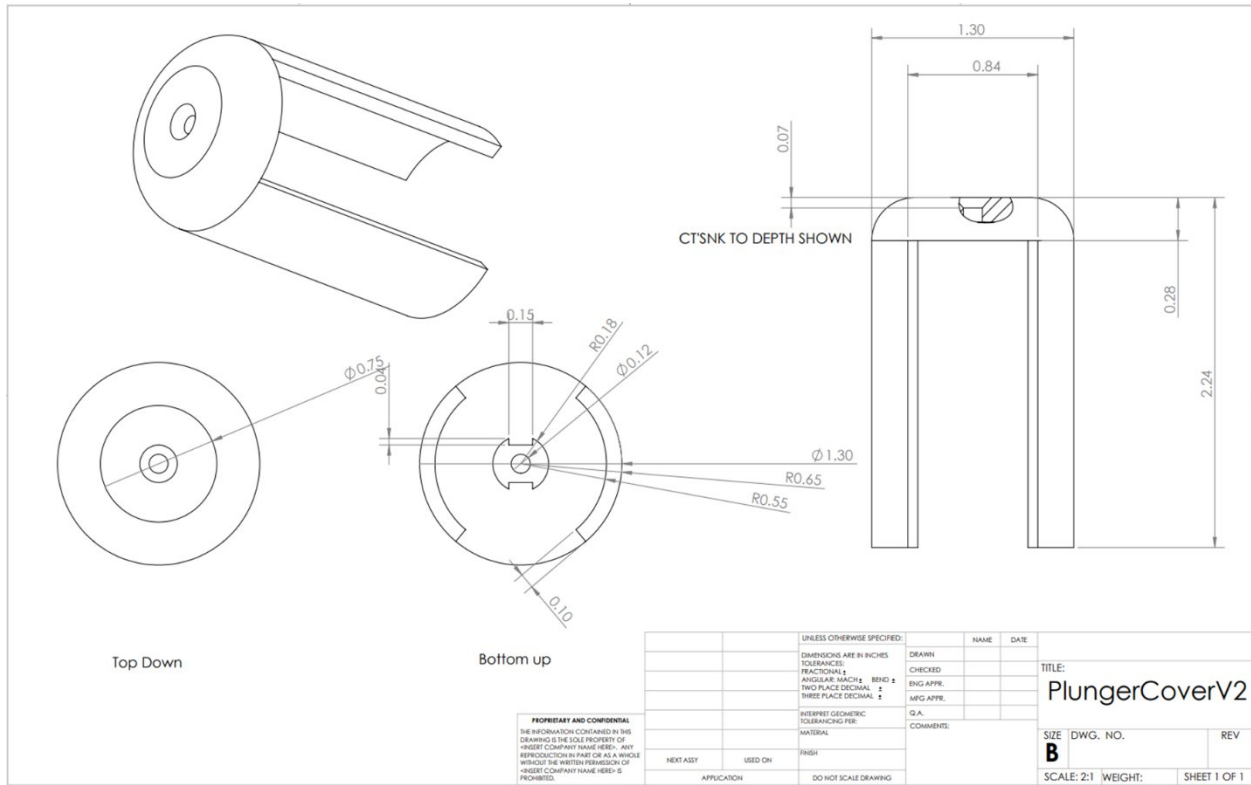


Figure 10: Plunger cover

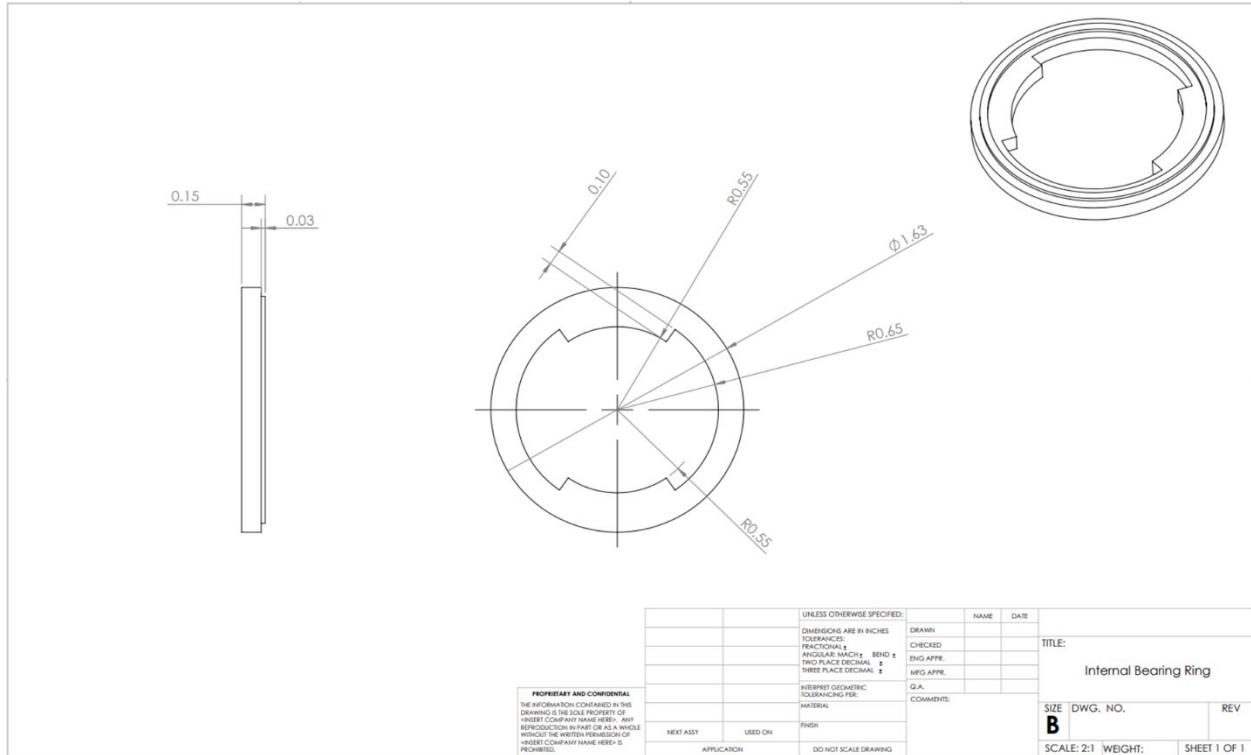


Figure 11: Internal bearing ring

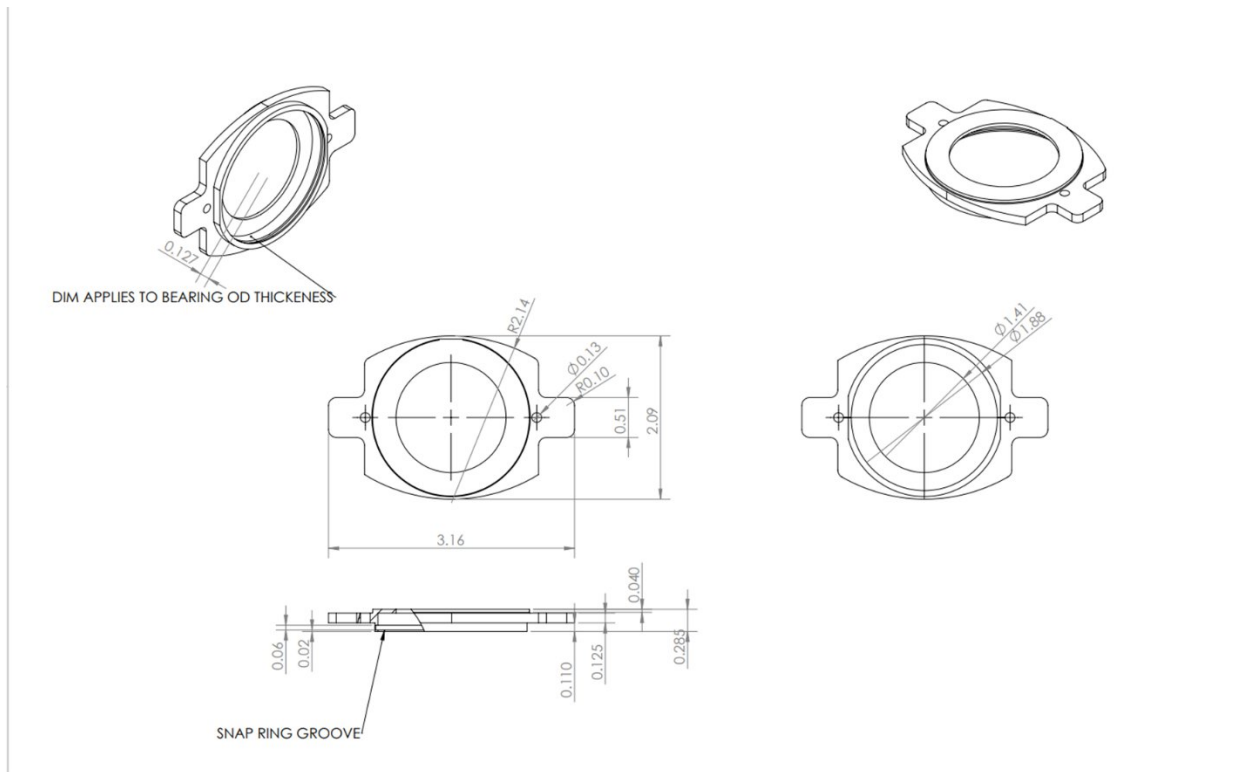


Figure 12: Platform

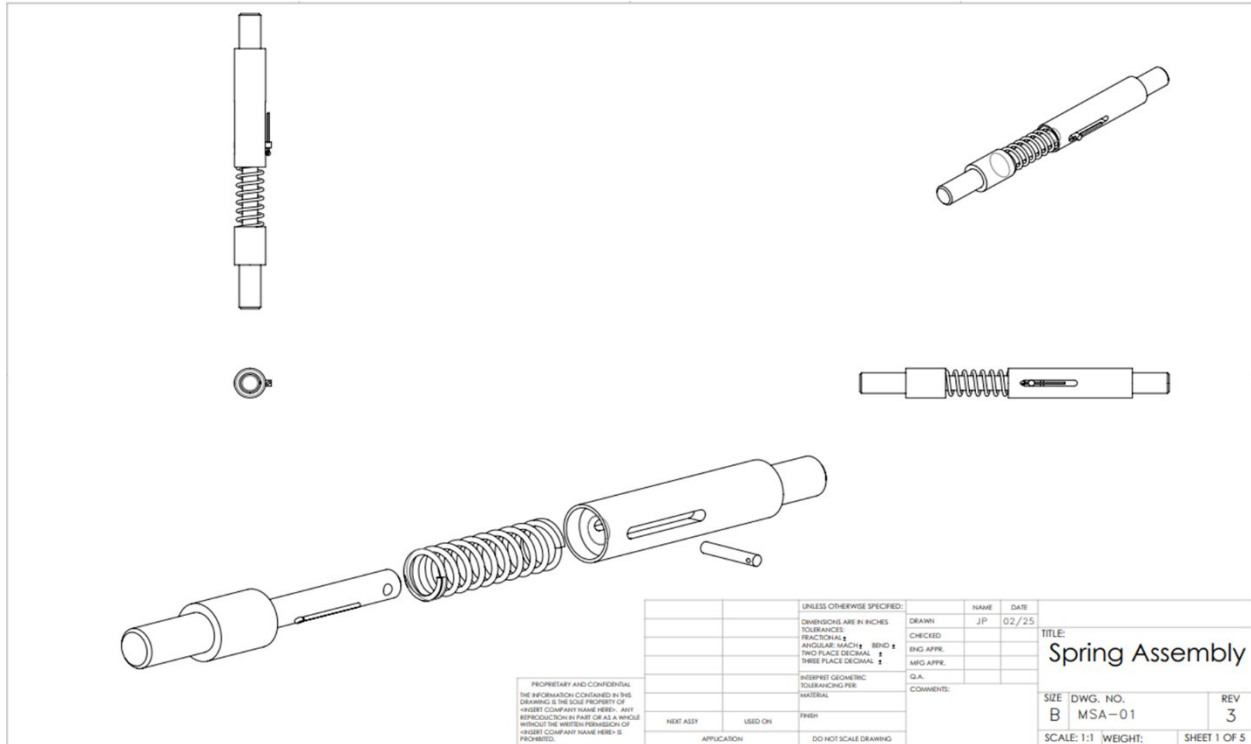


Figure 13: Spring assembly

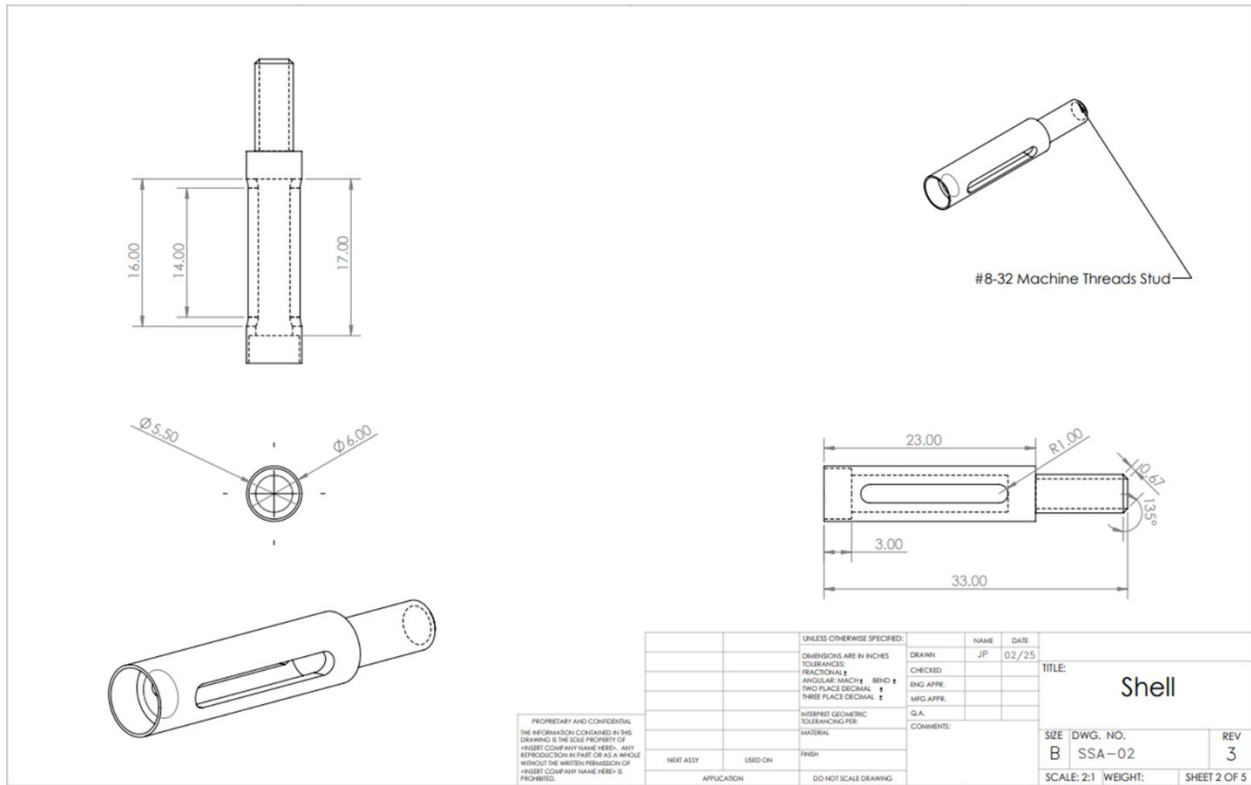


Figure 14: Shell



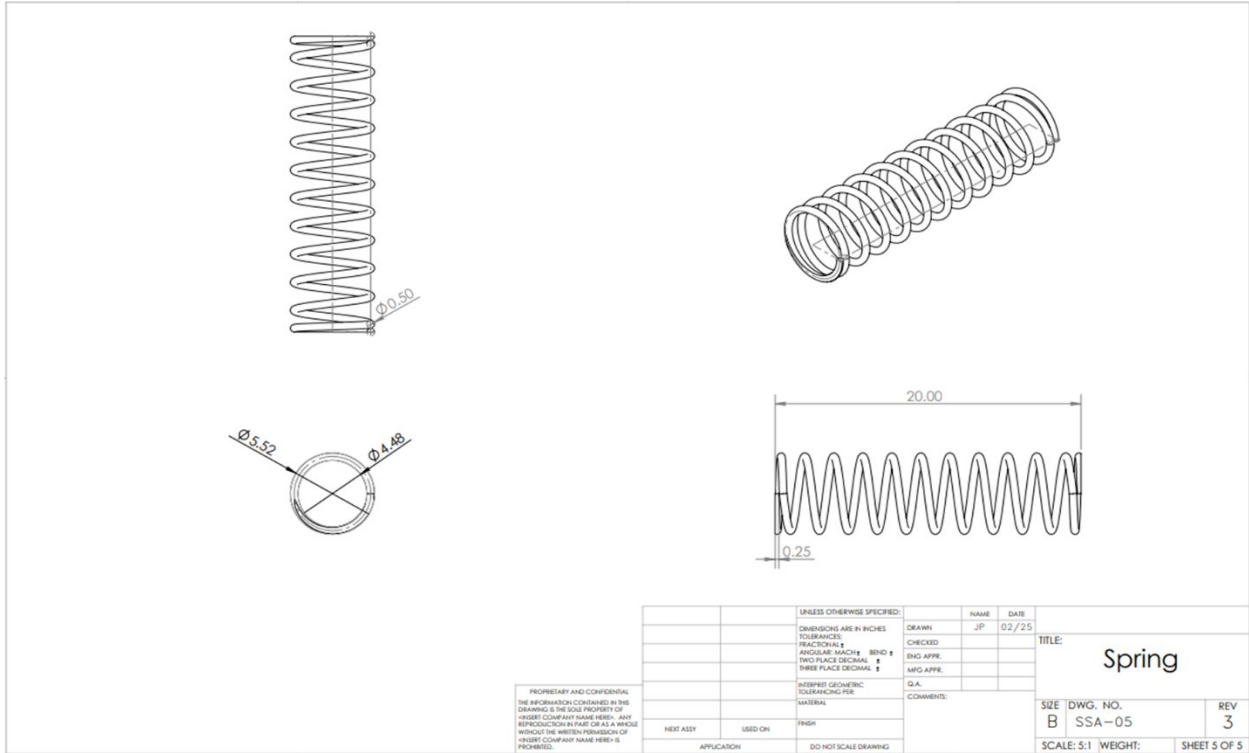


Figure 17: Spring

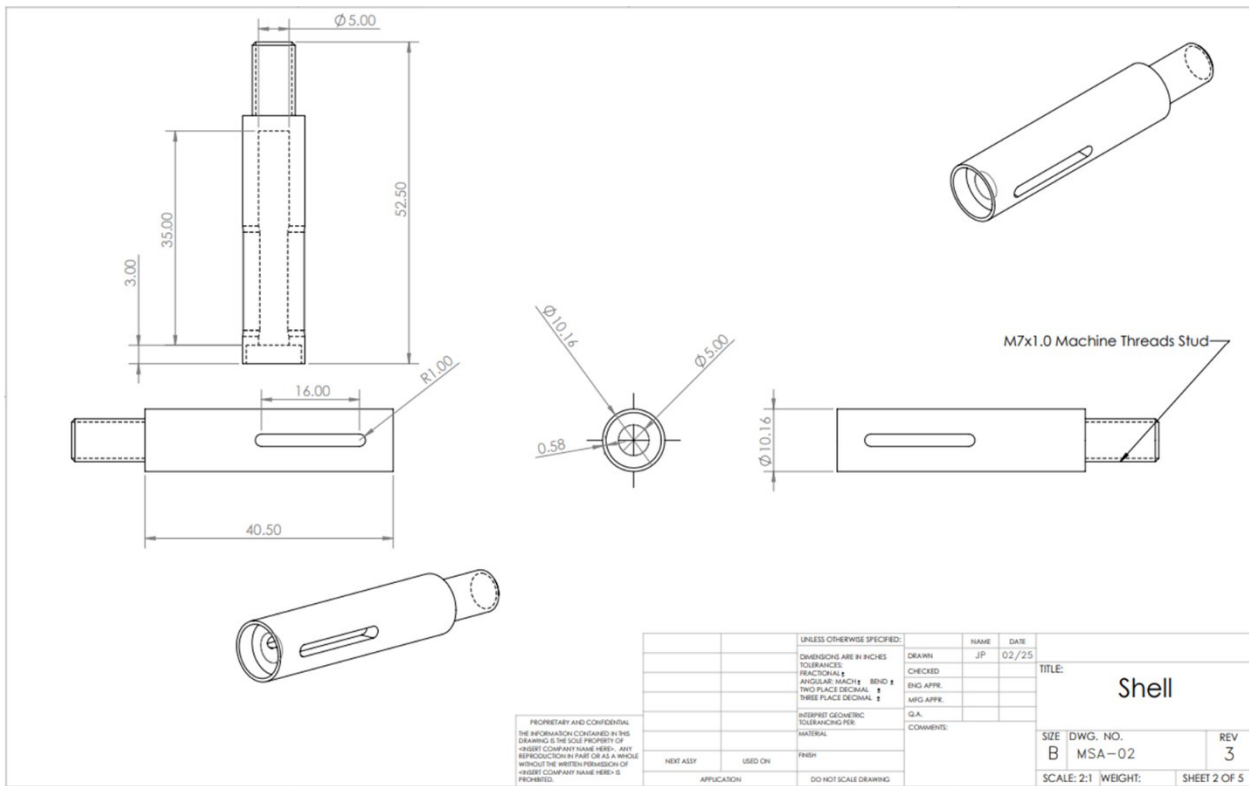


Figure 18: Medium assembly shell

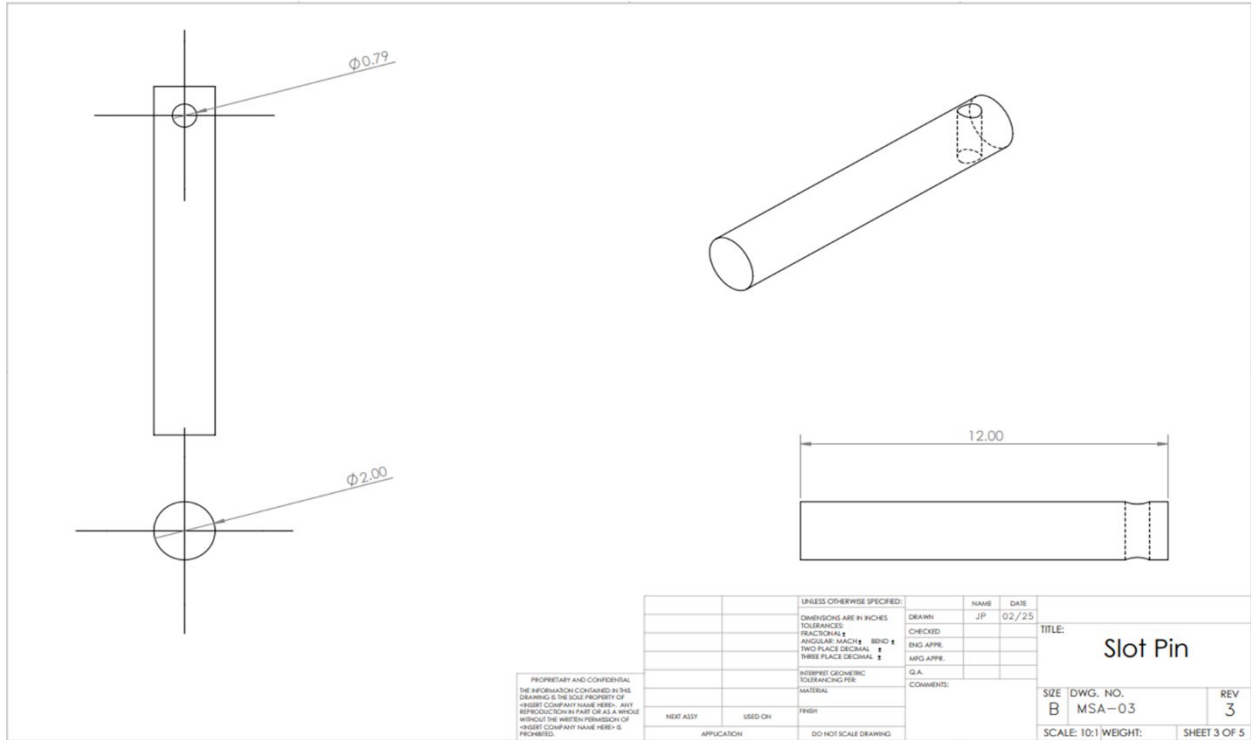


Figure 19: Medium assembly slot pin

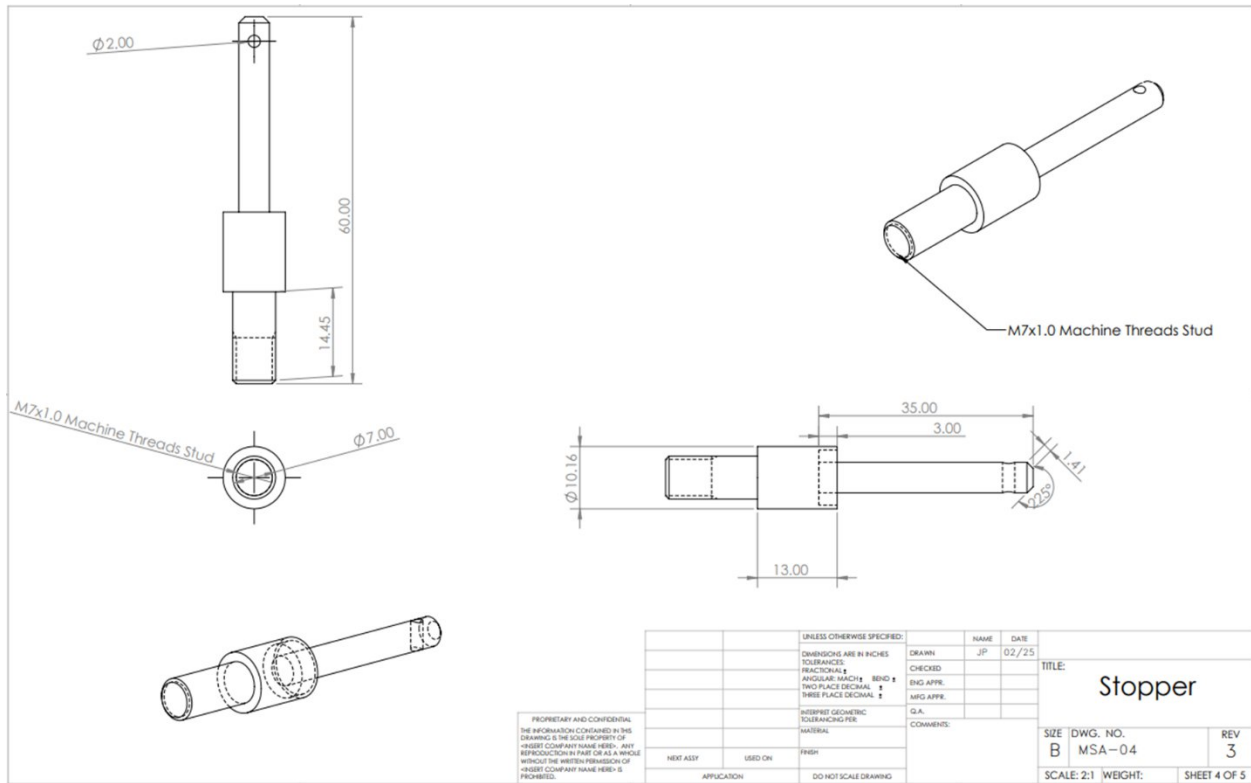


Figure 20: Medium assembly stopper

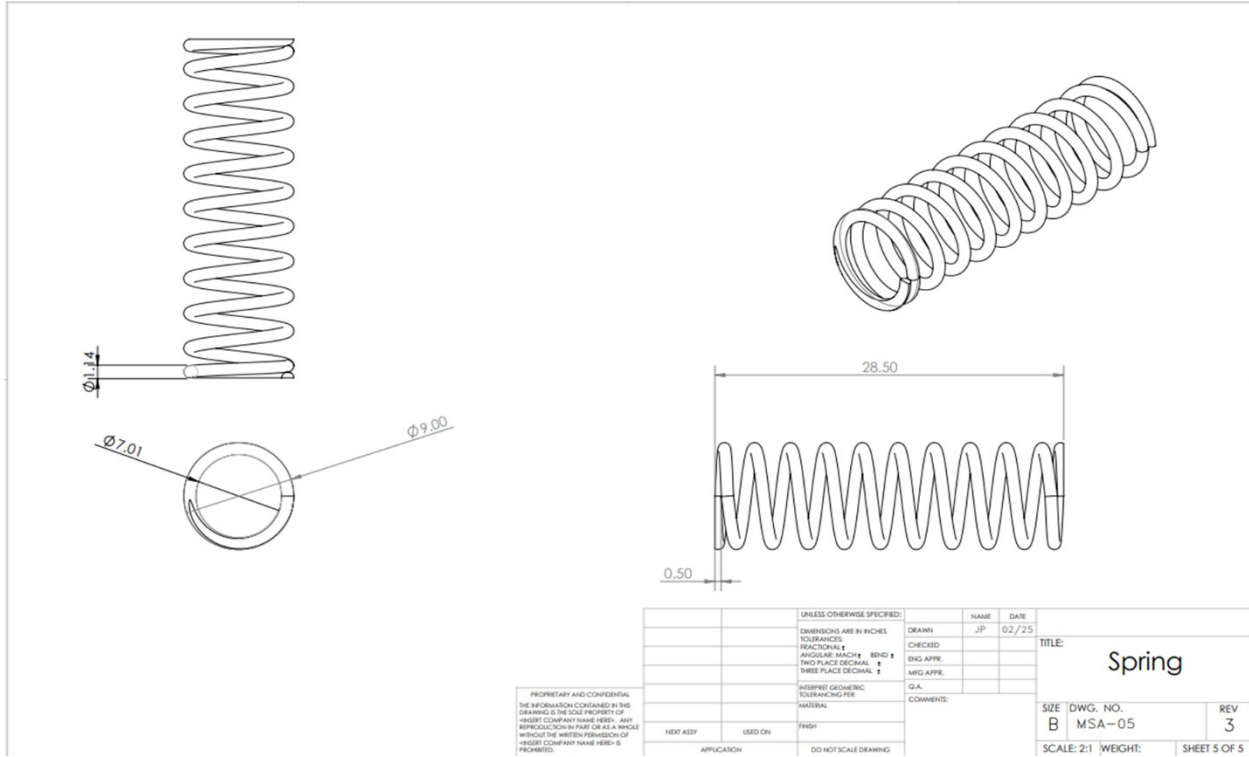


Figure 21: Medium assembly spring

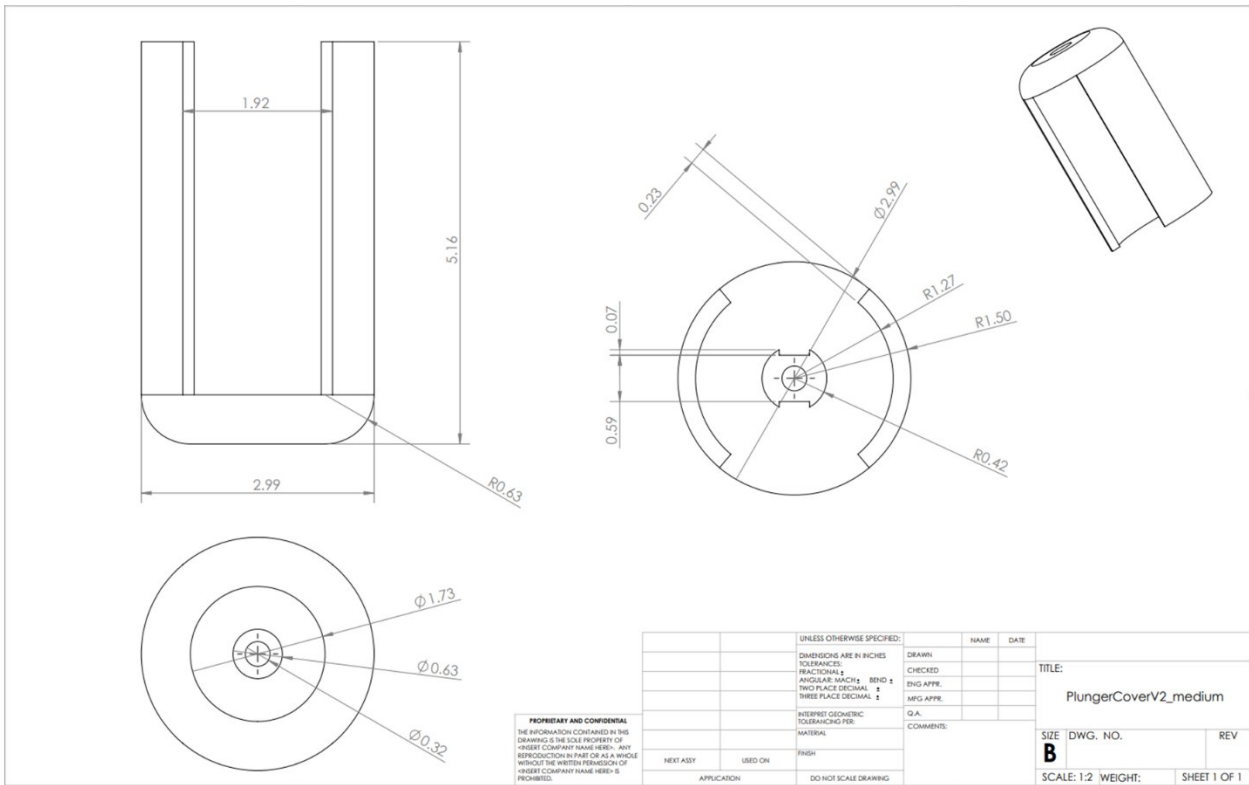


Figure 22: Medium assembly plunger cover

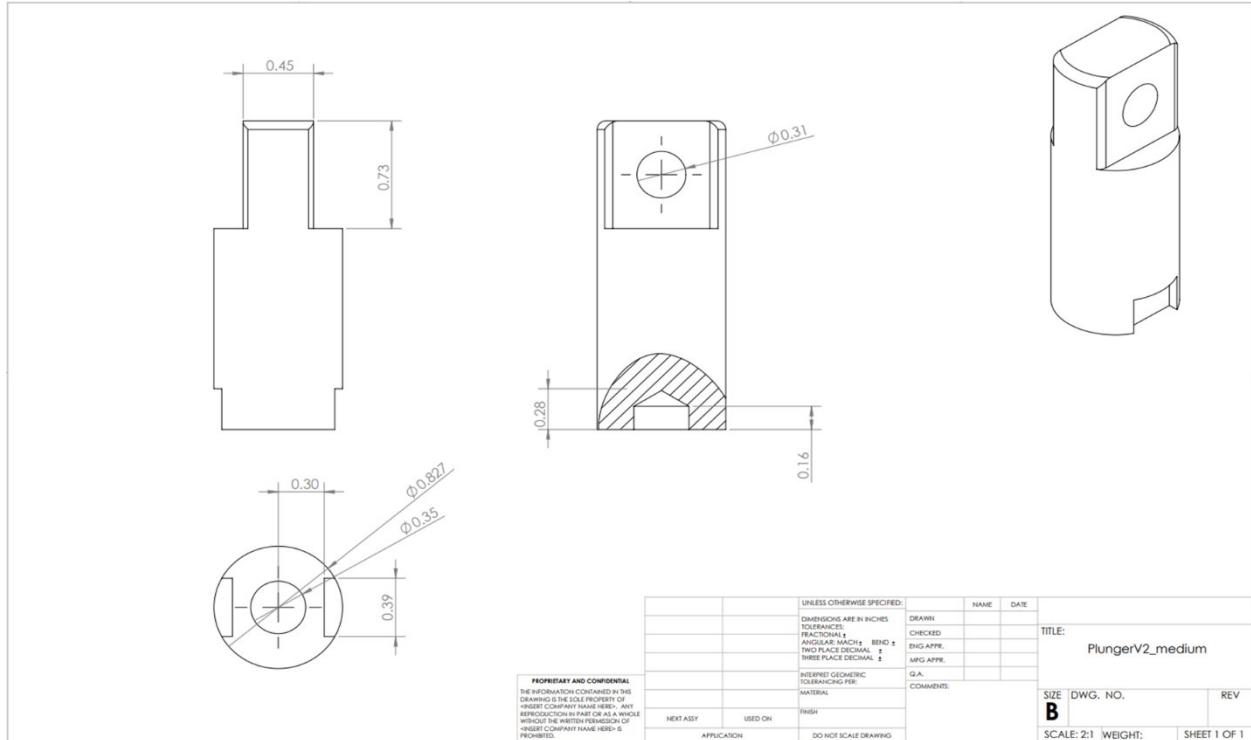


Figure 23: Medium assembly plunger

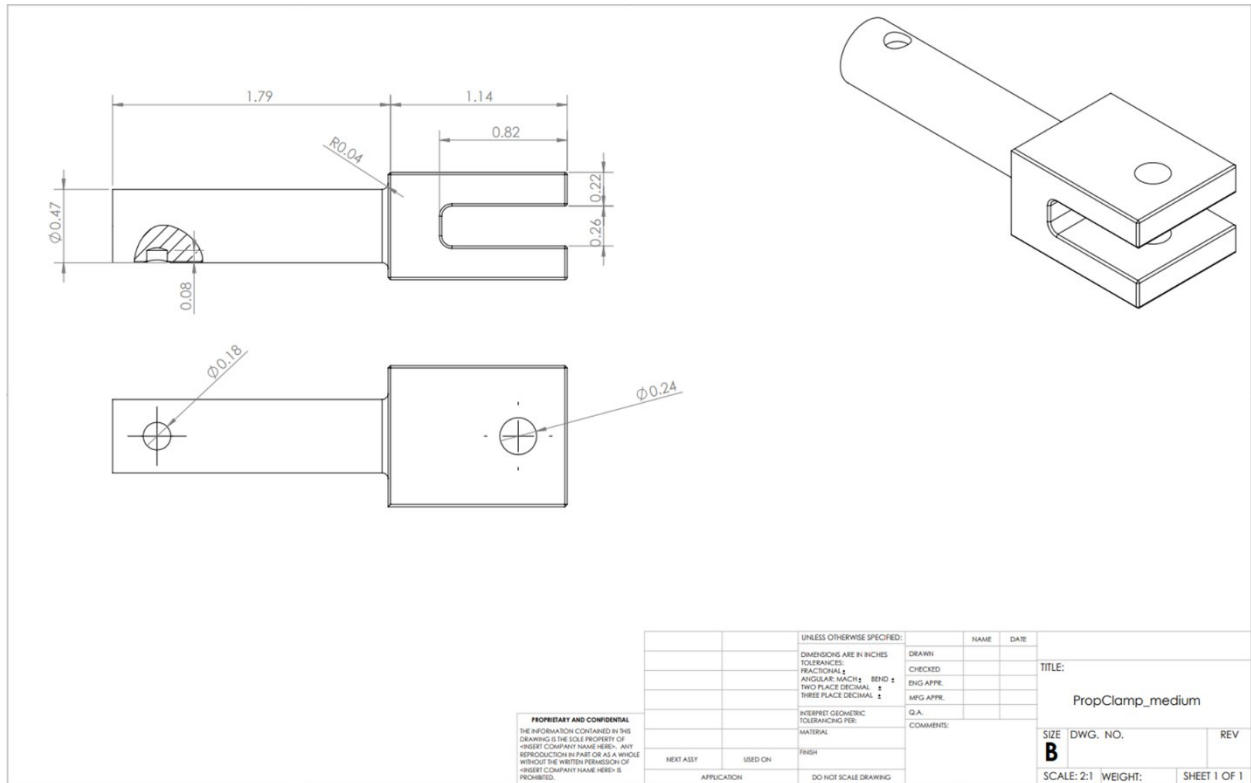


Figure 24: Medium assembly prop clamp

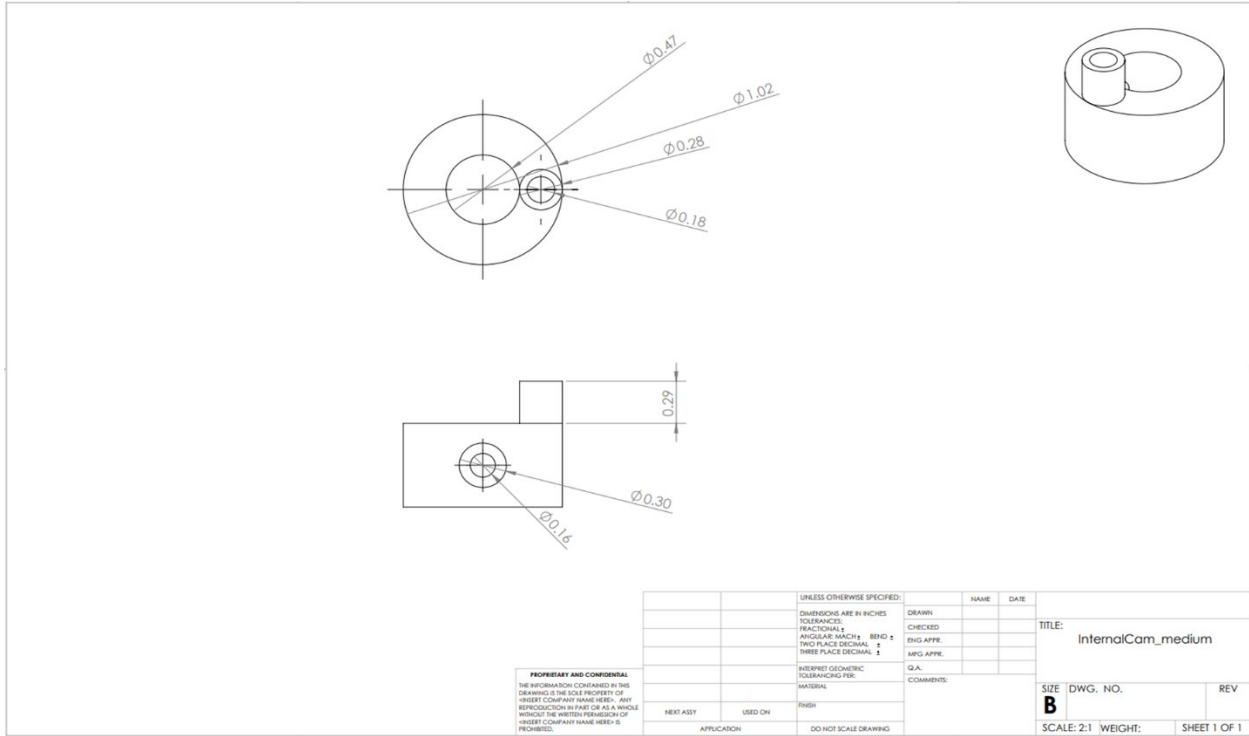


Figure 25: Medium assembly internal cam

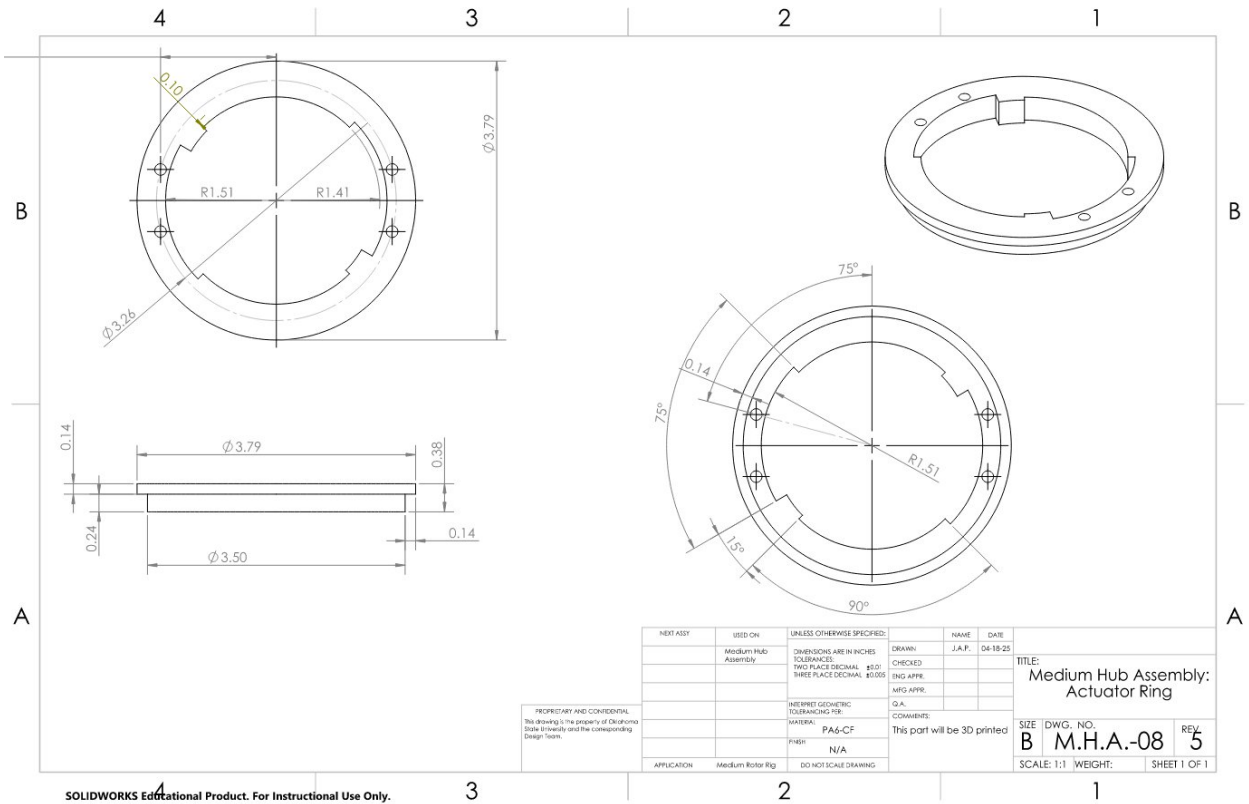


Figure 26: Medium assembly actuator ring

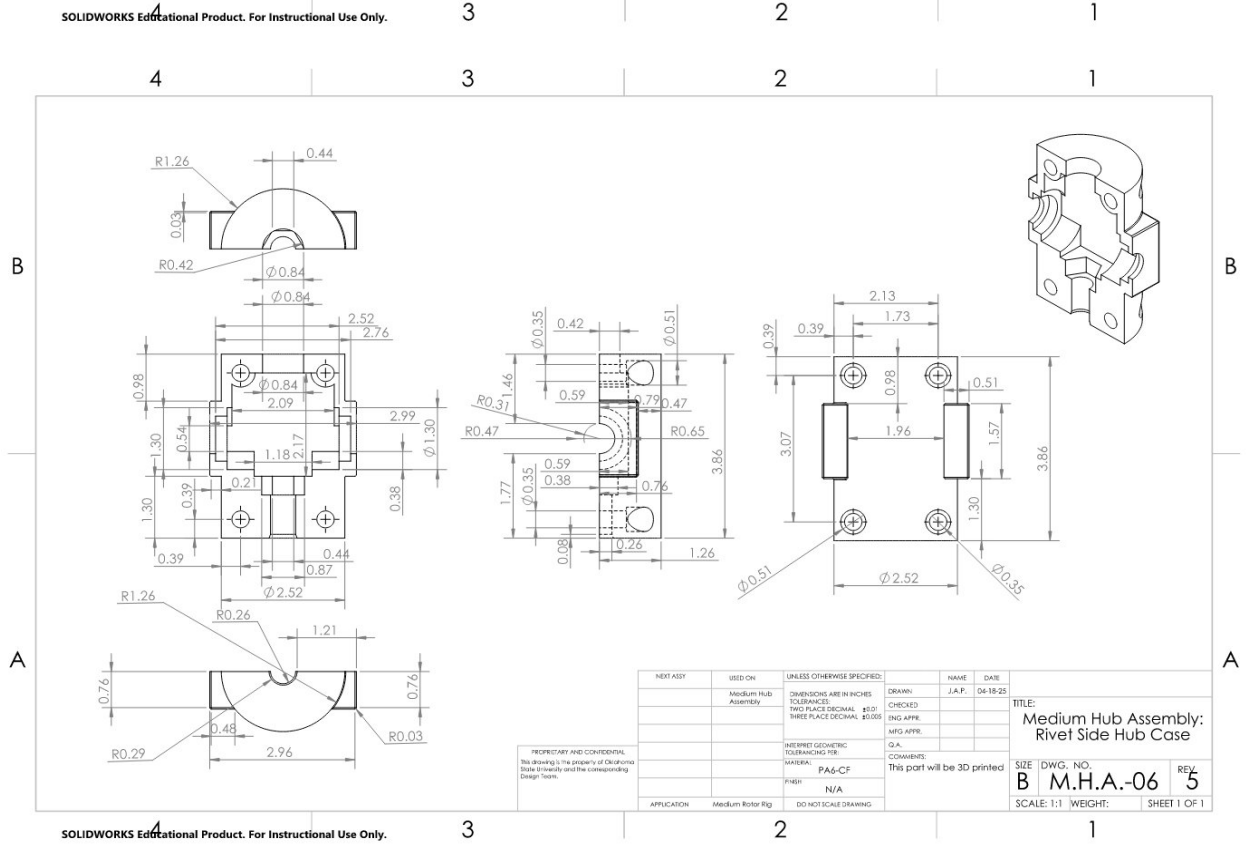
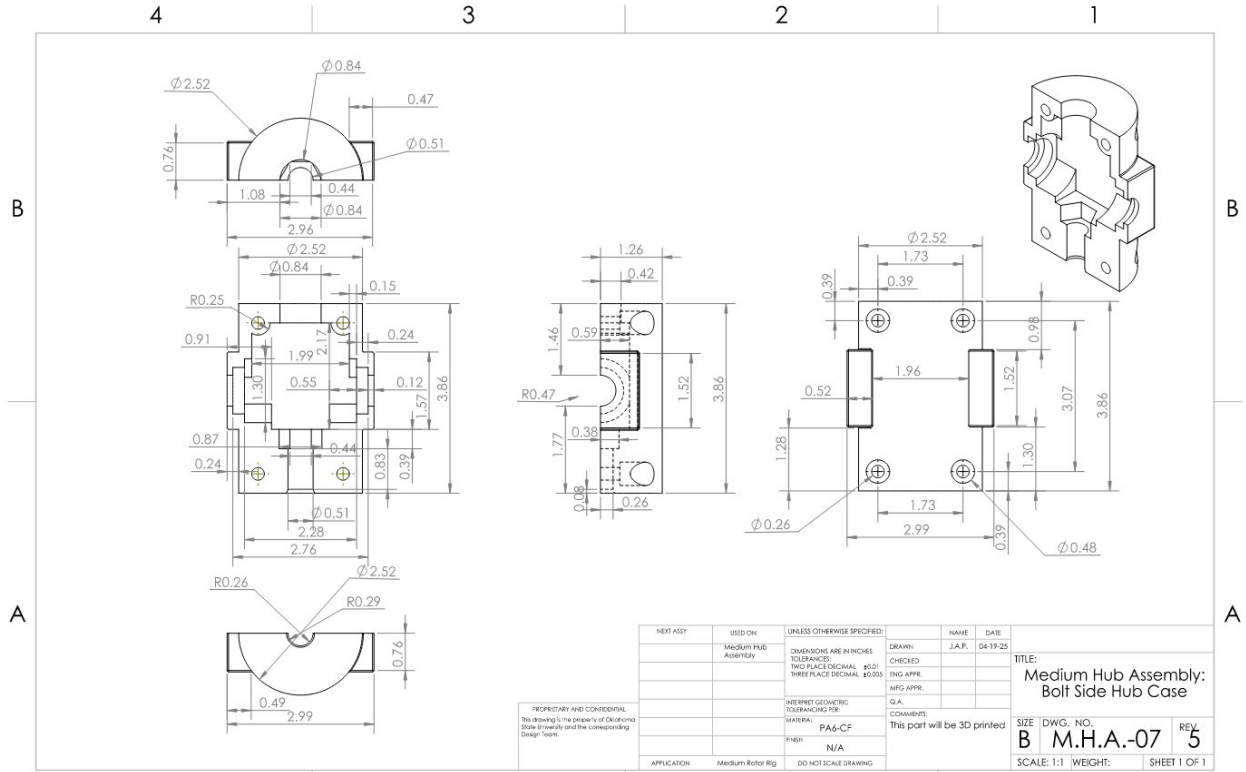


Figure 27-27A: Medium assembly hub

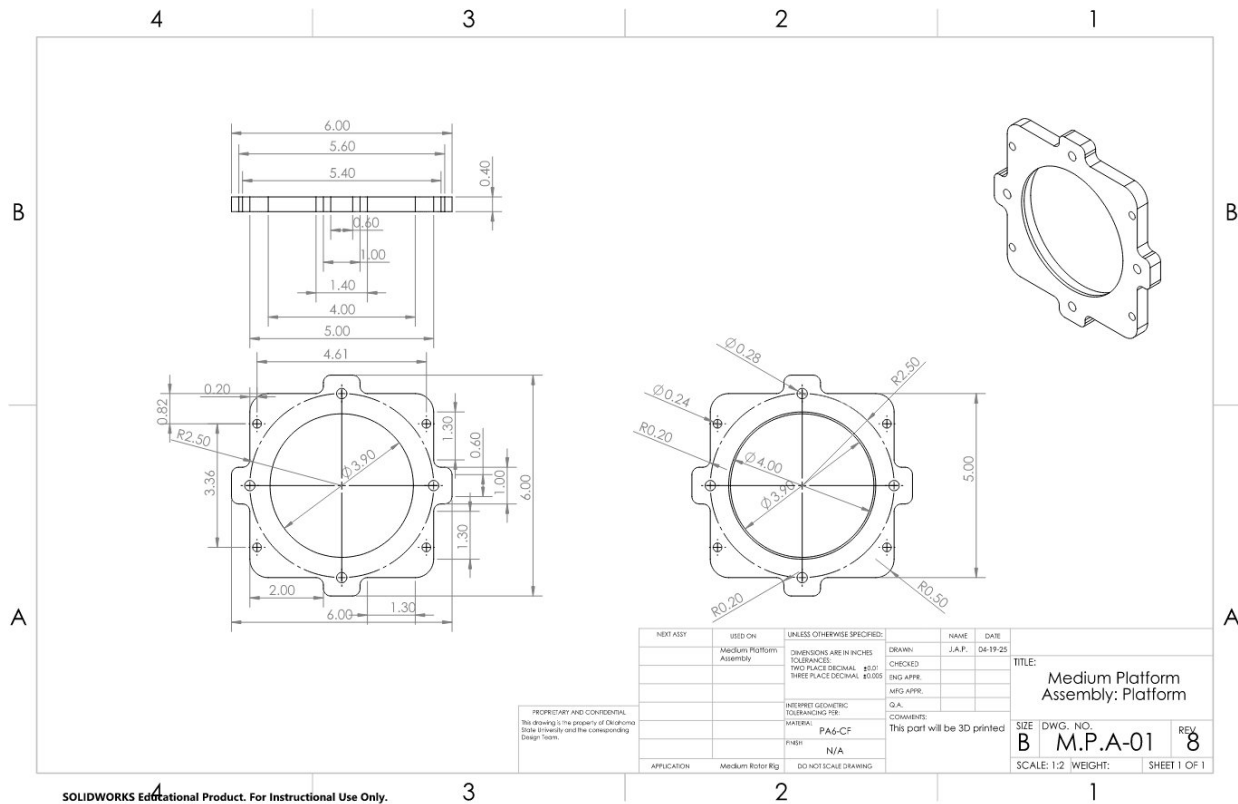


Figure 28: Medium assembly platform

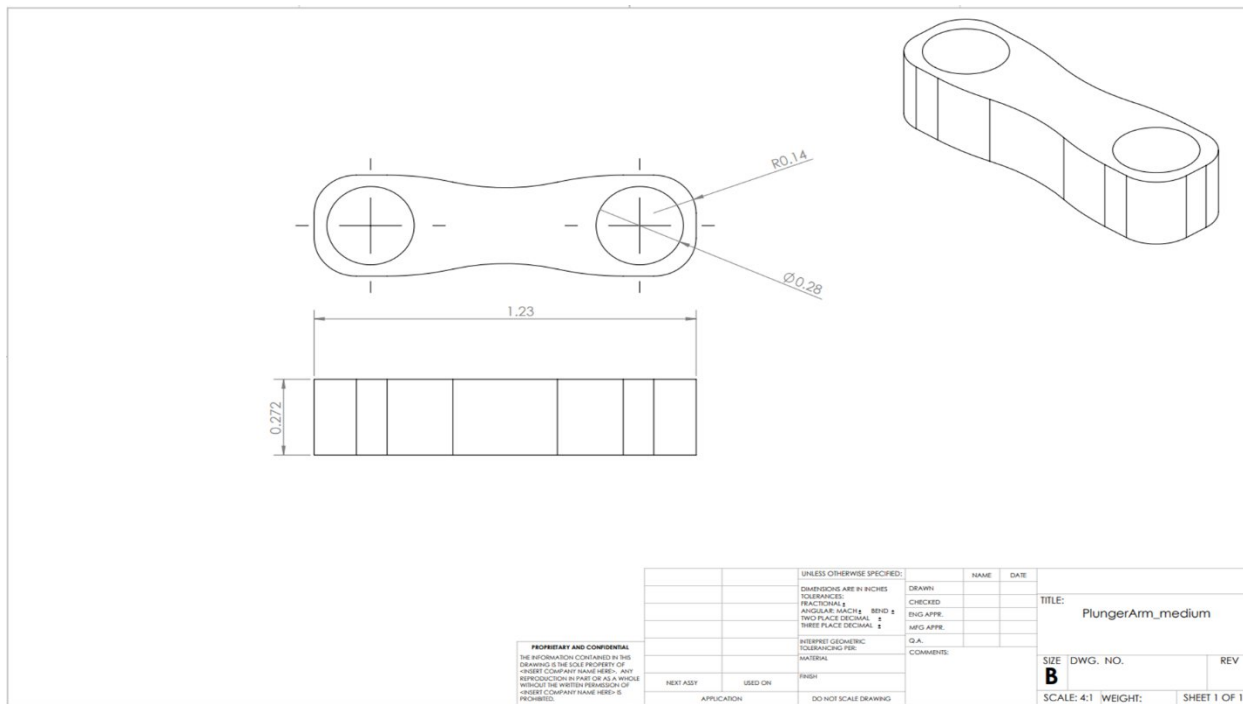


Figure 29: Medium assembly plunger arm

# Assembly Drawings

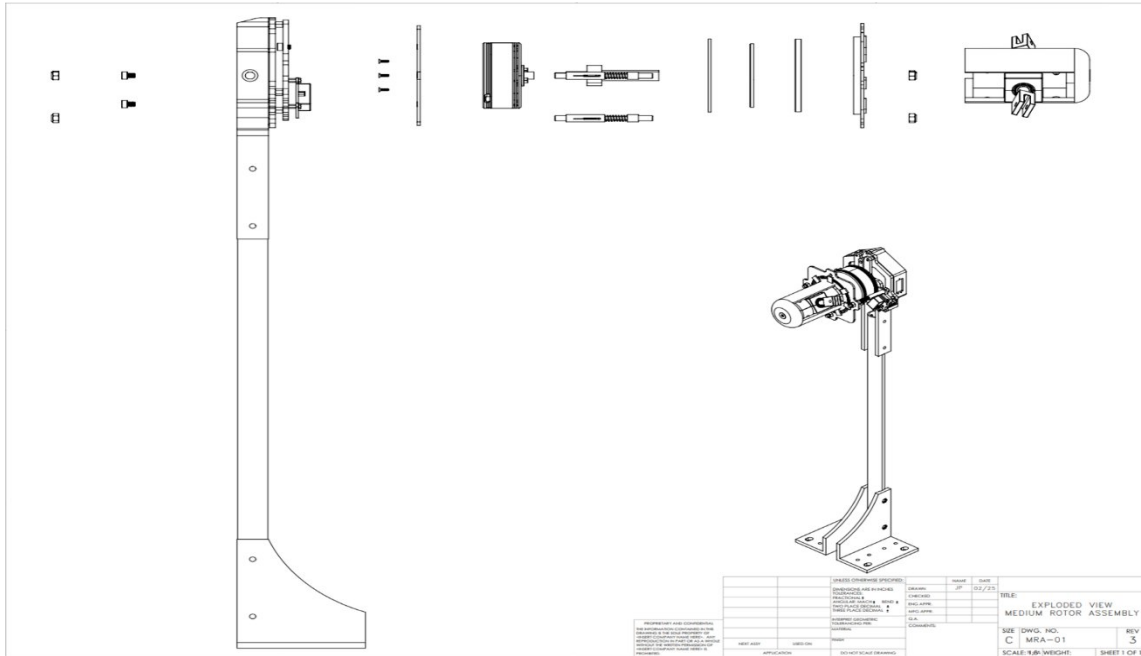


Figure 30: Exploded view medium rotor assembly

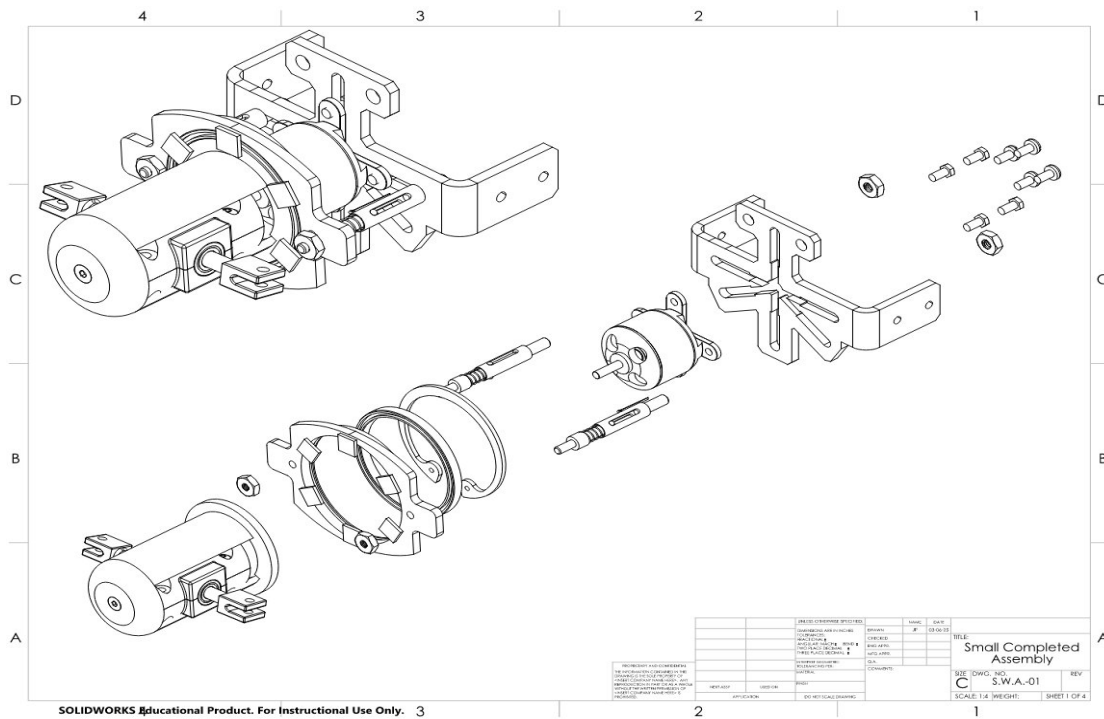


Figure 31: Small completed assembly

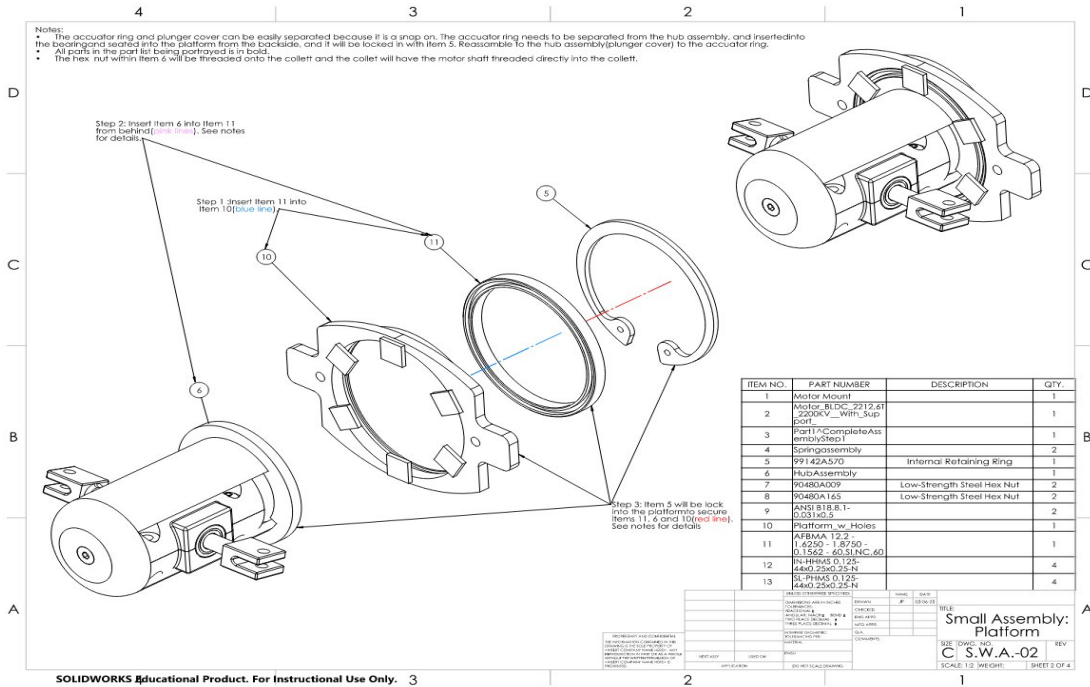


Figure 32: Small assembly: Platform

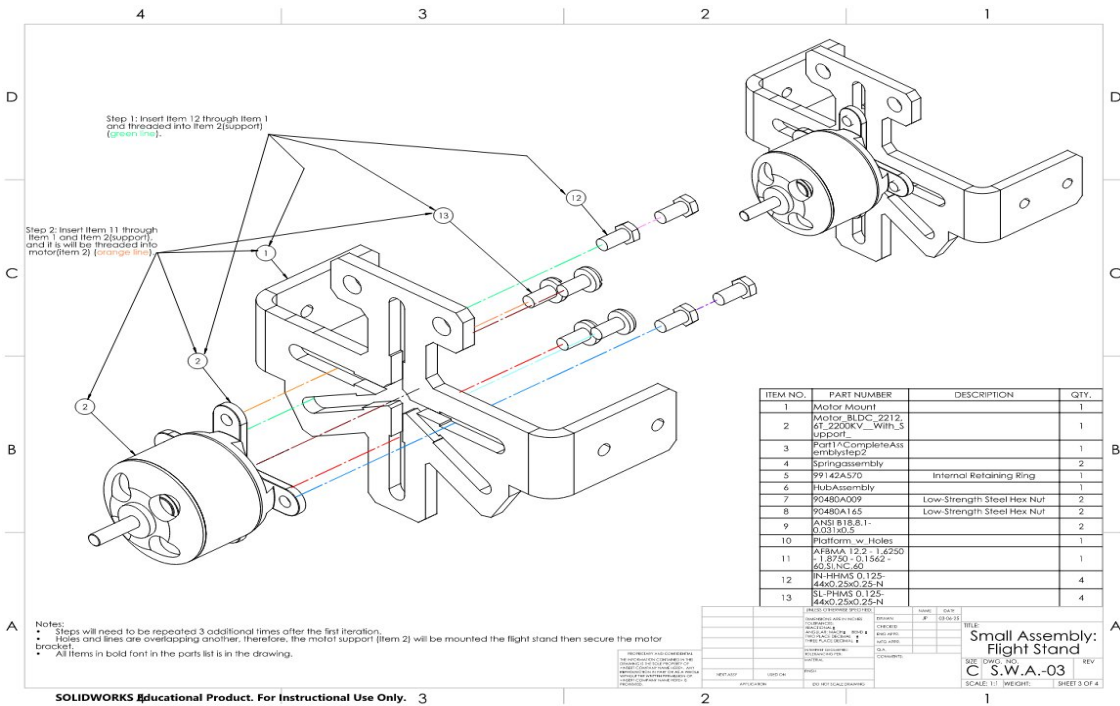


Figure 33: Small assembly: Flight stand

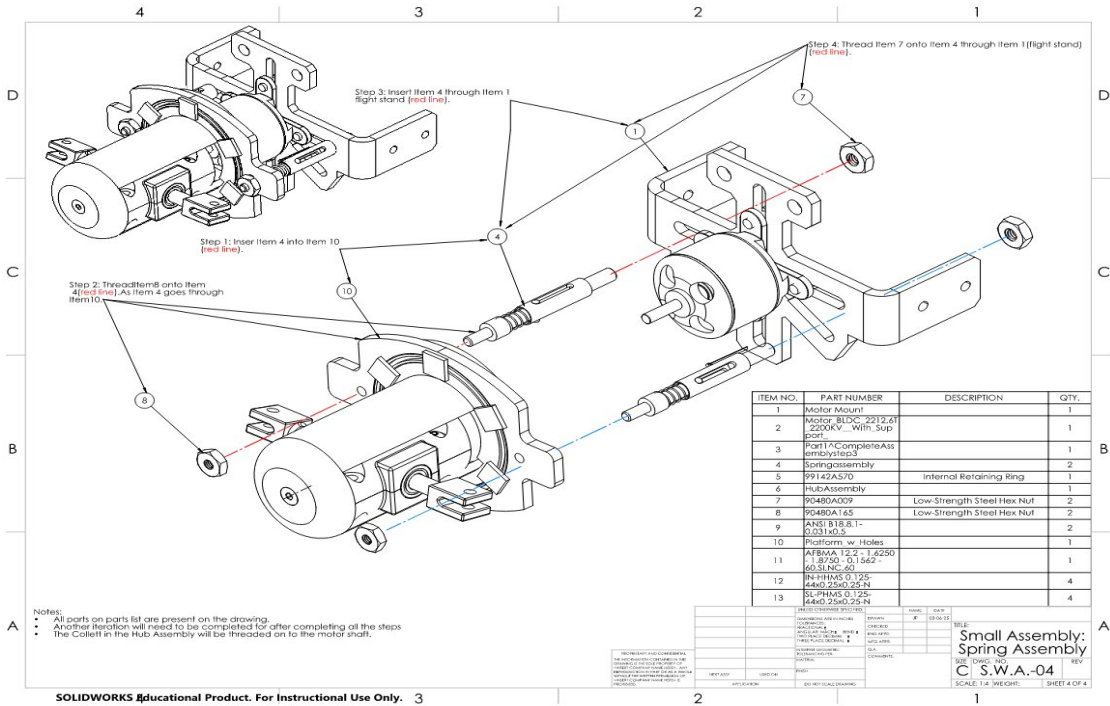


Figure 34: Small assembly: Spring assembly

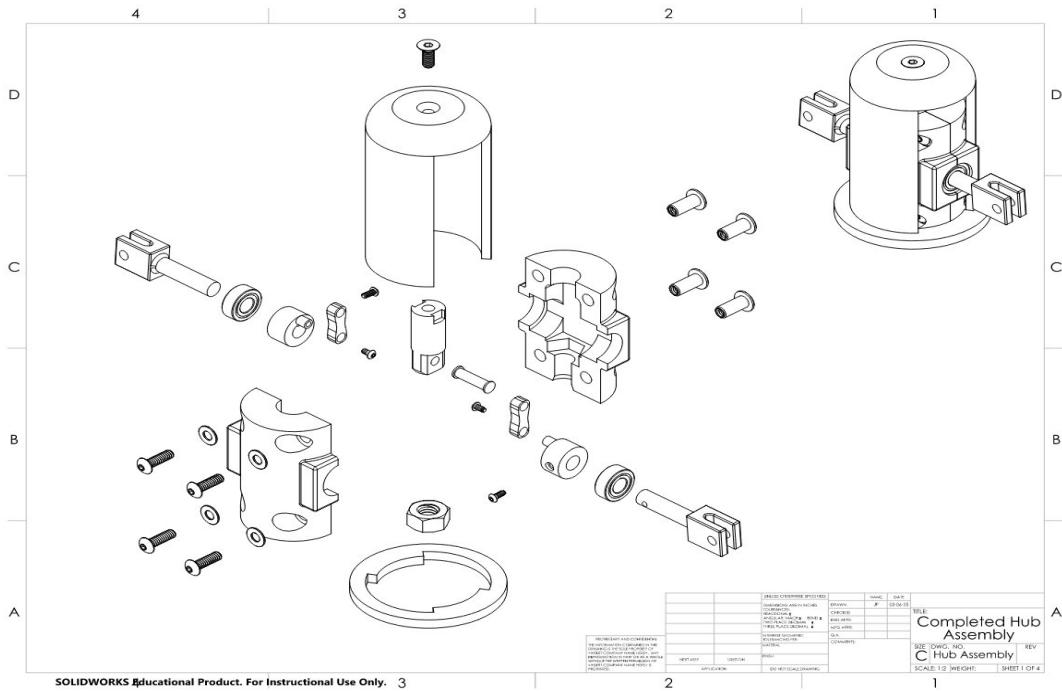


Figure 35: Complete hub assembly

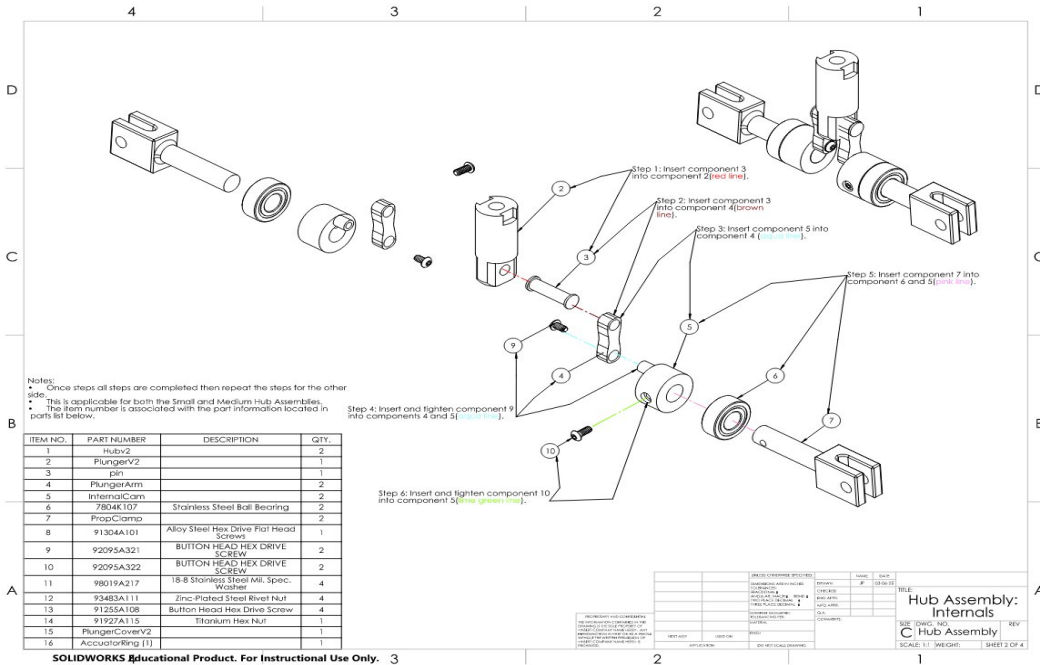


Figure 36: Hub assembly: Internals

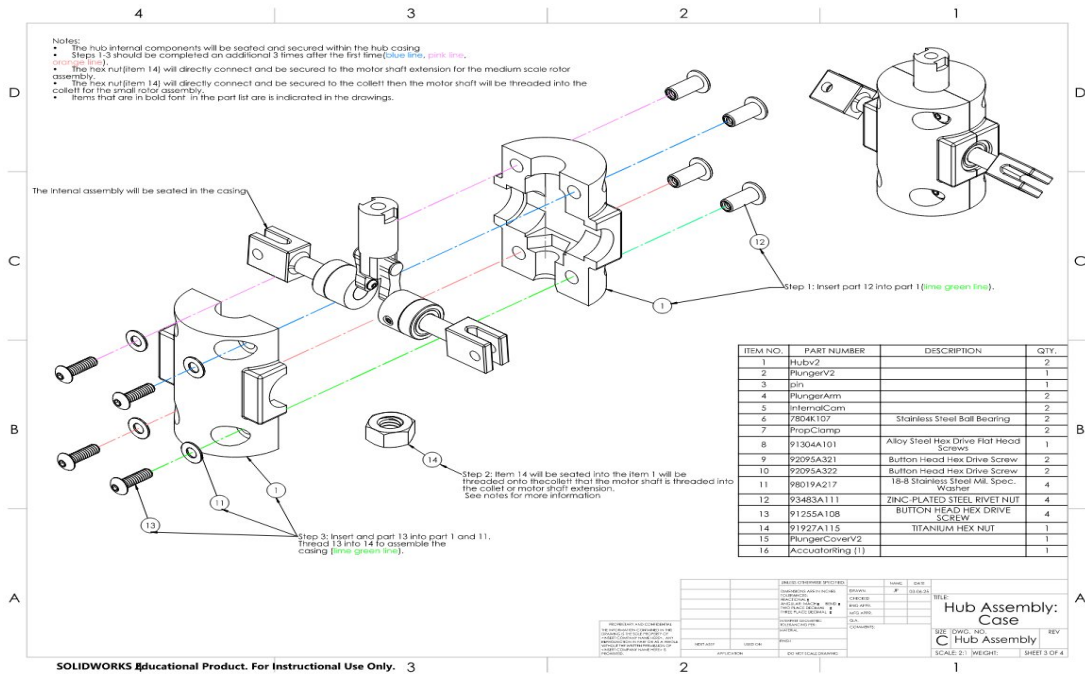


Figure 37: Hub assembly case

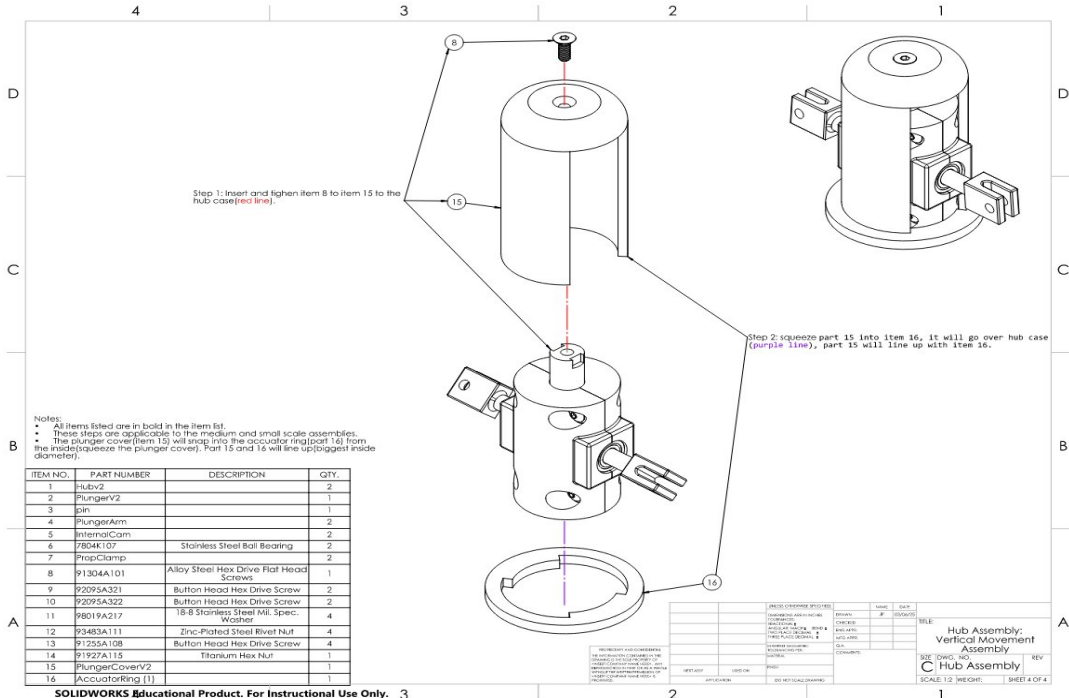


Figure 38: Hub assembly: Vertical movement assembly

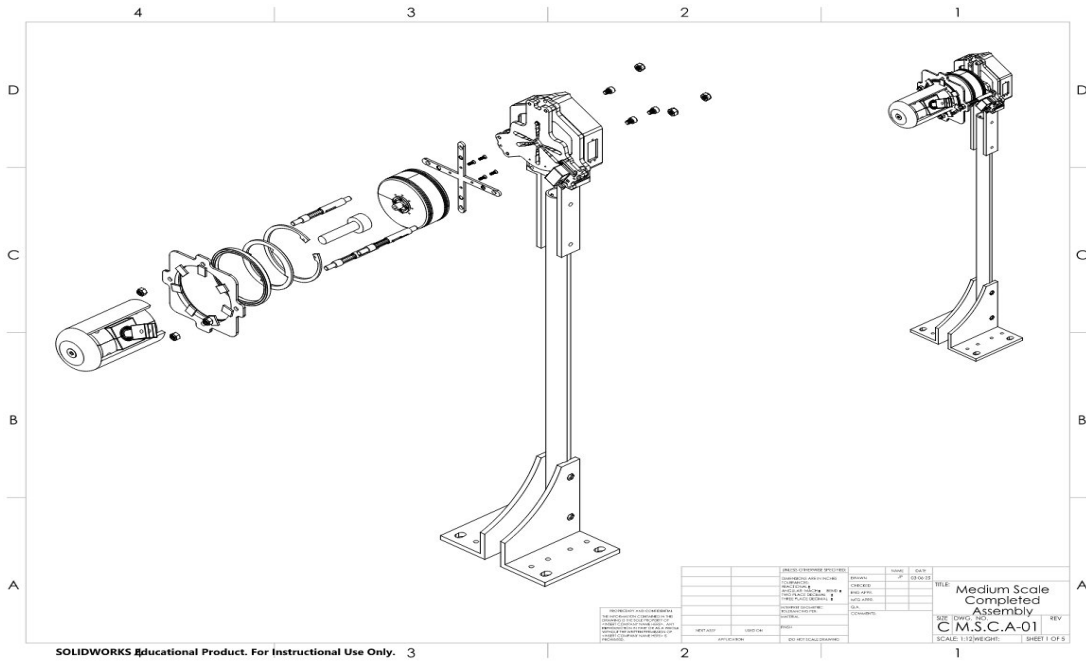


Figure 39: Medium completed assembly

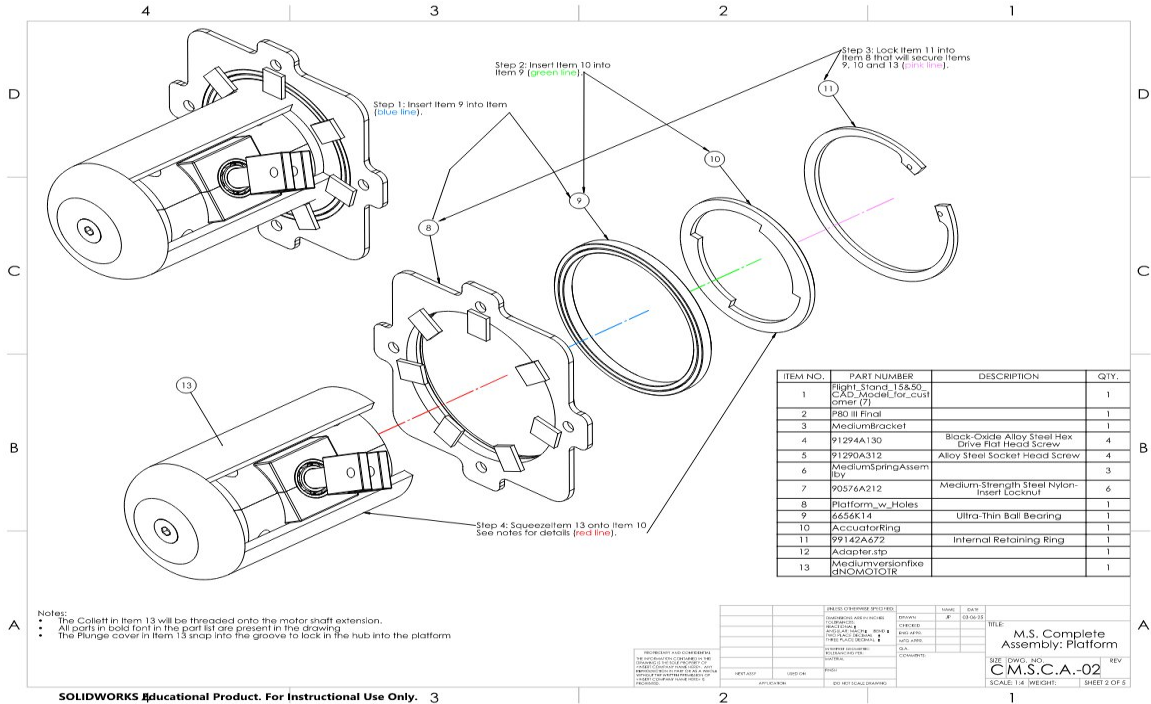


Figure 40: Medium assembly: Platform

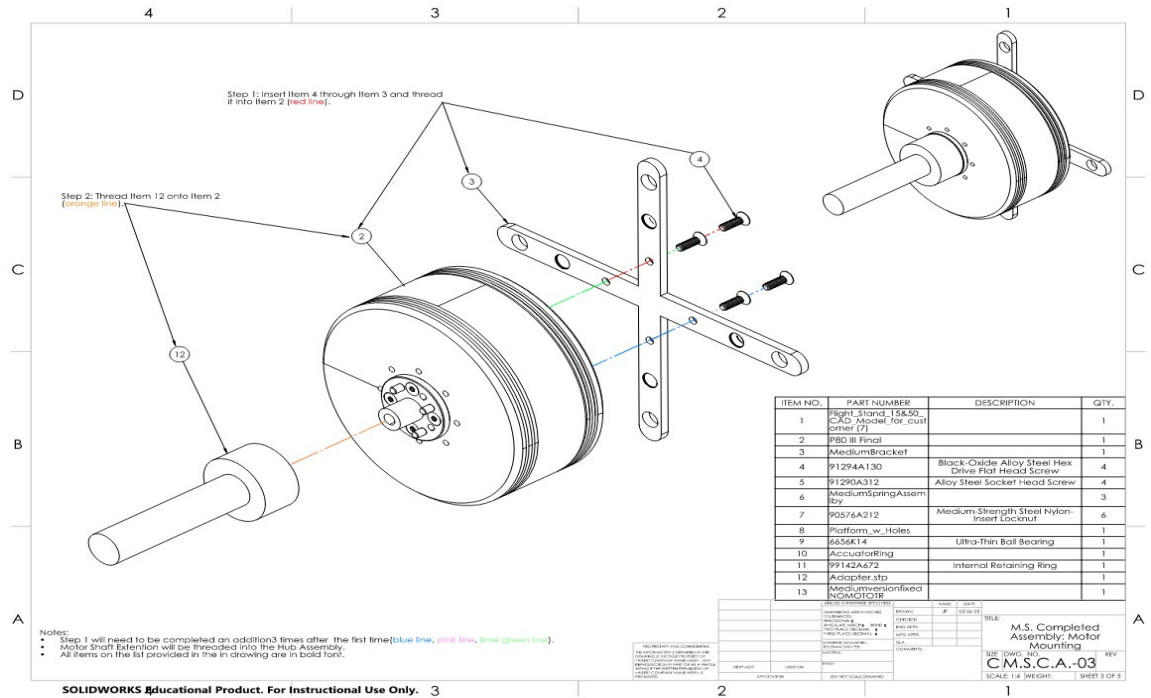


Figure 41: Medium assembly: Motor mount

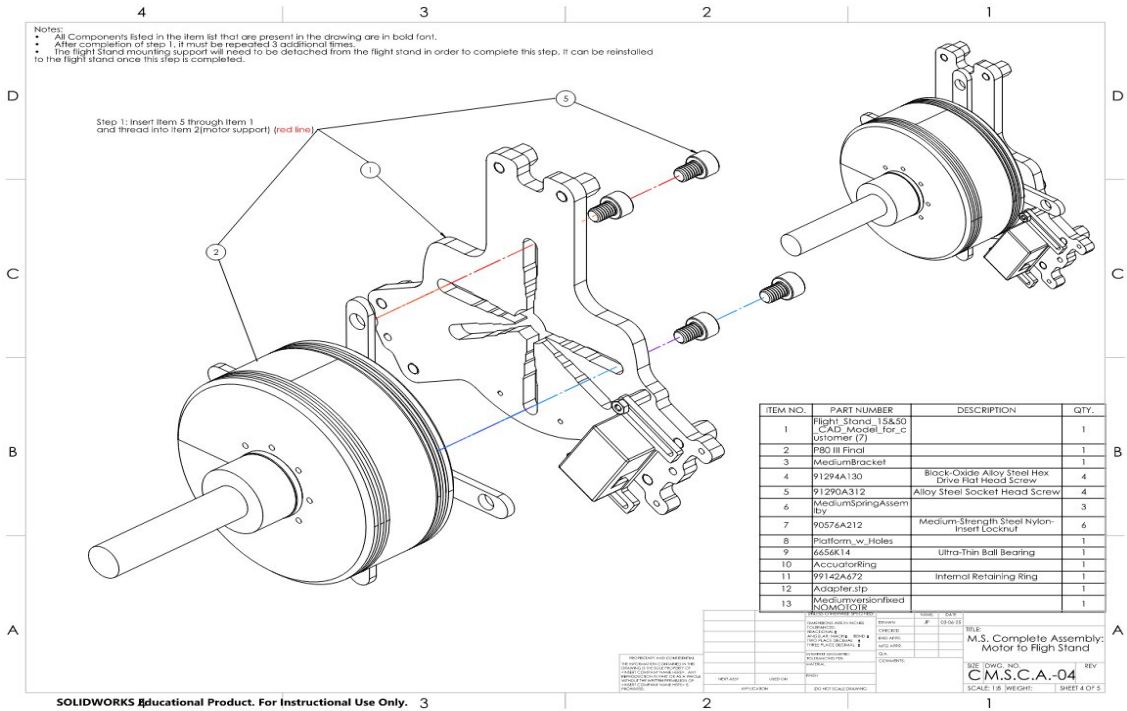


Figure 42: Medium assembly: Flight stand

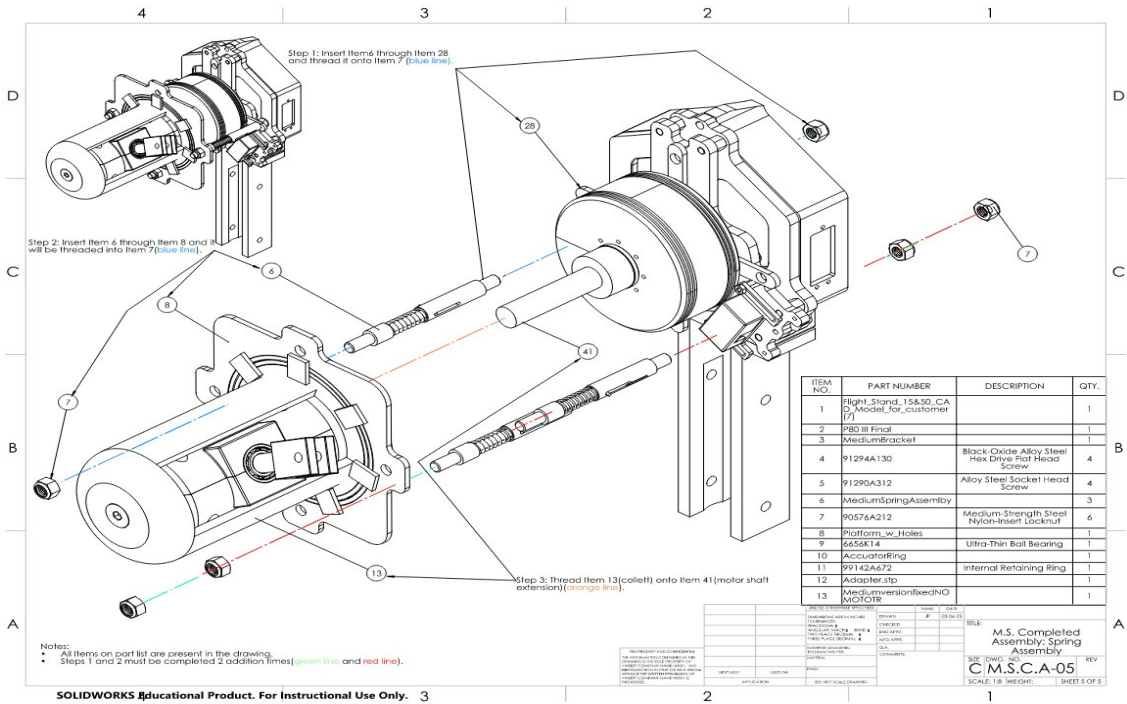


Figure 43: Medium assembly: Spring assembly

