Western University
Faculty of Engineering
Mechatronic Systems Engineering Program

CubeSat Attitude Determination and Control System

Design Analysis, Detailed Design Documentation & Prototype Feasibility

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1. Introduction

Western University's Faculty of Engineering received a grant from the Canadian Space Agency (CSA) to develop the CubeSat over the course of three years, beginning in May 2018. When a CubeSat is launched into space, its attitude must be determined and controlled for the entire mission lifetime. The design requirements of the CubeSat led to the following problem statement for the project:

Design a low-cost system to stabilize and control the pose of the CubeSat.

When the CubeSat is initially deployed from the International Space Station (ISS), the attitude determination and control system (ADCS) must detumble the CubeSat. During normal operation, the purpose of the ADCS is to orient the CubeSat to desired positions throughout its orbit. The antenna must be pointed towards the ground station to transmit and receive data. To take images, the ADCS should ensure the camera is both pointed towards the target location and stabilized well to take clear images. In order to do this, sensors are located on the CubeSat to acquire knowledge of its current position. The sensors chosen for the design are sun sensors, a magnetometer, and gyroscopes. With this knowledge actuators are used to manipulate the CubeSat to orient itself to the desired position. Magnetorquers were chosen as the actuators. Although there are ADCS that have been created for other CubeSat projects, this ADCS will be designed based on the specifications determined for this particular CubeSat.

The scope of this report covers the background information needed to understand the design analysis, detailed design documentation and prototype feasibility that have gone into creating simulations that justify the creation of the prototype. There is further discussion into how the prototype will be a sufficient demonstration of the theoretical design of the attitude determination and control system.

2. Design Analysis

2.1. Description of Computational Models

2.1.1. Sun Sensors

The sun sensor model takes in two inputs to output a sun vector in body coordinates. Using this sun vector, the ADCS will need one more independent vector to figure out the exact orientation of the CubeSat with respect to the Earth. In Section 3 – Detailed Design Documentation, the analysis and verification of this model is shown, as well as its implementation and interaction with the other components of the ADCS.

2.1.2. Magnetometer

The magnetometer takes in the direction of the Earth's magnetic field and quaternions as its two inputs. It then outputs a magnetic vector in body coordinates. Using a helper block, the International Geomagnetic Reference Field, the magnetometer simulation is able to output a magnetic vector to provide the second independent vector. In conjunction with the independent sun vector, the magnetometer is able to help provide the exact orientation of the ADCS with respect to Earth.

2.1.3. Gyroscope

The gyroscope takes in the angular rate and is used when the CubeSat is in eclipse. Since the sun sensors will be impractical during an eclipse, another independent vector is needed to determine the orientation of the ADCS. The gyroscope cannot be used instead of the sun sensor at all times because it accumulates a large drift and will become unusable if used for the entire mission lifetime. The effects of using the gyroscope are shown in Section 3 – Detailed Design

Documentation and its attitude determination capabilities explored in its Simulink model and analysis.

2.1.4. Tri-Axel Attitude Determination (TRIAD)

The TRIAD gives an estimate of the coordinates of the sun sensor and the magnetometer outputs in vector form. The exact functionality of the TRIAD is shown in Section 3 – Detailed Design Documentation and has been tested to ensure that it provides the correct results.

2.1.5. Extended Kalman Filter (EKF)

The TRIAD will provide vectors that can be used for attitude determination. However, these vectors will have been subjected to noise. Thus, the EKF will take inputs from the TRIAD and filter the noise before performing a final attitude determination algorithm.

2.1.6. Control Law for Detumbling Mode

Firstly, when the CubeSat is initially deployed from the ISS, it undergoes tumbling at a rate of about a few degrees per second around each of its three axes. At this time, the control law for detumbling must be robust and reduce this initial movement quickly in order for normal operation to occur. In Section 3 – Detailed Design Documentation, the quick detumbling of the CubeSat can be seen.

2.1.7. Control Law for Normal Operation

During normal operation, the CubeSat will need to perform different actions such as communication, where the antenna of the CubeSat must be pointed towards the ground station and imaging, where the camera of the CubeSat must be pointed towards a target location. At this time, the control law must determine how much torque it needs to get from its current orientation to the desired orientation. The success of the control law for normal operation can be found in Section 3 – Detailed Design Documentation and will be demonstrated through our prototype.

2.1.8. Magnetorquers

The control law will determine how much torque is needed to go from the current attitude to the desired attitude and the corresponding torque needed from the magnetorquers will dictate the current that will be run through the magnetorquers. The model and analysis of these actuators can be found in Section 3 – Detailed Design Documentation.

2.2. Design Analysis Contents

2.2.1. Power Consumption

Part Number	Name	Quantity	Supply Current	Supply Voltage	Power Supply
1000	NSS Fine Sun Sensor	6	<10 mA	5 V	50 mW
1001	Precision Navigation and Pointing Gyroscope	1	12 mA	2.7-3.6 V	43.2 mW
1002	3-Axis Digital Magnetometer IC	1	0.15 mA	1.7-3.6 V	0.54 mW
1003	Arduino Mega 2560 Rev3	1	50 mA	5V	250 mW
1004	Magnetorquer Rod	3	40 mA	5 V	200 mW
Total Current for ADCS: 112.15 mA Supply Voltage for ADCS: 5 V Total Power for ADCS: 543.74 mW Efficiency of ADCS: 50% Input Power Needed for ADCS: 1087.48 mW					
1006^{P}	MPU 6050 Gyroscope and Accelerometer Board	1	3.7 mA	2.375-3.46 V	12.8 mW
1007^{P}	Arduino Mega 2560 Rev3	1	50 mA	5 V	250 mW
1014^{P}	Standard Motor 12850 RPM 12VDC	3	116 mA	12 V	1392 mW
Total Current for ADCS Prototype: 169.7mA Supply Voltage for ADCS Prototype: 12 V Total Power for ADCS Prototype: 1654.8 mW Efficiency of ADCS Prototype: 50% Input Power Needed for ADCS Prototype: 3309.6 mW					

Table 1: Power Budget

The total power budget allotted for the ADCS design was 1.2 mW. Taking into consideration the power from the components listed above, the total power consumed by ADCS will be at a maximum of 1087.48 mW during the CubeSat's mission lifetime. The power budget for the ADCS prototype is less important as our prototype is not a 1:1 scale of our design; the rationale behind this decision will be discussed later in the report.

2.2.2. Safety of System

While designing the ADCS, safety was one of the top priorities. For example, when choosing components required for the ADCS, it was ensured that the materials would not emit any toxic fumes when in space since materials in a near-vacuum environment suffer from outgassing. To ensure that all physical components chosen would not emit toxic fumes, all components chosen were space-certified. If toxic fumes were to be released in the spacecraft during the transport of the CubeSat, the fumes could prove fatal in the spacecraft and/or International Space Station (ISS). These fumes would not be able to be dispersed in space as there is no ventilation on any spacecraft nor in the ISS.

2.2.3. Prototype Analysis - Actuation

The reactions wheels will be used to actuate the prototype using the principle of conservation of angular momentum. This is a viable solution to actuating in space as there are not many external forces acting on the system meaning that large torques are not required when actuating. A motor will spin a circular mass, referred to as a flywheel, fixed to the motor shaft. By changing the angular speed of the fly wheel, the system will experience a resultant torque that equates the initial and final angular momentums. The resultant torque felt by the prototype can be adjusted by changing the speed of the three flywheels, which will ultimately allow actuation control of the prototype.

However, there are certain design considerations that must be made. Firstly, the motors used to spin the flywheels must provide speeds of at least 2000 rpm. This is important as the flywheels need to be spinning at a non-zero value, ideally at a value above 500 rpm, even when the system needs to be stabilized. Having non-zero flywheel speeds means that the prototype will be more resistant to disturbance torques. The factors to determine whether these speeds are possible or not are the specifications of the motors as well as the inertia of the flywheels.

The weight and change in speed of the reaction wheel will determine the resultant torque that is needed for the prototype. The accuracy of the system is more important than having a fast system, thus a flywheel weighing 67.6 g was used. Although this flywheel is heavier than others commonly used for CubeSat projects, the prototype will be heavily influenced by gravity and will need greater resultant torques to effectively actuate.

After the inertia of the flywheel is determined, the motor needs to turn the prototype. Using the criteria of minimum acceptable speed that was previously determined, as well as the financial and mass budgets, the PAN14EE12AA1 standard DC motor was selected. The important characteristics of this motor include the stall torque (4.9 N·mm) and the rated 12V no-load speed (12850 rpm).

To verify that this motor would be sufficient for the prototype, it had to achieve speeds of at least 2000 rpm in a short time period of one second. This was confirmed using SolidWorks Motion Analysis and can be seen in Figures 1 to 3.

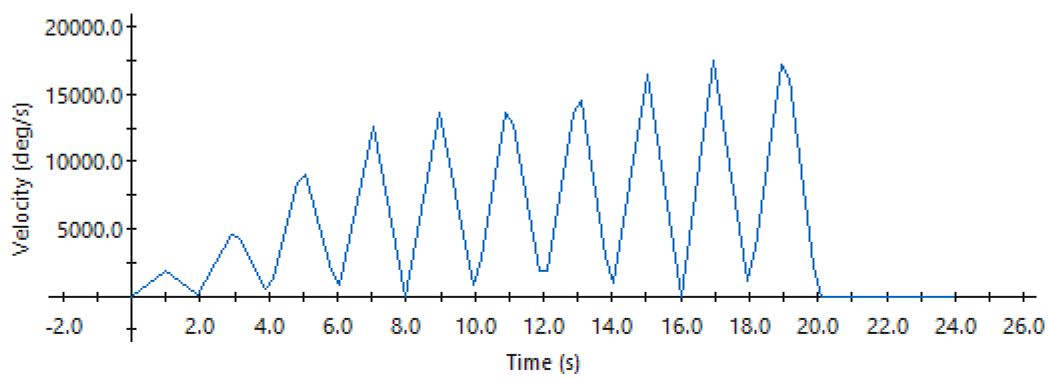

***Figure 1: Velocity vs. Time Graph of Part 1016 (*Standard Motor 12850 rpm 12VDC)**

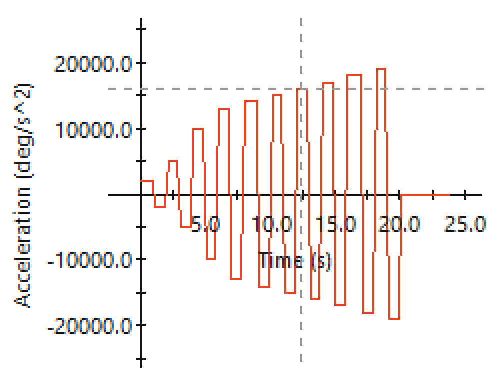

***Figure 2: Acceleration vs. Time Graph of Part 1016 (*Standard Motor 12850 rpm 12VDC)**

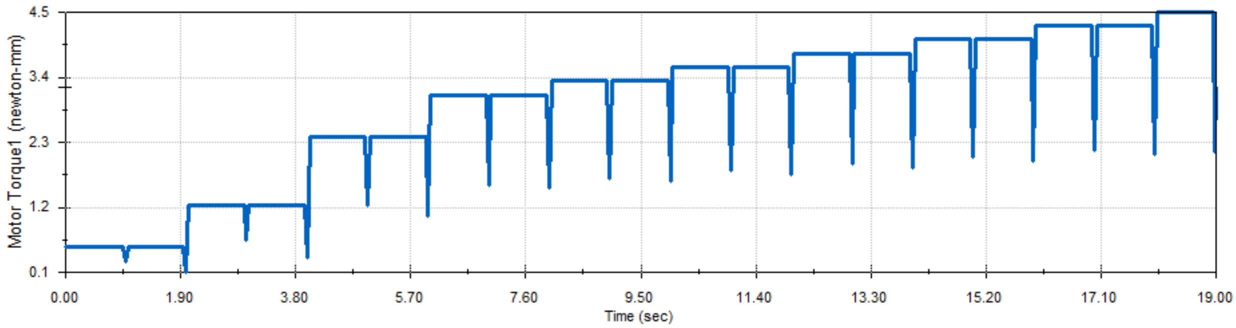

Figure 3: Motor Torque vs. Time Graph of Part 1016 (**Standard Motor 12850 rpm 12VDC)**

From these results, it can be seen that the maximum change in angular speed that can be achieved in one second is 20,000 °/sec, or 3500 rpm. This is well above the minimum requirement selected above. The maximum angular acceleration possible is 4.5 N·mm, which is just under the 4.9 N·mm stall torque.

2.3. Design Analysis Files

2.3.1. Datasheets

This section includes the datasheets for components for both the ADCS design and ADCS prototype and includes the following contents:

1. ***ADCS Design Datasheets***
    a. ***Part 1000 – NSS Fine Sun Sensor.pdf***
    b. ***Part 1001 – Precision Navigation and Pointing Gyroscope.pdf***
    c. ***Part 1002 – 3-Axis Digital Magnetometer IC.pdf***
    d. ***Part 1003 – Arduino Mega 2560 Rev3.pdf***
    e. ***Part 1004 – Magnetorquer Rod.pdf***
2. ***ADCS Prototype Datasheets***
    a. ***Part 1008 – MPU 6050 Gyroscope and Accelerometer Board.pdf***
    b. ***Part 1016 – Standard Motor 12850 RPM 12VDC.pdf***
    c. ***Part 1030 – Magnetic Magnetometer Sensor Evaluation Board.pdf***

2.3.2. Part Drawings

This section includes all the part and assembly drawings made for both the ADCS design and ADCS prototype and includes the following contents:

1. ***Part Drawings for ADCS Design***
    a. ***Part 1000 - NSS Fine Sun Sensor.SLDDRW***
    b. ***Part 1000 - NSS Fine Sun Sensor.SLDPRT***
    c. ***Part 1001 - Precision Navigation and Pointing Gyroscope.SLDDRW***
    d. ***Part 1001 - Precision Navigation and Pointing Gyroscope.SLDPRT***
    e. ***Part 1002 - 3Axis Digital Magnetometer IC.SLDDRW***
    f. ***Part 1002 - 3Axis Digital Magnetometer IC.SLDPRT***
    g. ***Part 1003 - Arduino Mega 2560 Rev3.SLDDRW***
    h. ***Part 1004 - Magnetorquer Rod.SLDDRW***
    i. ***Part 1004 - Magnetorquer Rod.SLDPRT***
2. ***Part Drawings for ADCS Prototype***
    a. ***Full Assembly of Prototype.SLDDRW***

b. ***Full Assembly of Testbed for Prototype.SLDASM***
c. ***Full Assembly of Testbed for Prototype.SLDPRT***
d. ***Part 1008 - MPU 6050 Gyroscope and Accelerometer Board.SLDDRW***
e. ***Part 1009 - MSEduino.SLDDRW***
f. ***Part 1010 - Battery Holder.SLDDRW***
g. ***Part 1012 - 1' Black Delrin Acetal Resin Rod 1-1/2" Diameter.SLDPRT***
h. ***Part 1012 - 1' Black Delrin Acetal Resin Rod 11/2" Diameter.SLDDRW***
i. ***Part 1013 - Highly CorrosionResistant Stainless Steel Ball 1" Diamater.SLDPRT***
j. ***Part 1013 - Highly CorrosionResistant Stainless Steel Ball 1" Diameter.SLDDRW***
k. ***Part 1014 - Acrylic Sheet.SLDDRW***
l. ***Part 1016 - Standard Motor 12850 RPM 12VDC.SLDDRW***
m. ***Part 1017 - PanelMount Compressed Air Regulator.SLDDRW***
n. ***Part 1017 - PanelMount Compressed Air Regulator.SLDPRT***
o. ***Part 1018 - BlackOxide Alloy Steel Hex Drive Flat Head Screw 1"-8 Thread Size 21/2" Long.SLDPRT***
p. ***Part 1018 - BlackOxide Alloy Steel Hex Drive Flat Head Screw 1"8 Thread Size 21/2" Long.SLDDRW***
q. ***Part 1019 - BlackOxide Alloy Steel Hex Drive Flat Head Screw 1/4"-20 Thread Size, 1/2" Long.SLDPRT***
r. ***Part 1019 - BlackOxide Alloy Steel Hex Drive Flat Head Screw 1/4"20 Thread Size, 1/2" Long.SLDDRW***
s. ***Part 1020 - Wooden Board.SLDDRW***
t. ***Part 1020 - Wooden Board.SLDPRT***
u. ***Part 1021 - PushtoConnect Tube Fitting for Air.SLDDRW***
v. ***Part 1021 - PushtoConnect Tube Fitting for Air.SLDPRT***
w. ***Part 1022 - Reducing Adapter, 1/8 NPT Female x 1/16 NPT Male.SLDDRW***
x. ***Part 1022 - Reducing Adapter, 1/8 NPT Female x 1/16 NPT Male.SLDPRT***
y. ***Part 1023 - Straight Adapter for 1/4" Tube OD x 1/8 NPT Male.SLDPRT***
z. ***Part 1023 - Straight Adapter, for 1/4" Tube OD x 1/8 NPT Male.SLDDRW***
aa. ***Part 1023 - Straight Adapter, for 1/4" Tube OD x 1/8 NPT Male.SLDPRT***

bb. ***Part 1024 - IndustrialShape Hose Coupling Size 1/4", ZincPlated Steel Ply, 1/4 NPTF Male End.SLDDRW***

cc. ***Part 1024 - IndustrialShape Hose Coupling Size 1/4", ZincPlated Steel Ply, 1/4" NPTF Male End.SLDPRT***

dd. ***Part 1025 - PushtoConnect Tube Fitting for Air with Shut-Off Adapter, for 1/4" Tube OD, 1/4 NPT Male.SLDDRW***

ee. ***Part 1025 - PushtoConnect Tube Fitting for Air with ShutOff Adapter for 1/4" Tube OD, 1/4 NPT Male.SLDDRW***

ff. ***Part 1025 - PushtoConnect Tube Fitting for Air with ShutOff Adapter, for 1/4" Tube OD, 1/4 NPT Male.SLDPRT***

gg. ***Part 1028 - Low Carbon Steel Disc.SLDDRW***

hh. ***Part 1029 - 1.5A 2 Way MX1508 DC Motor Driver, PWM Speed Control.SLDDRW***

ii. ***Part 1030 - Magnetic Magnetometer Sensor Evaluation Board.SLDDRW***

2.3.3. Prototype Files

1. ***MPU6050*** folder by Jeff Rowberg contains the following contents:

    a. ***Examples*** folder

        i. ***MPU6050_DMP6*** folder

            1. ***MPU6050_DMP6.ino***
            2. ***Processing*** folder

                a. ***MPUTeapot*** folder

                    i. MPUTeapot.pde

        ii. ***MPU6050_raw*** folder

            1. ***MPU6050_raw.ino***

    b. ***Helper_3dmath.h***

    c. ***MPU6050_6Axis_MotionApps20.h***

    d. ***MPU6050_9Axis_MotionApps41.h***

    e. ***MPU6050.cpp***

    f. ***MPU6050.h***

    This folder must be installed inside Arduino (Arduino --> libraries). To test whether the gyroscope is reading the correct values, when opening the Arduino IDE, go to File -->

Examples --> MPU6050 --> Examples --> MPU6050_DMP6. Compile and upload the code to the Arduino. If the gyroscope is working correctly, the words “Initializing I2C devices…” should be shown when opening the serial monitor. Afterwards, press any key and the rates calculated in the yaw, pitch and roll axes should be displayed. After the gyroscope values have stabilized, the gyroscope can be moved and should change in relation to how the gyroscope is being oriented.

2. ***toxiclibs-complete-0020*** folder by Karsten Schmidt needs to be downloaded and placed in Processing --> libraries in order for the gyroscope 3-D simulation to work. In the Arduino IDE, go to File --> Examples --> MPU6050 --> Examples --> MPU6050_DMP6 and comment out the line that says #define OUTPUT_READABLE_YAWPITCHROLL and uncomment the line that says #define OUTPUT_TEAPOT. Then, compile and upload this code to the Arduino, but do not open the serial monitor. After this, open the Processing IDE, and open the Processing example by going to MPU6050 --> Examples -->MPU6050_DMP6 --> Processing --> MPUTeapot. In the code, change the following line to String portName = “/dev/ttyUSB1”;. After doing so, press play and a 3-D model of the CubeSat will appear in a Java window. This model will change as you orient the gyroscope as it is a real-time model.

2.3.4. Simulink & MATLAB Files

1. ***CompleteAttDetSim_edited.slx*** is a complete list of all
2. ***CubeSatTLE.txt***
3. ***earth.jpg***
4. ***earthSatSys_Ideal.WRL***
5. ***earthSatSys_Real.WRL***
6. ***InitialiseJ2.m***

7. ***keplerEq.m***

8. ***planetearth.jpg***

9. ***stars.jpg***

3. Detailed Design Documentation

3.1. Simulink Models

3.1.1. Sun Sensors

The sun sensor is modeled in Simulink to accept two inputs (Figure 4). The position of the sun is in ECI coordinates, calculated using the sun position model (Section 3.1.9.1 – Sun Block) and a quaternion that will rotate from Earth-Centered Inertial (ECI) coordinates to body coordinates. It outputs a sun vector in body coordinates, or the position of the sun as seen by the CubeSat. In the second level of the sun sensor block (Figure 5) a random quaternion is calculated using the errorquatgen function in MATLAB. This is applied to the sun vector to add noise. Next, the vector is rotated into body coordinates, by applying the input quaternion, and normalized to give the output sun vector.

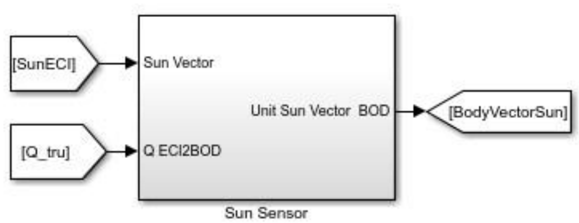

Figure 4: Level 1 of the Sun Sensor Model in Simulink

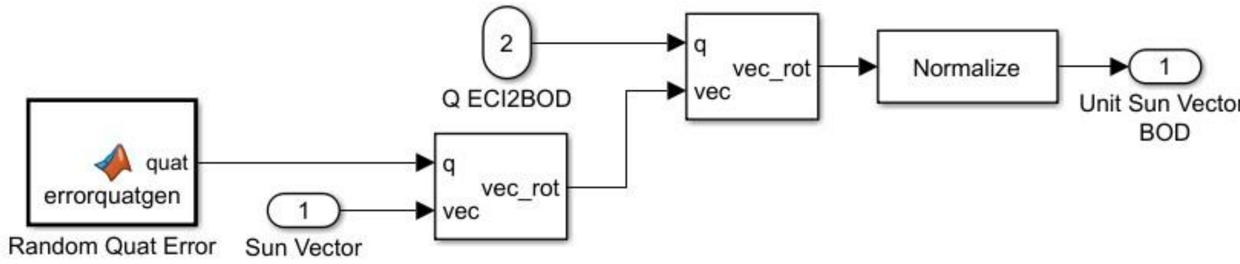

Figure 5: Level 2 of the Sun Sensor Model in Simulink

3.1.2. Gyroscope

The gyroscope takes in the angular rate and adds noise to model an actual gyroscope output as shown in Figures 6 and 7.

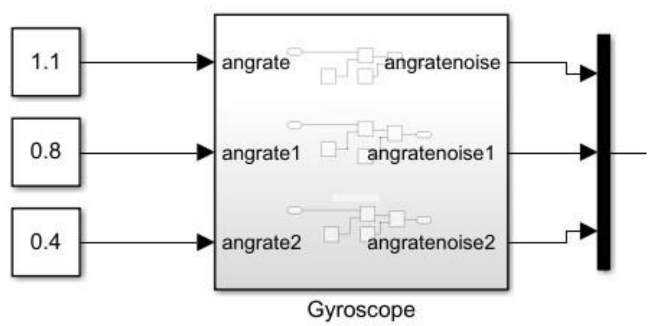

Figure 6: Level 1 of Gyroscope Simulink Block

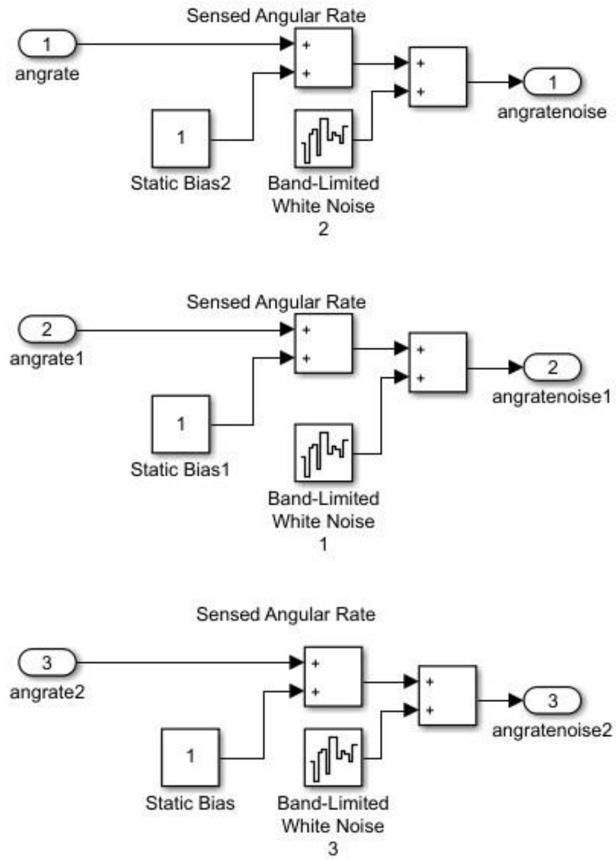

Figure 7: Level 2 of Gyroscope Simulink Block

3.1.3. Magnetometer

The magnetometer has two inputs: the direction of the Earth's magnetic field in ECI coordinates (Section 3.1.9.2 – International Geomagnetic Reference Field), and a quaternion that will rotate from ECI coordinates to body coordinates. It has one output; a magnetic vector in body coordinates, or the direction of the Earth's magnetic field as seen by the CubeSat (Figure 8). In the second level of the sensor (Figure 9), the magnetic vector is rotated to body coordinates, and normalized. In the third level of the sensor (Figure 10), noise is added to the sensor using the function NoiseGenerator and the resolution of the sensor and output range are taken into account.

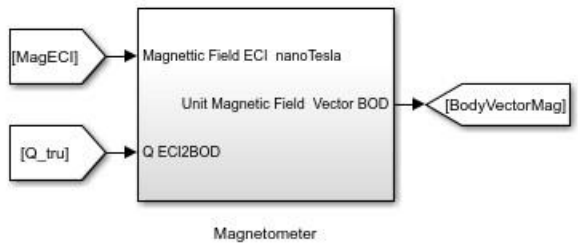

Figure 8: Level 1 of the Magnetometer Model in Simulink

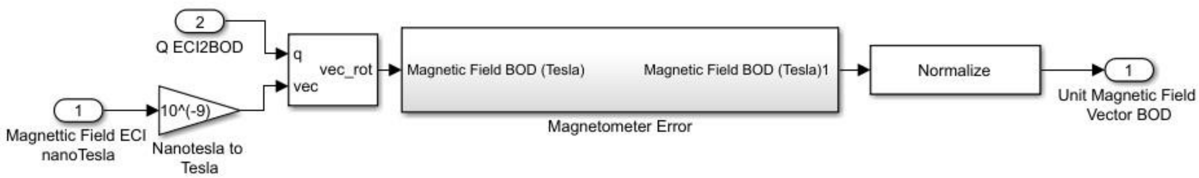

Figure 9: Level 2 of the Magnetometer Model in Simulink

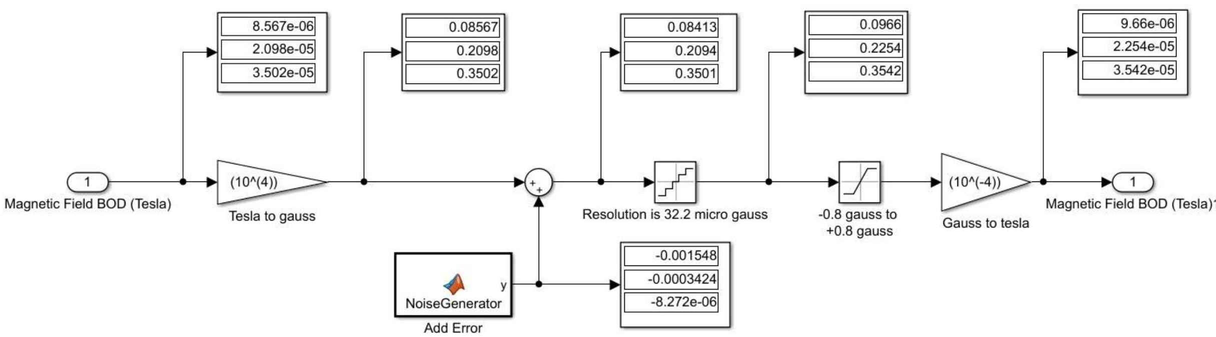

Figure 10: Level 3 of the Magnetometer Model in Simulink

3.1.4. Tri-Axel Attitude Determination (TRIAD)

In the first level of the optimized TRIAD it takes in two reference vectors, two body vectors and two sigma values, and outputs the attitude matrix (Figure 11). In the second level of the optimized TRIAD (Figure 12), the two TRIAD functions generate an attitude matrix using the two reference vectors and two measured vectors. Then the optimized TRIAD function applies a state estimator and normalizes the result to calculate the attitude matrix.

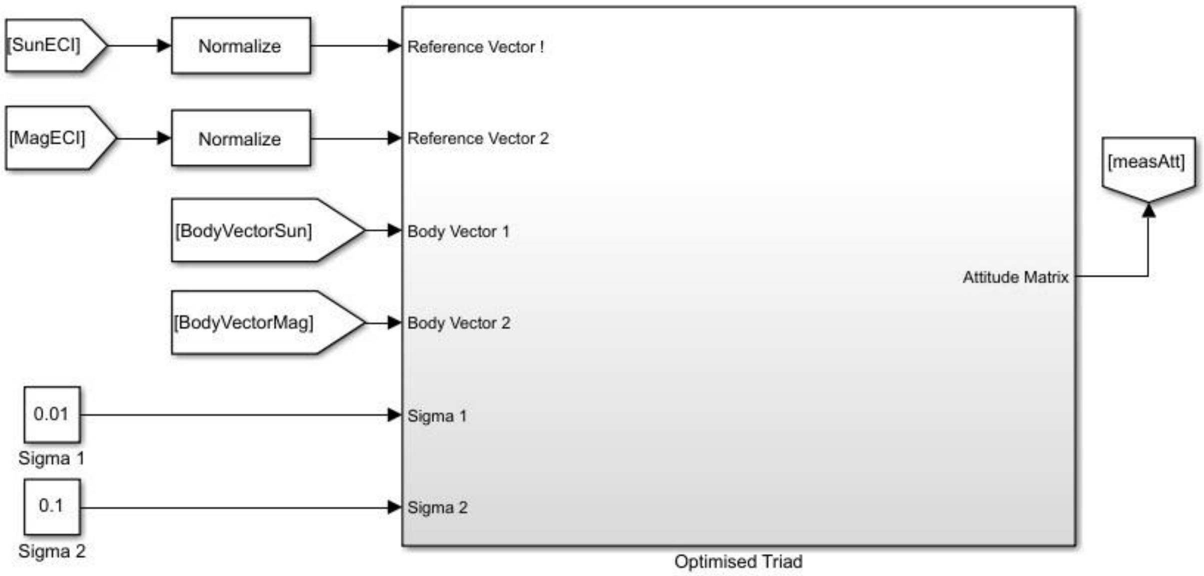

Figure 11: Level 1 of the TRIAD Model in Simulink

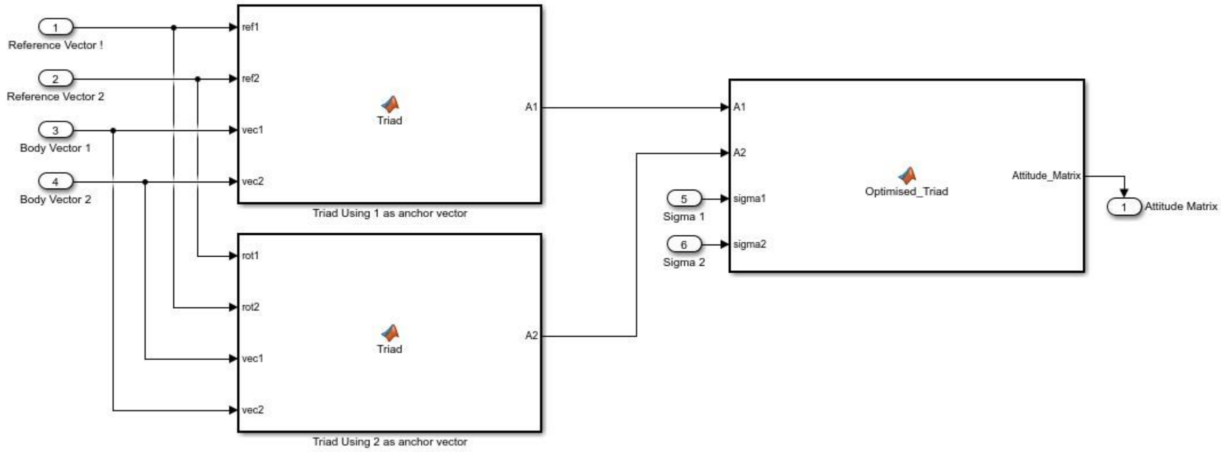

Figure 12: Level 2 of the TRIAD Model in Simulink

3.1.5. Magnetorquer

The magnetorquer takes in a pulse width modulation signal for the x,y and z axes and outputs the torque vector required to actuate the CubeSat to the desired position as shown in Figures 13 and 14.

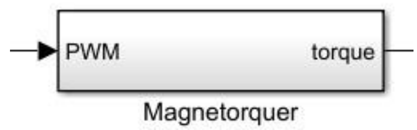

Figure 13: Level 1 of Magnetorquer Simulink Block

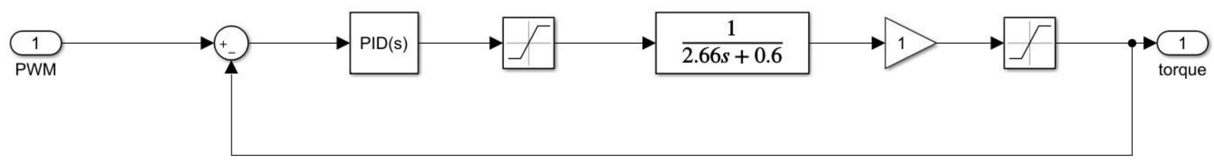

Figure 14: Level 2 of the Magnetorquer Simulink Block

3.1.6. Control Law (B-dot)

The B-dot control law takes in a magnetic vector in body coordinates and an angular velocity from the gyroscope, and it outputs an actuation level to be passed to the magnetorquers (Figure 15). The B-dot function is provided under the MATLAB function section.

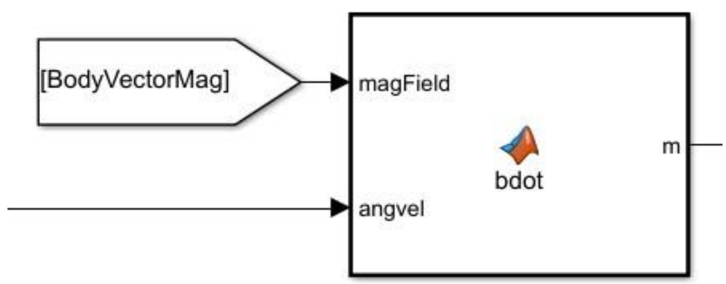

Figure 15: B-dot Control Law in Simulink

3.1.7. Attitude Propagator

The attitude propagator takes in a position vector and a velocity vector in ECI coordinates, and outputs an attitude matrix (Figure 16). It then normalizes the two vectors and passes them along with two reference vectors through a TRIAD (Figure 17).

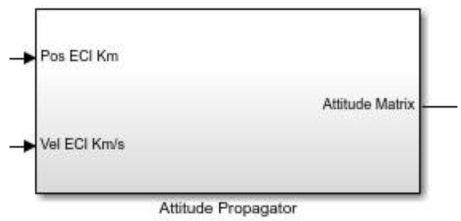

Figure 16: Level 1 of Attitude Propagator Simulink Block

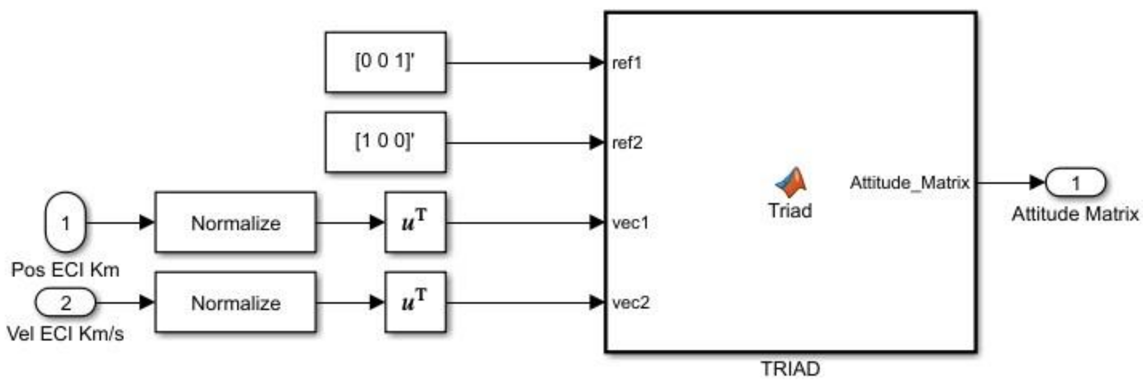

Figure 17: Level 2 of Attitude Propagator Simulink Block

3.1.8. Helper Blocks

3.1.8.1. Sun Position

Figures 18 and 19 show the sun position block that calculates the position of the sun in ECI coordinates. It takes a date in calendar format and the simulation time as inputs and uses functions julian and fracjday to convert the input date from calendar format to Julian date format [1]. This is then used, along with the desired position of the satellite to calculate the suns position in ECI coordinates.

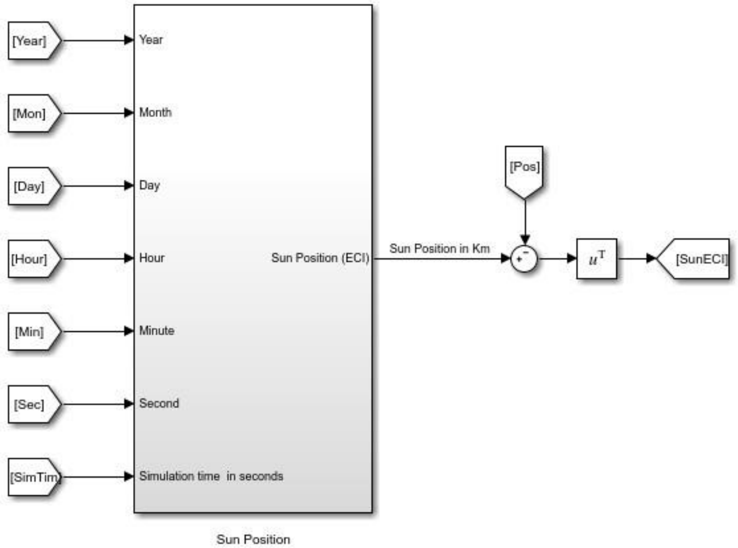

Figure 18: Level 1 of Sun Position Block

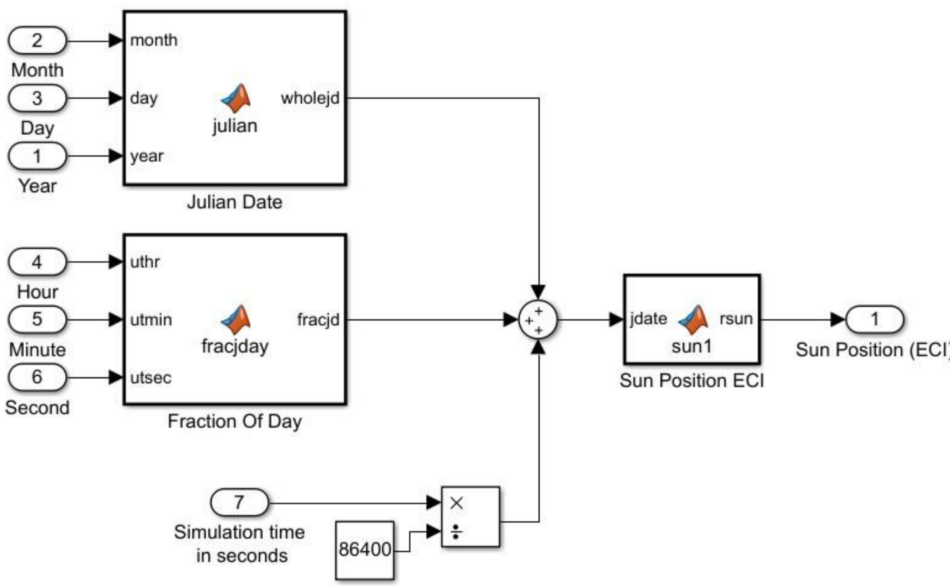

Figure 19: Level 2 of Sun Position Block

3.1.8.2. International Geomagnetic Reference Field (IGRF)

Figures 20 and 21 show the IGRF model. It takes in the desired position in meters, along with a calendar format date and the simulation time. It outputs the magnetic field in ECI coordinates. The sub-block contains the functions Magfield_spherical, locst, rECI2ECEF and msph2inert.

The Magfied_spherical function converts the magnetic field into local spherical coordinates [2]. The locst function takes in the date and the longitude and computes the local sidereal time [3]. The rECI2ECEF function converts from ECI to earth-centered, earth-fixed (ECEF) coordinates [4]. Finally, the msph2inert converts local spherical coordinates into ECI coordinates.

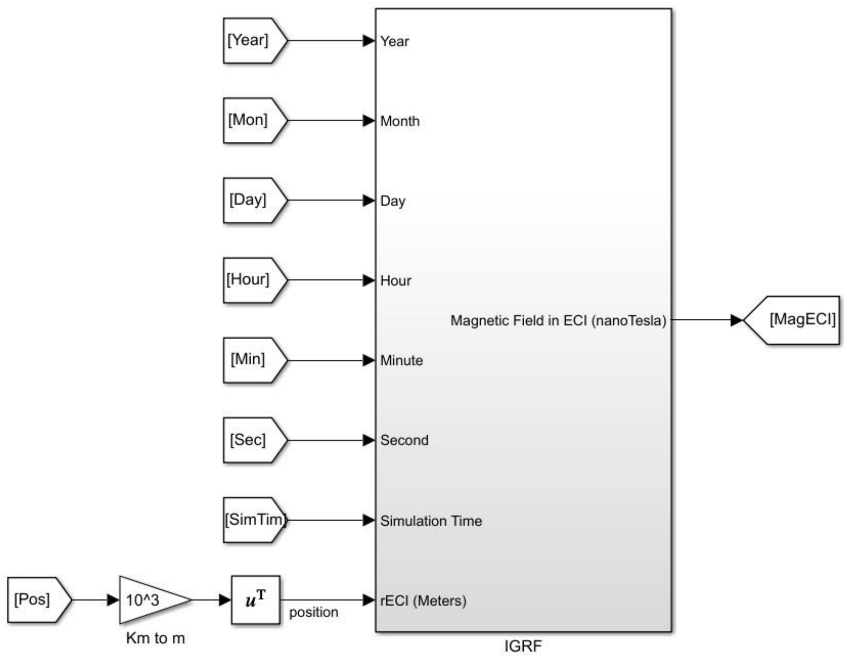

Figure 20: Level 1 of IGRF Block

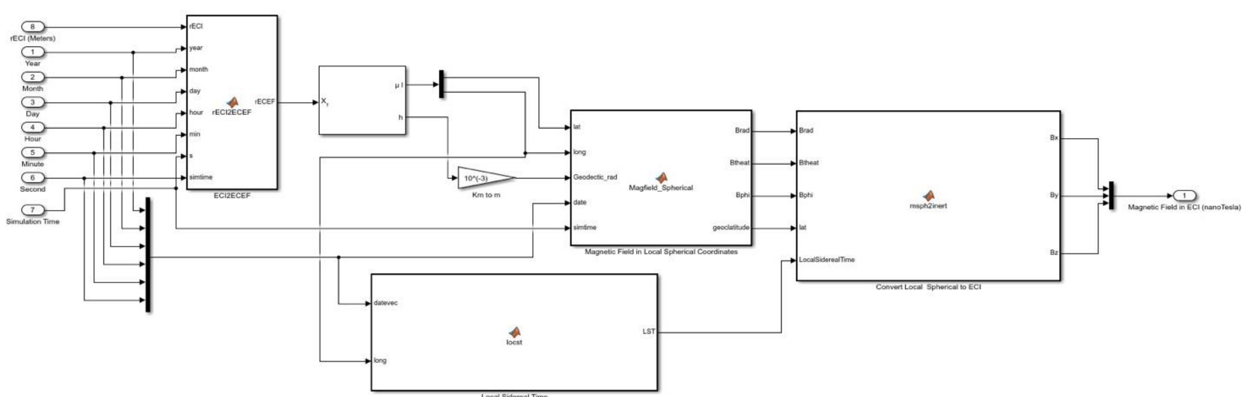

Figure 21: Level 2 of IGRF Block

3.1.8.3. J2 Propagator

This block generates an ideal orbit (Figures 22 and 23). This was provided by the orbital CubeSat team.

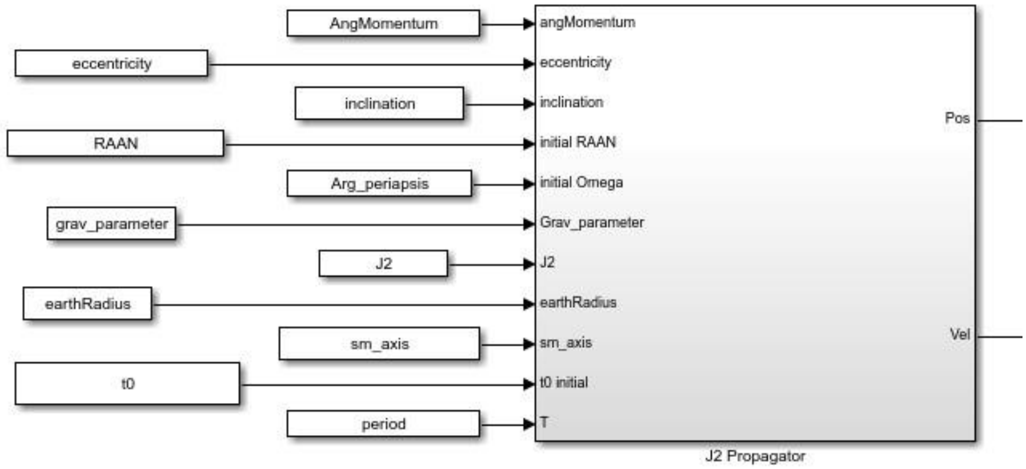

Figure 22: Level 1 of J2 Propagator

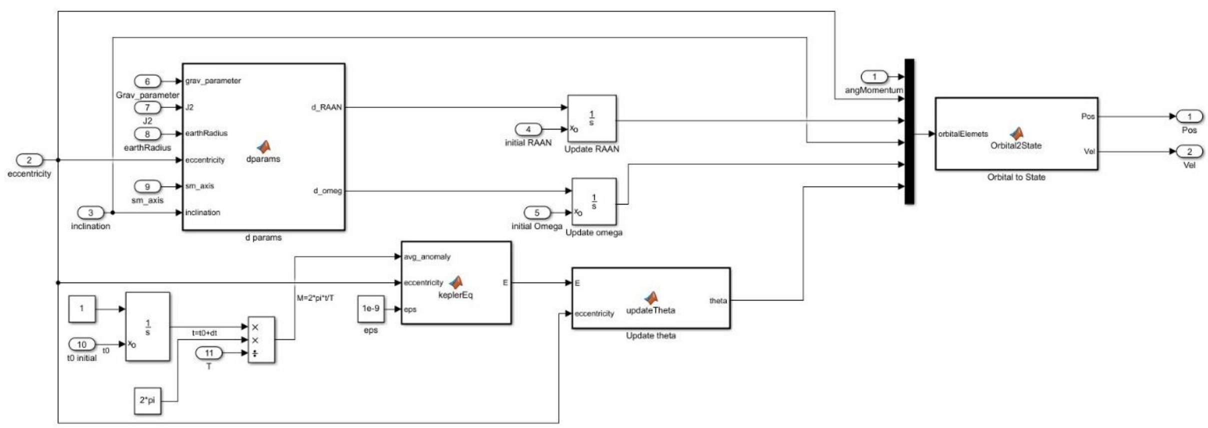

Figure 23: Level 2 of J2 Propagator

3.1.9. Overall System

Figure 24 shows the overall ADCS system.

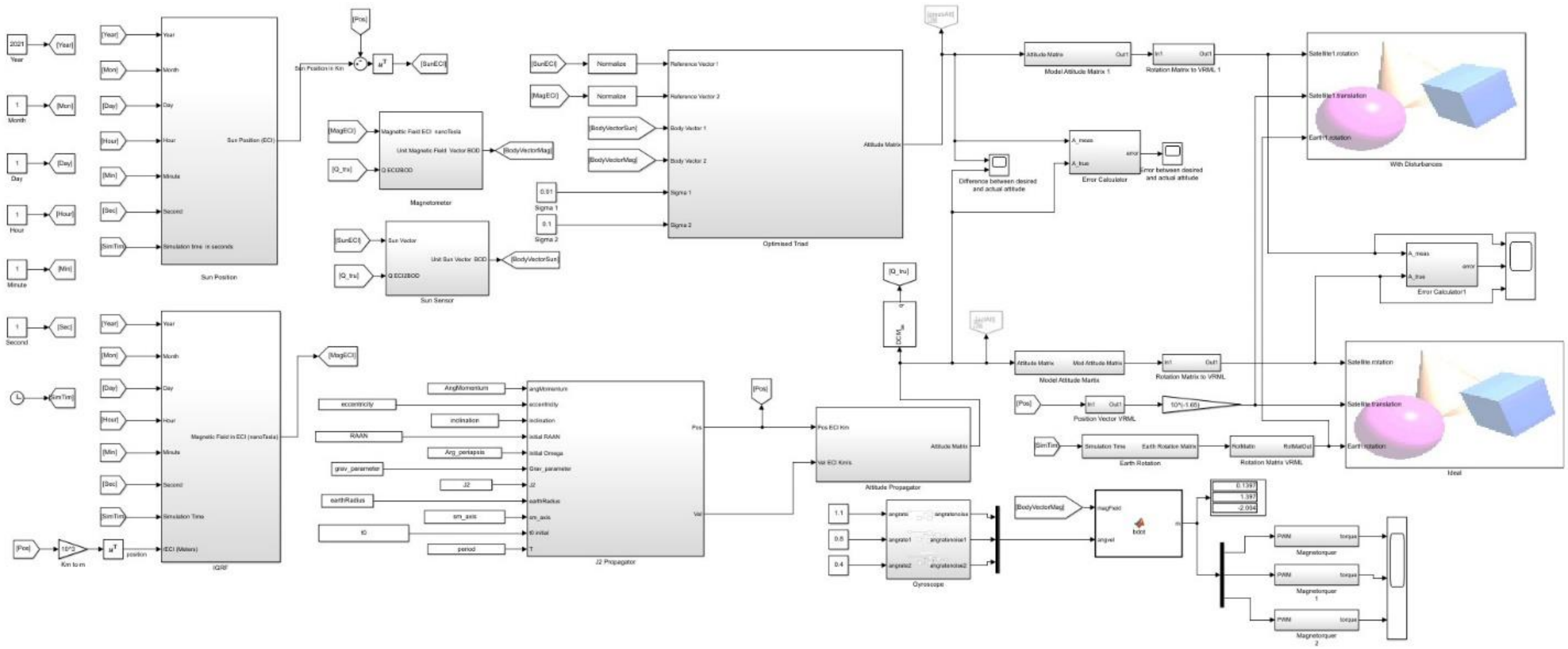

Figure 24: Overall ADCS in Simulink

3.2. MATLAB Code

3.2.1. Sun Sensor

errorquatgen() MATLAB Code

```
function quat = errorquatgen()
%generate quaternion for rotation of given angle (rad) around random axis
%computing first term of quaternion
angle=normrnd(0,0.0029);
q0=cos(angle/2);
%random axis
a=rand;
b=rand;
c=rand;
axis=[a b c];
%normalise the random axis
n=norm(axis);
a=a/n;
b=b/n;
c=c/n;
%computing quaternoin
q1=a*sin(angle/2);
q2=b*sin(angle/2);
q3=c*sin(angle/2);
quat=[q0 q1 q2 q3];
end
```

3.2.2. Magnetometer

NoiseGenerator() MATLAB Code

```
function y = NoiseGenerator()
RSS_err=0.12*1/100;
FullScale=0.8;
y=randn(3,1)*RSS_err*FullScale;
end
```

3.2.3. TRIAD

Triad(ref1,ref2,vec1,vec2) MATLAB Code

```
function A1=Triad(ref1,ref2,vec1,vec2)
%This function generates an attitude matrix two reference and two measured
%vectors.

%Calculate body tirad
triad1body=vec1./norm(vec1);
triad2body=cross(triad1body,vec2)./norm(cross(triad1body,vec2));
triad3body=cross(triad1body,triad2body)./...
    norm(cross(triad1body,triad2body));

%Calculate reference tirad
triad1reference=ref1./norm(ref1);
triad2reference=cross(triad1reference,ref2)...
    ./norm(cross(triad1reference,ref2));
triad3reference=cross(triad1reference,triad2reference)./...
    norm(cross(triad1reference,triad2reference));

%Calculate attituce matrix
A1= triad1body*(triad1reference.') + triad2body*(triad2reference.')...
    + triad3body*(triad3reference.');
```

Optimised_TRIAD(A1,A2,sigma1,sigma2) MATLAB Code

```
function Attitude_Matrix=Optimised_Triad(A1,A2,sigma1,sigma2)

LinearEstimator=((sigma2)^2/((sigma1)^2+(sigma2)^2))...
    *A1+((sigma1)^2/((sigma1)^2+(sigma2)^2))*A2;
%Orthogonalise
Attitude_Matrix=0.5*(LinearEstimator+(inv(LinearEstimator).'));
```

3.2.4. Initialization

InitializeJ2 MATLAB Code

```
%define parameters
grav_parameter = 398600.4415;  %in km^3/s^2
earthRadius = 6378.137; % in km
J2 = 0.0010836;
earth_rot = 360*(1 + 1/365.25)/(3600*24);  % Earth's rotation [deg/s]

%read in
fname = 'CubeSatTLE.txt';    % TLE file name
% Open the TLE file and read TLE elements
fid = fopen(fname, 'rb');


%while not at end of file
while ~(feof(fid))
% read data form two-line element set for cubesat orbit
D1 = fscanf(fid,'%23c%*s',1);
D2 = fscanf(fid,'%d%6d%*c%5d%*3c%*2f%f%f%5d%*c%*d%5d%*c%*d%d%5d',[1,9]);
D3 = fscanf(fid,'%d%6d%f%f%f%f%f%f%f',[1,9]);
jd_Fraction = D2(1,4)*24*3600; % Epoch Date and Julian Date Fraction
Ballistic_Coeff = D2(1,5);
inclination = D3(1,3); %in degrees
RAAN = D3(1,4);  %Right Ascension of Ascending Node in degrees
eccentricity = D3(1,5)/1e7;
Arg_periapsis = D3(1,6); %in degrees
avg_anomaly = D3(1,7); %in degrees
avg_motion = D3(1,8); % in revolutions per day

% defineing Orbital parametres
sm_axis = (grav_parameter/(avg_motion*2*pi/(24*3600))^2)^(1/3);%kilometers
period = 2*pi*sqrt(sm_axis^3/grav_parameter); % in minutes
rp = sm_axis*(1-eccentricity);
AngMomentum = (grav_parameter*rp*(1 + eccentricity))^0.5;
E = keplerEq(avg_anomaly*pi/180,eccentricity,2^(-52));
True_anom =  acos((cos(E) -eccentricity)/(1 - eccentricity*cos(E)))...
    *180/pi; %in degrees

E = 2*atan(tand(True_anom/2)*((1-eccentricity)/(1+eccentricity))^0.5);
avg_anomaly = E  - eccentricity*sin(E);
t0 = avg_anomaly/(2*pi)*period;
end
```

KeplerEq(avg_anomaly,eccentricity,eps) MATLAB Code

```
function E = keplerEq(avg_anomaly,eccentricity,eps)
En  = avg_anomaly;
Ens = En - (En-eccentricity*sin(En)- avg_anomaly)/...
    (1 - eccentricity*cos(En));
while ( abs(Ens-En) > eps )
    En = Ens;
    Ens = En - (En - eccentricity*sin(En) - avg_anomaly)/...
        (1 - eccentricity*cos(En));
end
E = Ens;
end
```

3.2.5. Sun Position

julian (month,day,year) MATLAB Code

```
function wholejd = julian (month, day, year)
wholejd=0;
y = year;
m = month;
b = 0;
c = 0;

if (m <= 2)
   y = y - 1;
   m = m + 12;
end

if (y < 0)
   c = -.75;
end
 % check for valid calendar date
 if (year < 1582)
    % null
 elseif (year > 1582)
    a = fix(y / 100);
    b = 2 - a + floor(a / 4);
 elseif (month < 10)
    % null
```

```
elseif (month > 10)
   a = fix(y / 100);
   b = 2 - a + floor(a / 4);
elseif (day <= 4)
   % null
elseif (day > 14)
   a = fix(y / 100);
   b = 2 - a + floor(a / 4);
   fprintf('\n\n  this is an invalid calendar date!!\n');
   return;
end

jd = fix(365.25 * y + c) + fix(30.6001 * (m + 1));
wholejd = jd + day + b + 1720994.5;
```

fracjday(uthr,utmin,utsec)

```
function fracjd=fracjday(uthr, utmin, utsec)
fracjd=uthr / 24 + utmin / 1440 + utsec / 86400;
```

sun1(jdate) MATLAB Code

```
function rsun  = sun1 (jdate)
atr = pi / 648000;
rsun = zeros(3, 1);

% time arguments
djd = jdate - 2451545;
t = (djd / 36525) + 1;

% fundamental arguments (radians)
gs =2.0*pi*((0.993126+0.0027377785*djd)-fix(0.993126+0.0027377785*djd));
lm = 2.0*pi*((0.606434+0.03660110129*djd)-fix(0.606434+0.03660110129*djd));
ls = 2.0*pi*((0.606434+0.03660110129*djd)-fix(0.606434+0.03660110129*djd));
g2 = 2.0*pi*((0.606434+0.03660110129*djd)-fix(0.606434+0.03660110129*djd));
g4 = 2.0*pi*((0.606434+0.03660110129*djd)-fix(0.606434+0.03660110129*djd));
g5 = 2.0*pi*((0.606434+0.03660110129*djd)-fix(0.606434+0.03660110129*djd));
rm = 2.0*pi*((0.606434+0.03660110129*djd)-fix(0.606434+0.03660110129*djd));

% geocentric, ecliptic longitude of the sun (radians)
plon = 6910*sin(gs)+72*sin(2*gs)-17*t*sin(gs);
plon = plon-7*cos(gs-g5)+6*sin(lm-ls)+5*sin(4*gs-8*g4+3*g5);
plon = plon-5*cos(2*(gs-g2))-4*(sin(gs-g2)-cos(4*gs-8*g4+3*g5));
plon = plon+3*(sin(2*(gs-g2))-sin(g5)-sin(2*(gs-g5)));
plon = ls+atr*(plon-17*sin(rm));
```

```matlab
% geocentric distance of the sun (kilometers)
rsm = 149597870.691*(1.00014-0.01675*cos(gs)-0.00014*cos(2*gs));

% obliquity of the ecliptic (radians)
obliq = atr*(84428-47*t+9*cos(rm));

% geocentric, equatorial right ascension and declination (radians)
a = sin(plon)*cos(obliq);
b = cos(plon);

epsilon = 0.0000000001;
pidiv2 = 0.5 * pi;
dontenterflag=0;
c=0;
if (abs(a) < epsilon)
    rascy = (1 - sign(b)) * pidiv2;
    dontenterflag=1;
else
    c = (2 - sign(a)) * pidiv2;
end
if ((abs(b) < epsilon)&&dontenterflag~=1)
    rascy = c;
else
    rascy = c + sign(a) * sign(b) * (abs(atan(a / b)) - pidiv2);
end
rasc = rascy;
decl = asin(sin(obliq) * sin(plon));

% geocentric position vector of the sun (kilometers)
rsun(1) = rsm * cos(rasc) * cos(decl);
rsun(2) = rsm * sin(rasc) * cos(decl);
rsun(3) = rsm * sin(decl);
```

3.3. Simulation Results

3.3.1. Rotational Error

The rotational error between the desired and actual error can be seen in Figure 25 to 28. Spikes in the error are seen when there is an abrupt change in the desired rotation as the desired rotation lags the actual rotation.

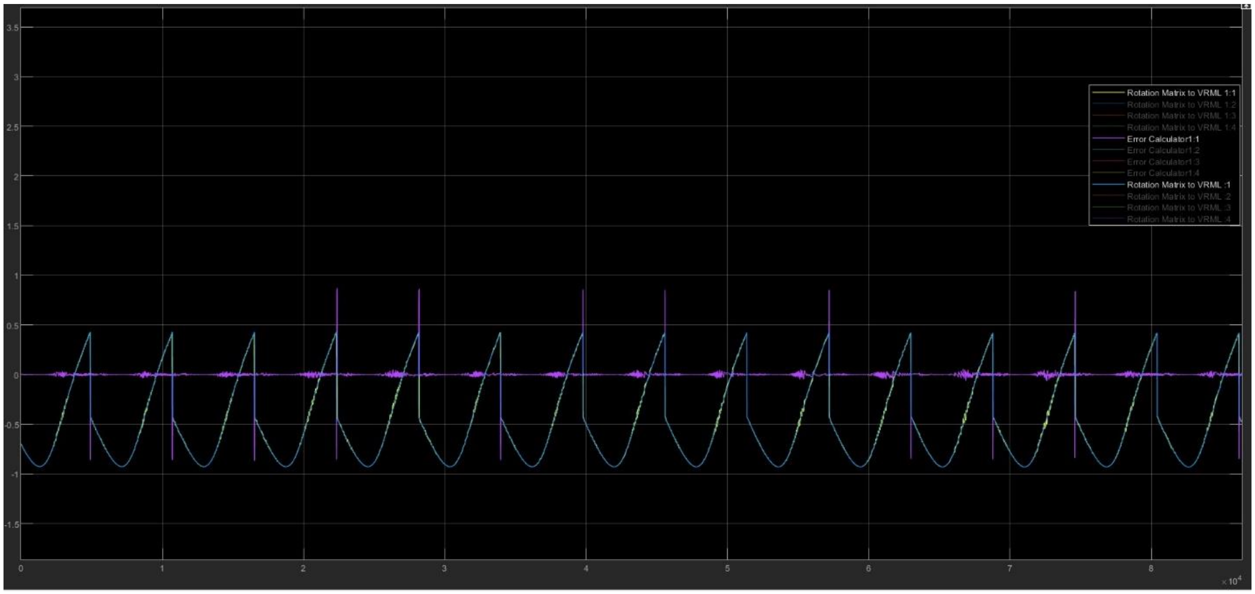

Figure 25: Graph 1 of Rotational Error

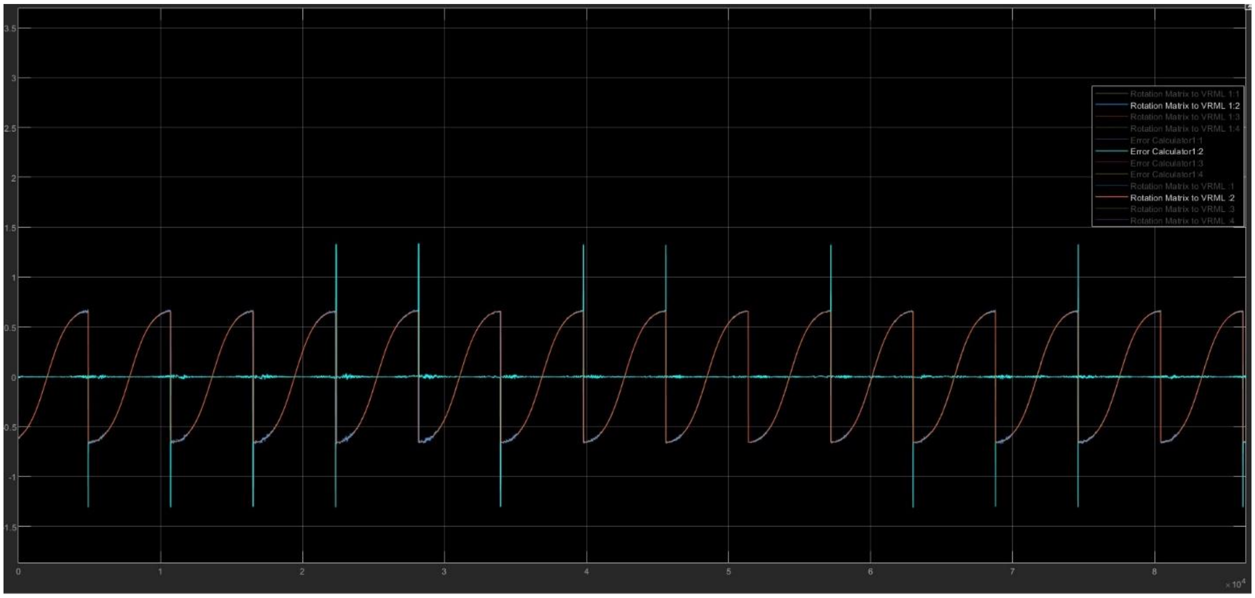

Figure 26: Graph 2 of Rotational Error

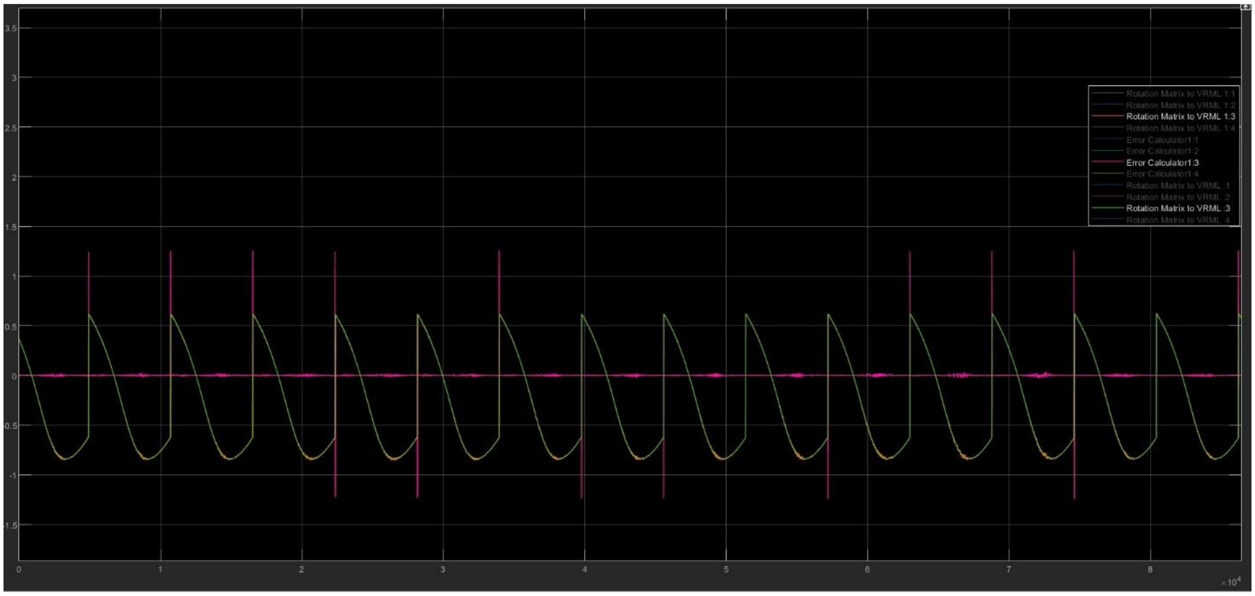

Figure 27: Graph 3 of Rotational Error

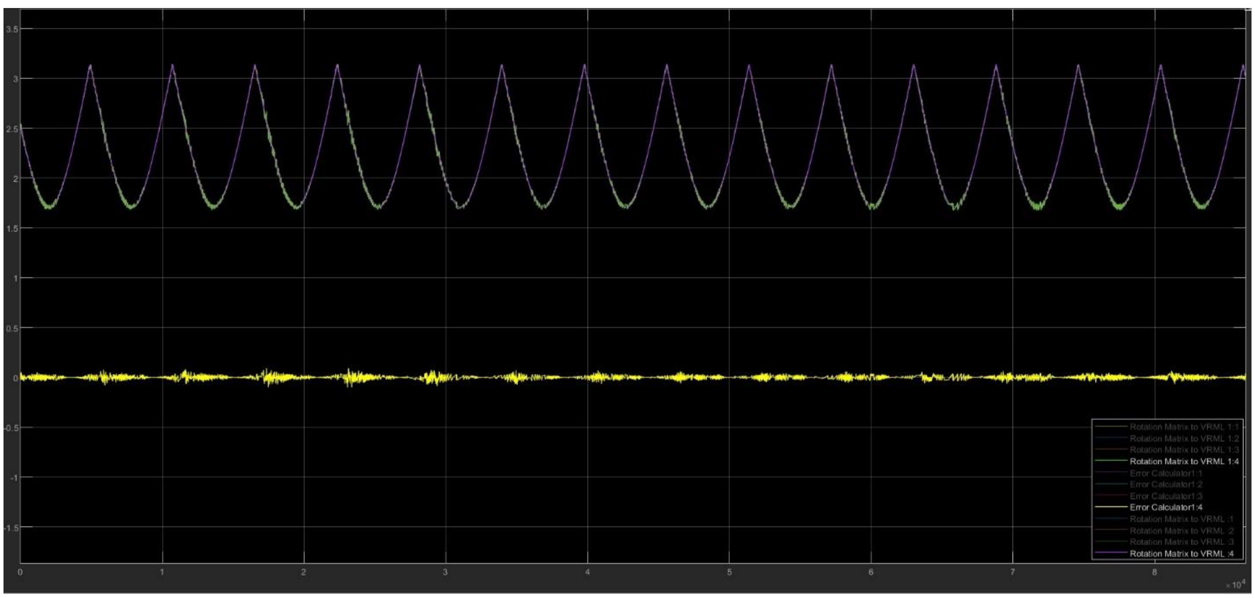

Figure 28: Graph 4 of Rotational Error

3.3.2. Actual Attitude Compared to Desired Attitude

The actual and desired attitudes are given in Figure 29-31. It is shown in the actual attitude follows the desired attitude well. The error between all desired and actual attitude signals is given in Figure 32.

Figure 29: Graph 1 of Desired Attitude Compared to Actual Attitude

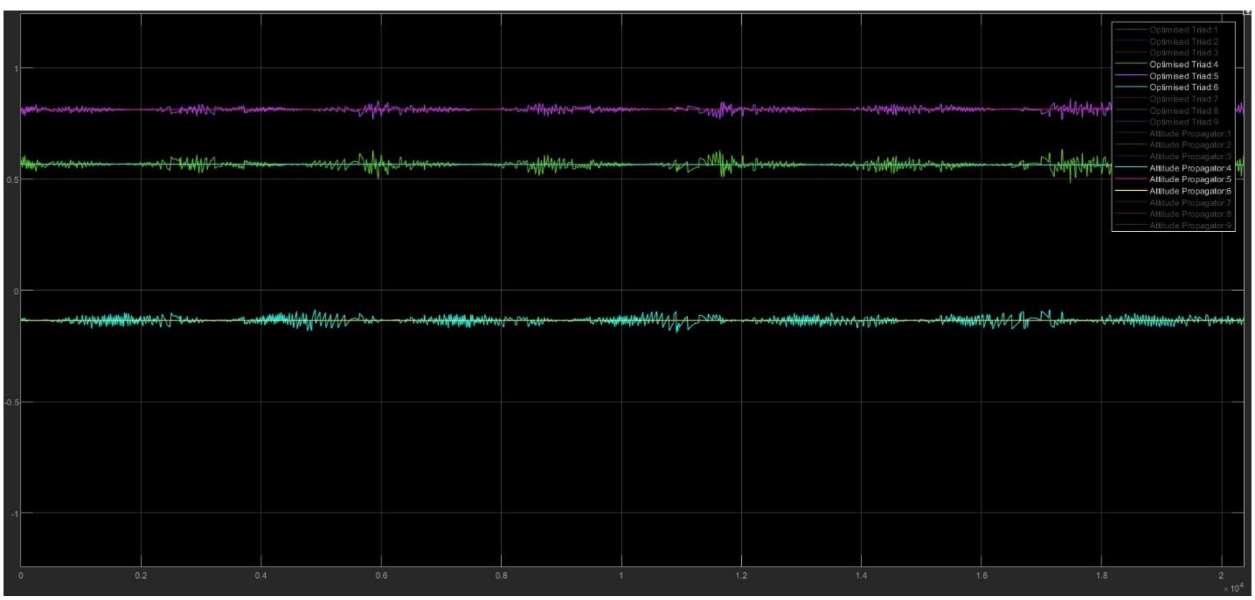

Figure 30: Graph 2 of Desired Attitude Compared to Actual Attitude

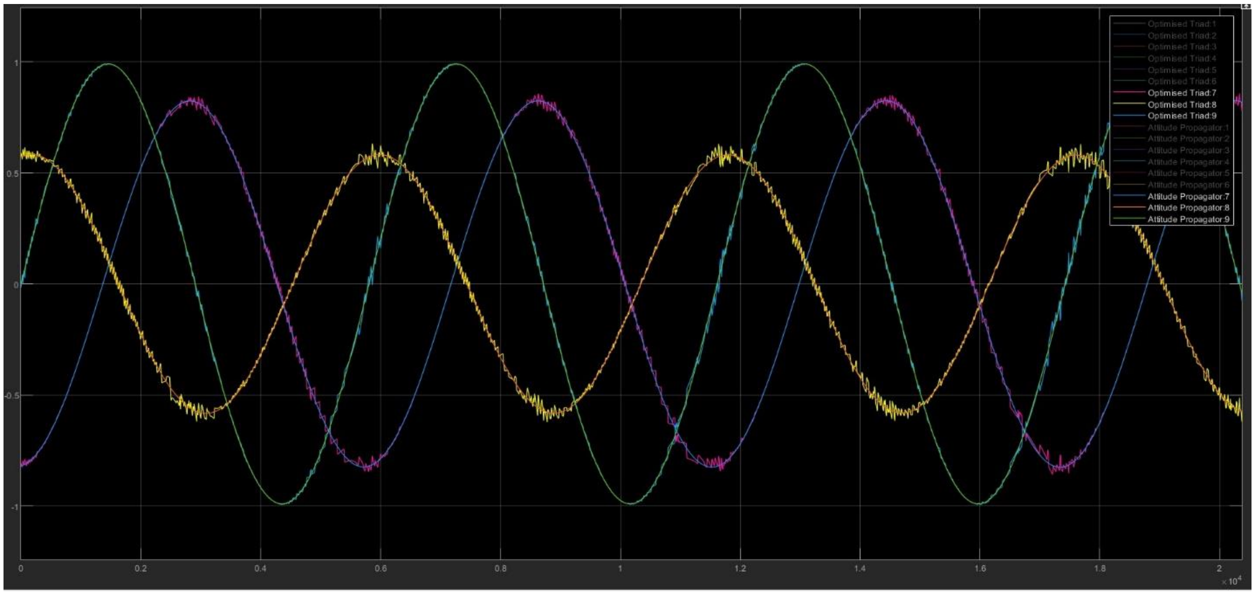

Figure 31: Graph 3 of Desired Attitude Compared to Actual Attitude

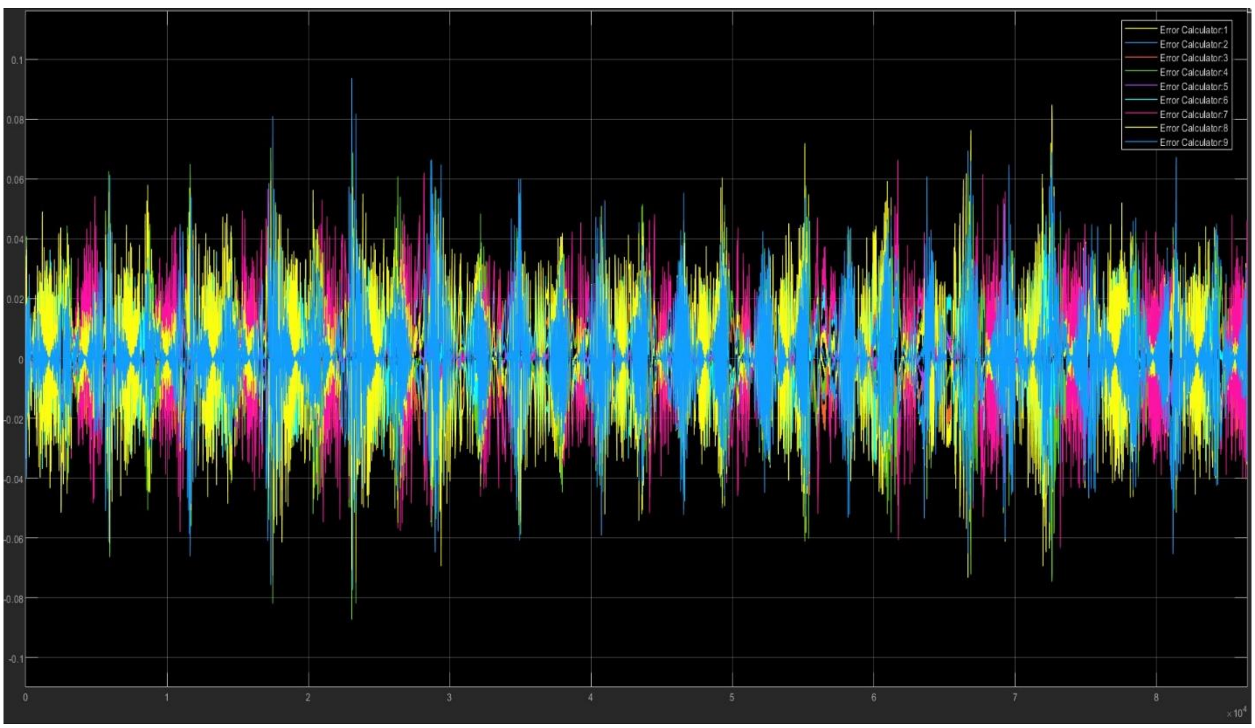

Figure 32: Graph 4 of Desired Attitude Compared to Actual Attitude

3.3.3. Output Torque

The output torque in each axis can be shown in Figures 33 to 35.

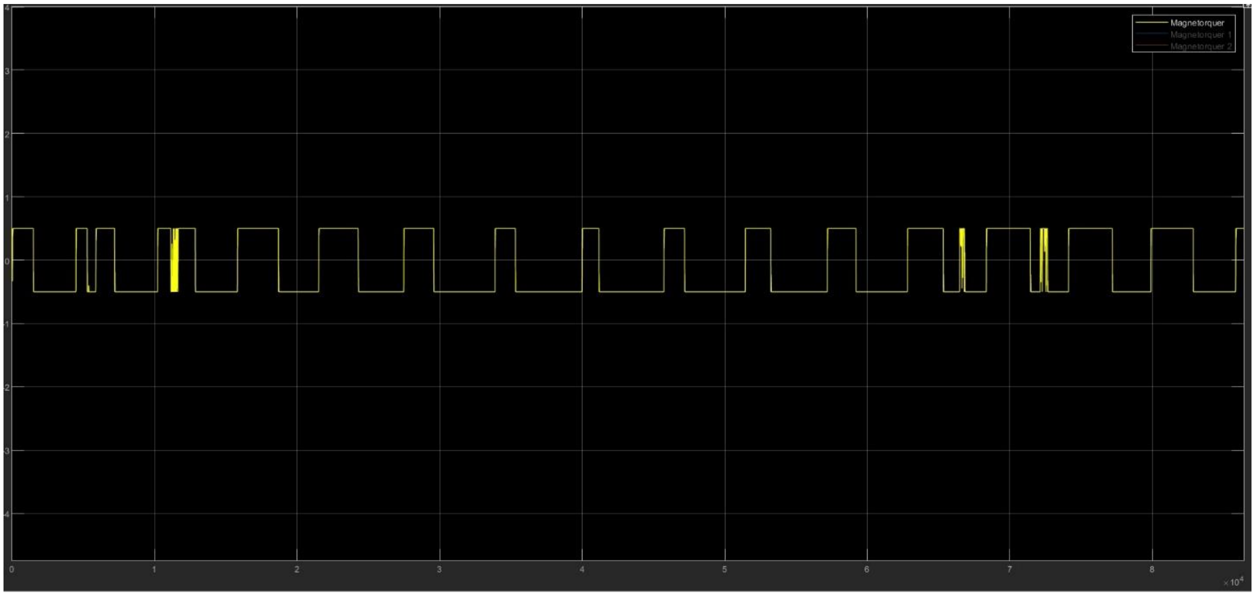

Figure 33: Output Torque in x-axis

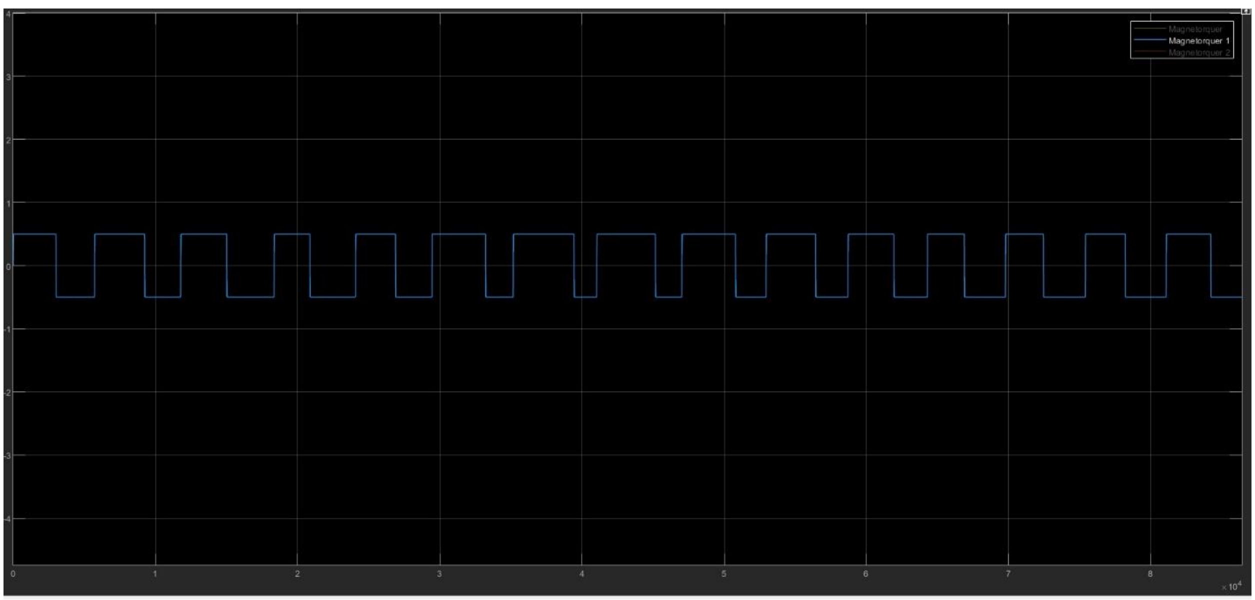

Figure 34: Output Torque in y-axis

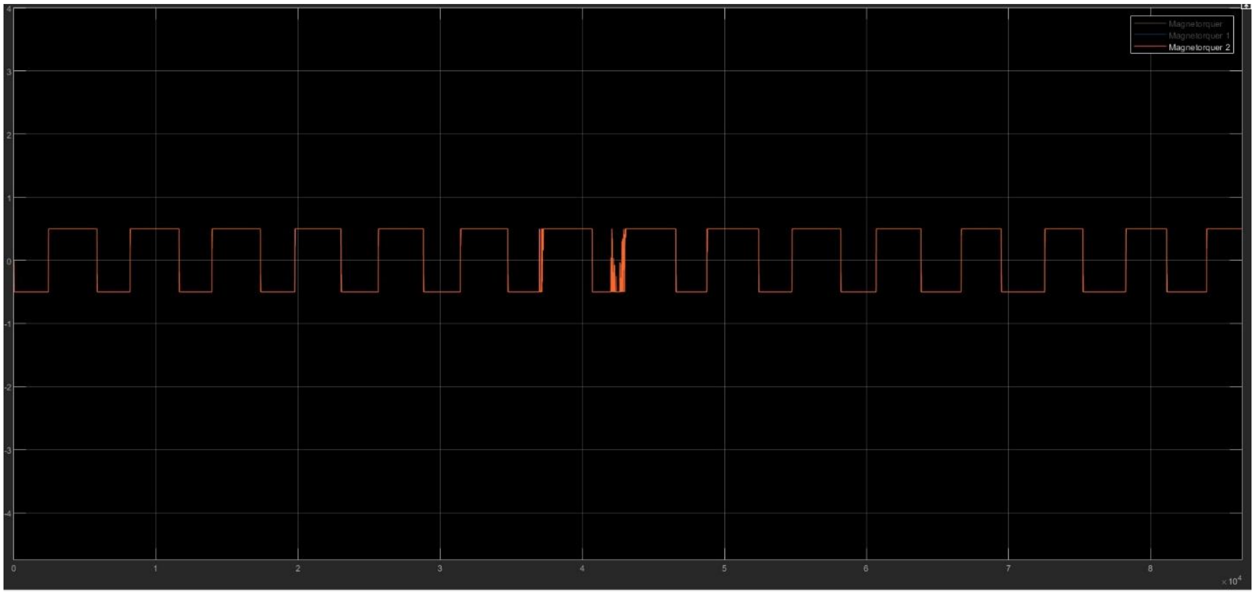

Figure 35: Output Torque in z-axis

3.3.4. Control Law Detumbling

The following graph shows that the control law will allow the CubeSat to detumble quickly and efficiently with the angular velocity of each axis going to zero.

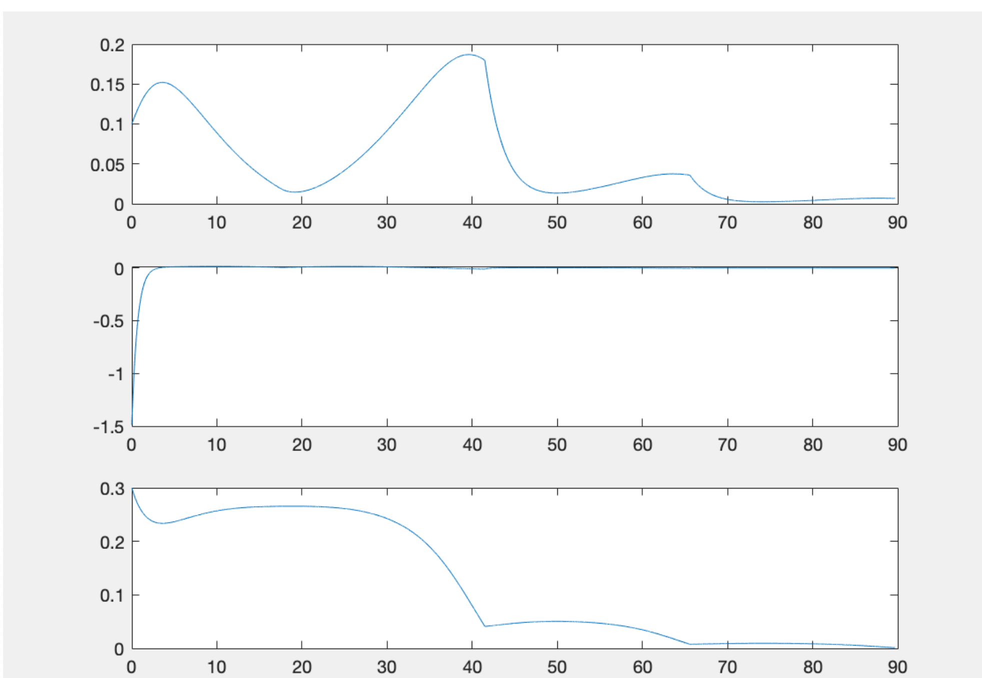

Figure 36: Plots of Control Law Detumbling CubeSat

3.4. Part Drawings for ADCS Design

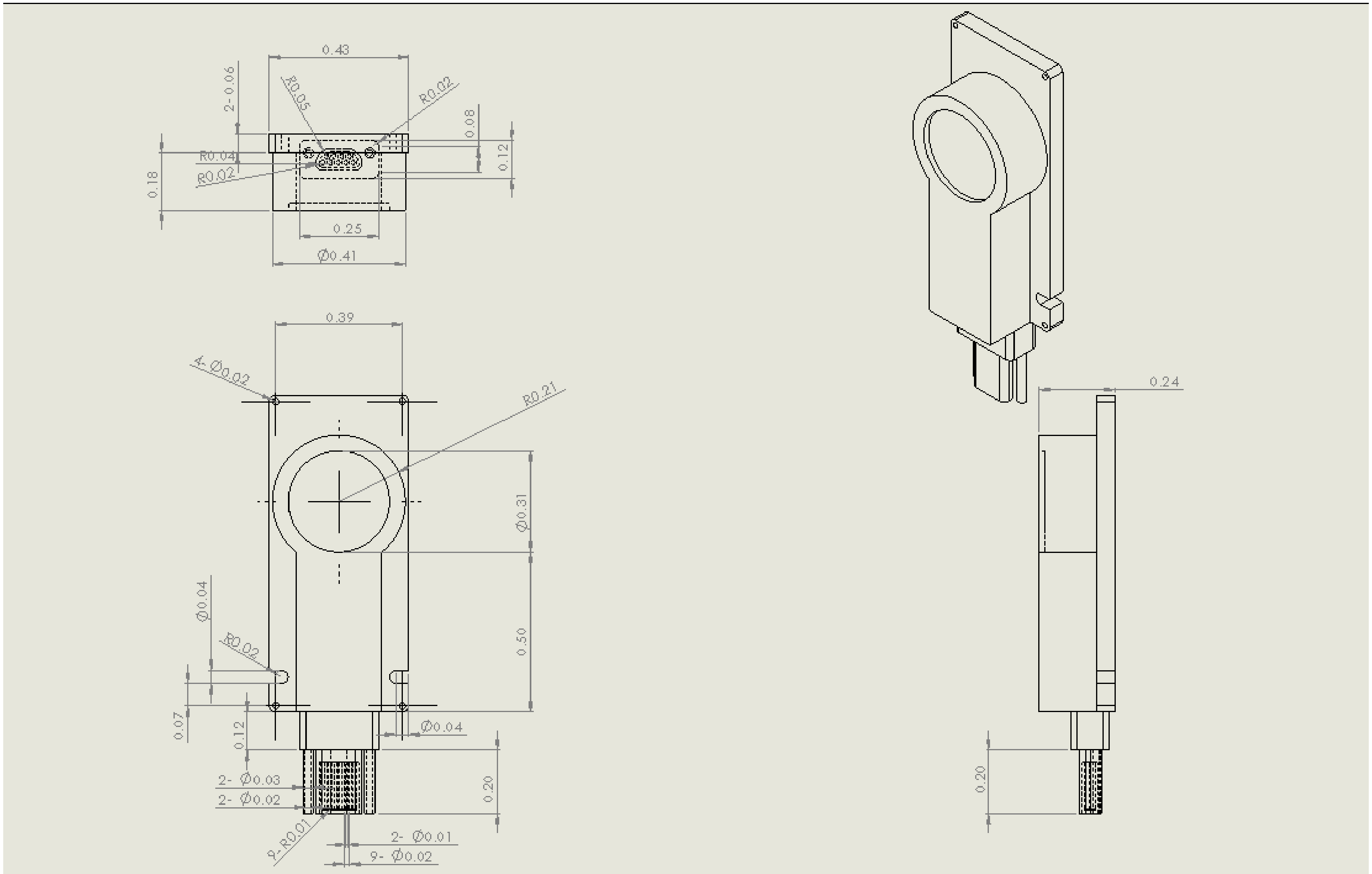

Figure 37: Part 1000 (NSS Fine Sun Sensor) Part Drawing

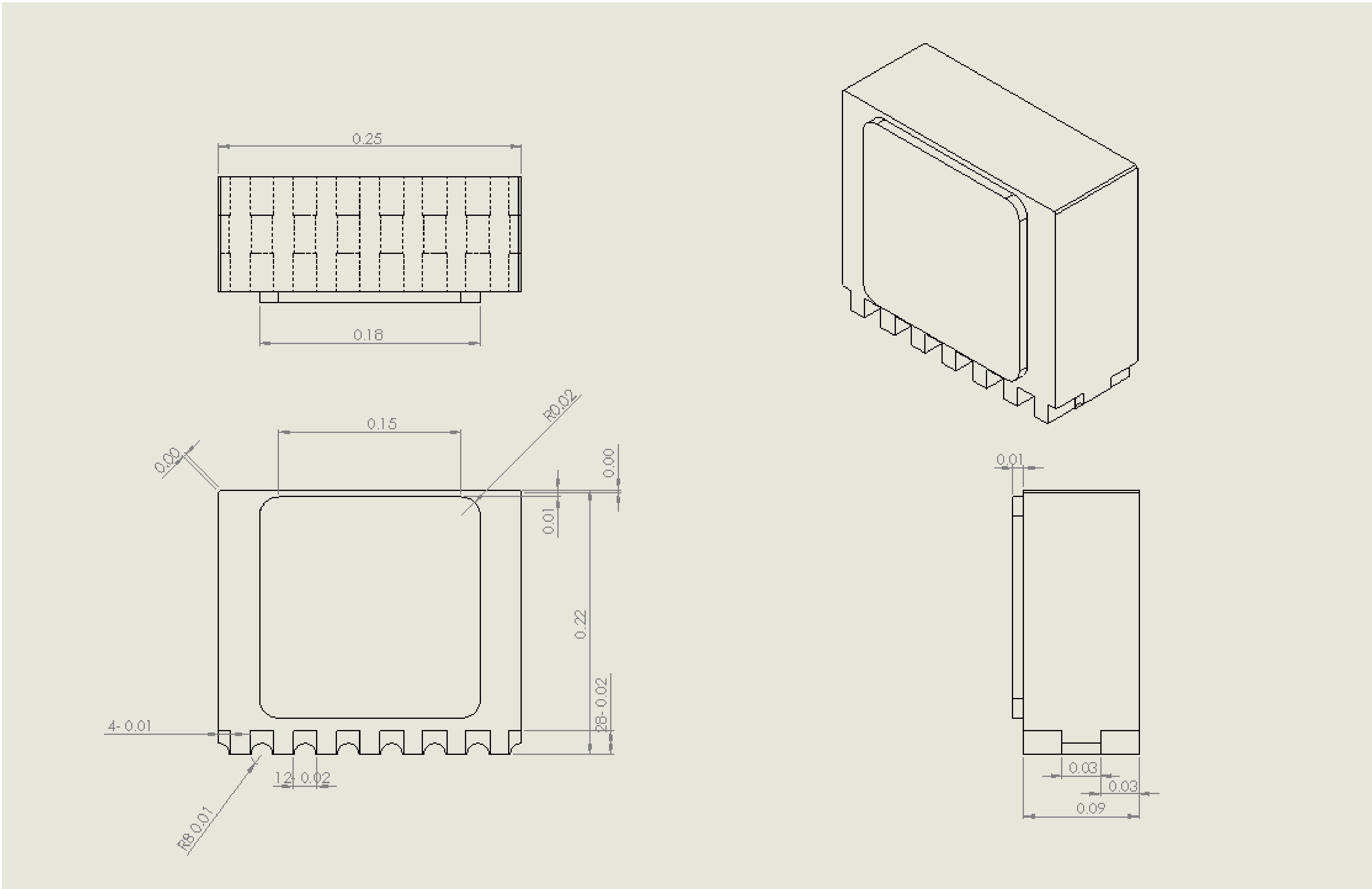

Figure 38: Part 1001 (Precision Navigation and Pointing Gyroscope) Part Drawing

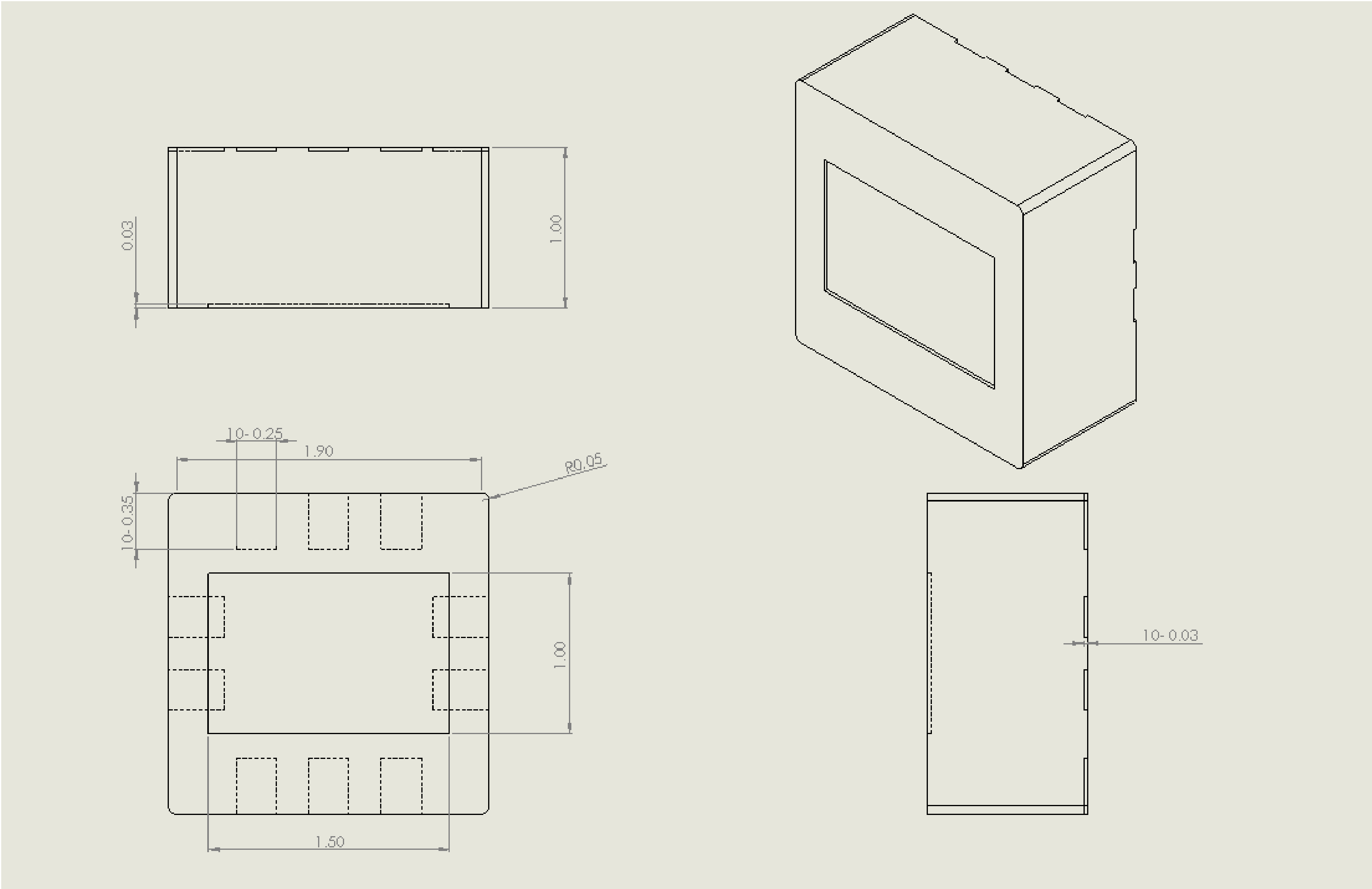

Figure 39: Part 1002 (3-Axis Digital Magnetometer IC) Part Drawing

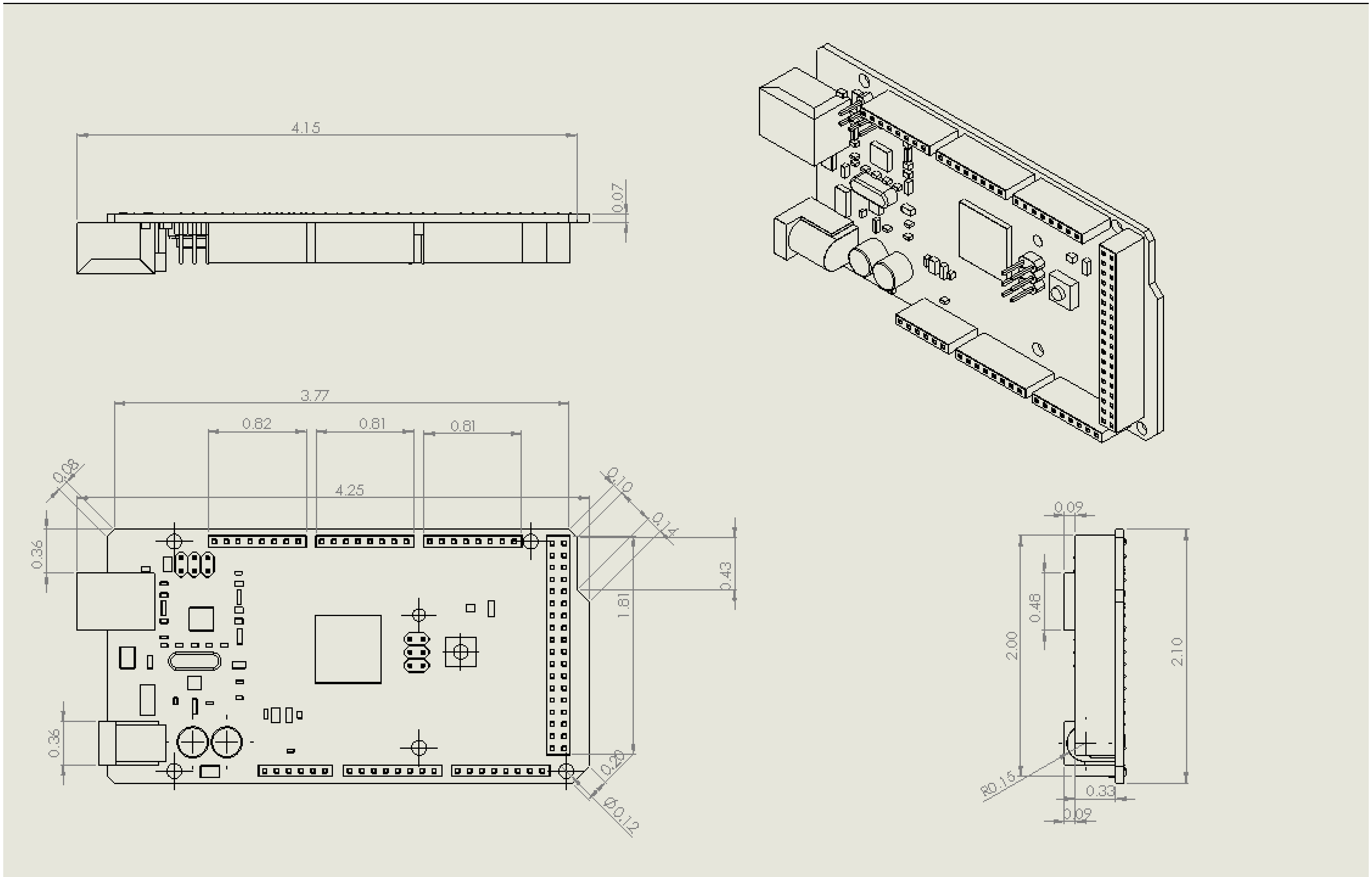

Figure 40: Part 1003 (Arduino Mega 2560 Rev3) Part Drawing

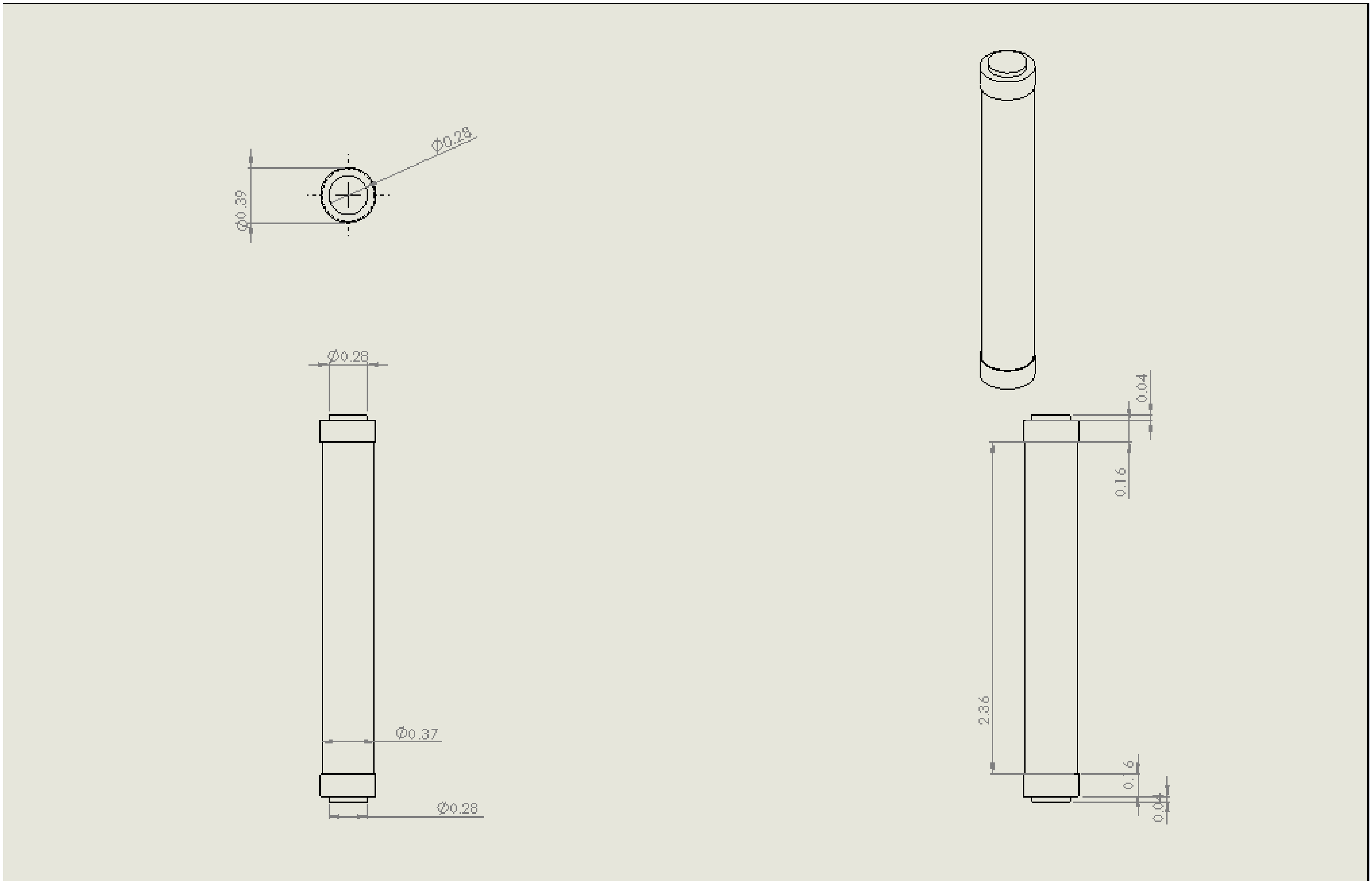

Figure 41: Part 1004 (Magnetorquer Rod) Part Drawing

3.5. CAD Drawings for ADCS Design

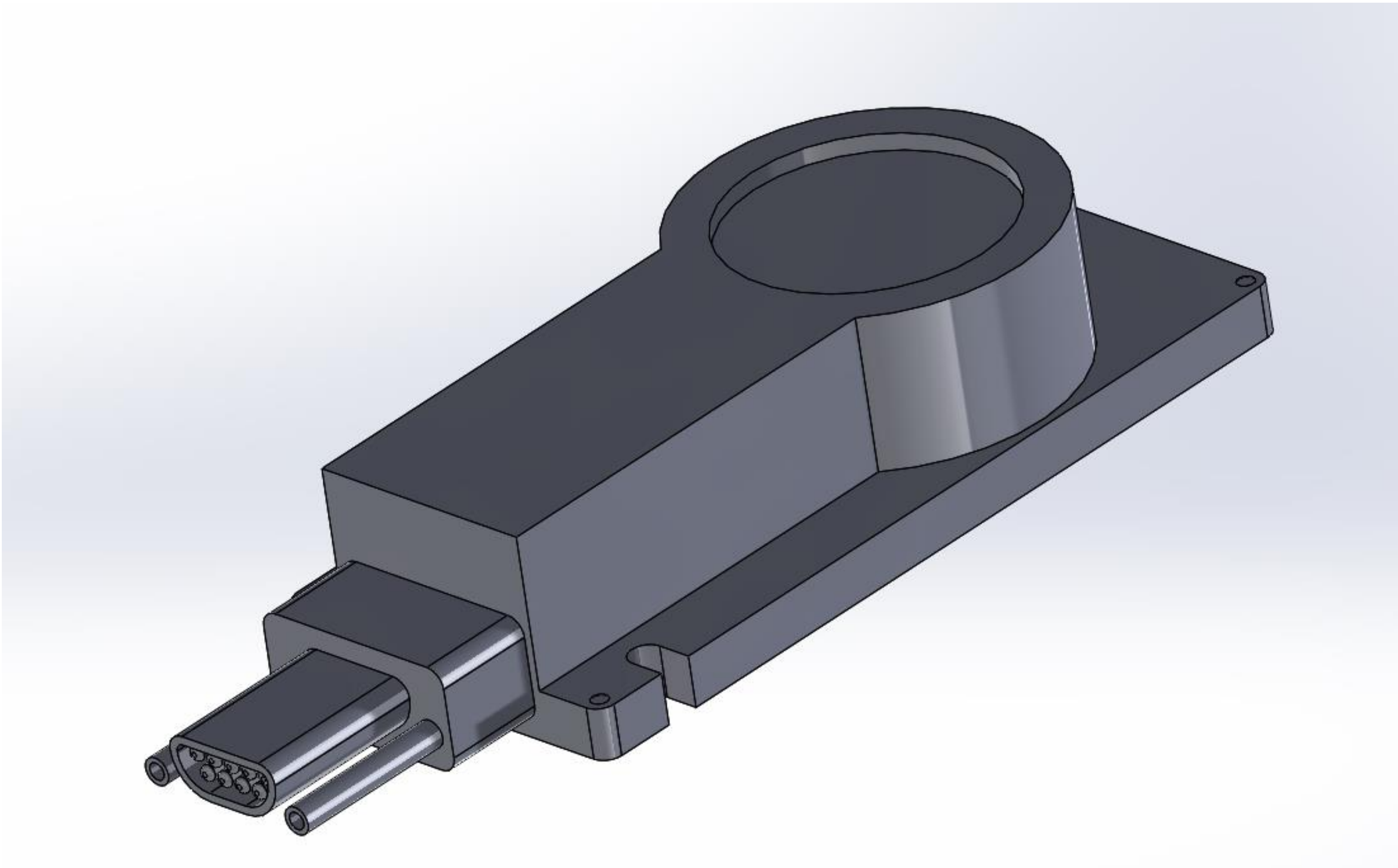

Figure 42: Part 1000 (NSS Fine Sun Sensor) CAD Drawing

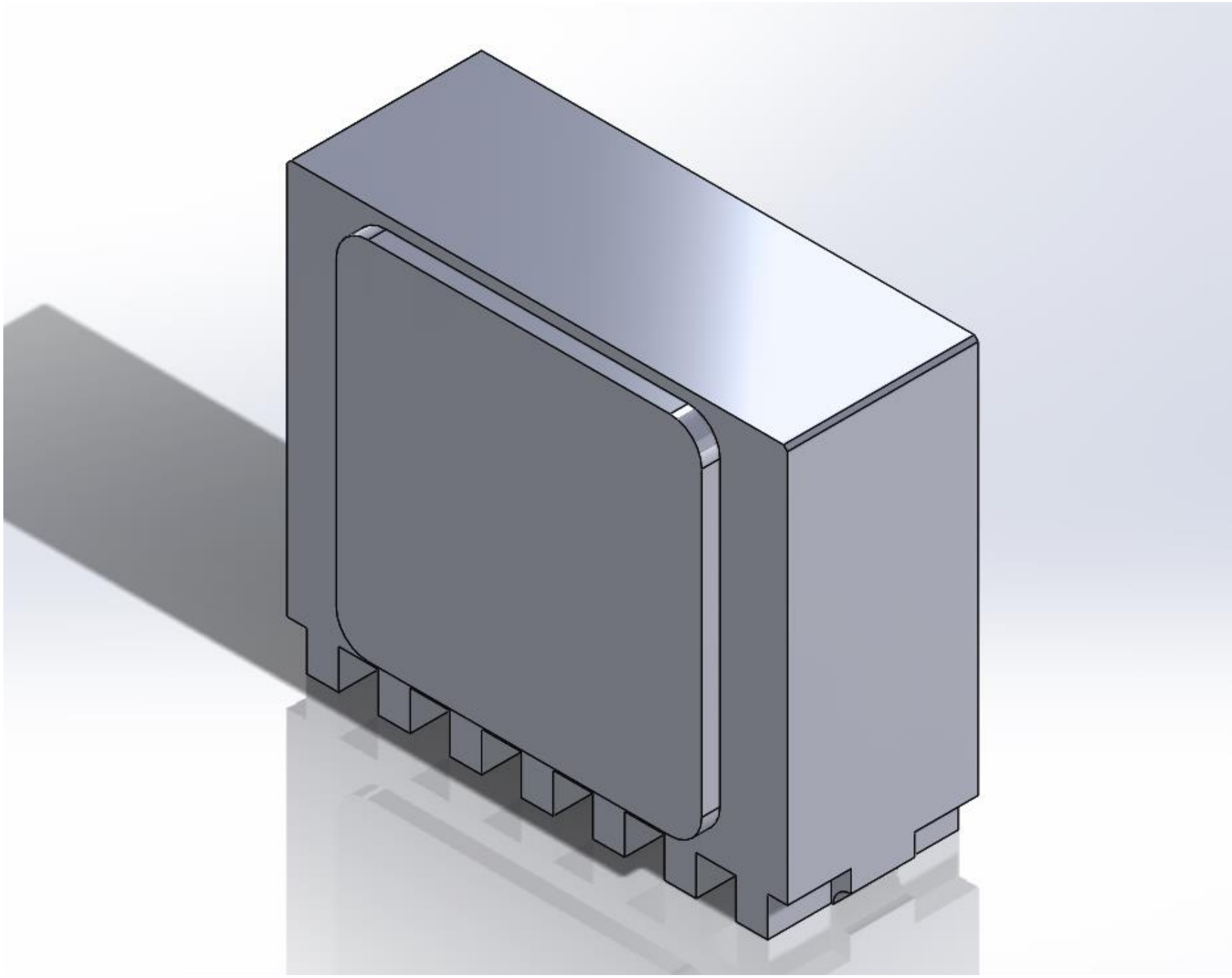

Figure 43: Part 1001 (Precision Navigation and Pointing Gyroscope) CAD Drawing

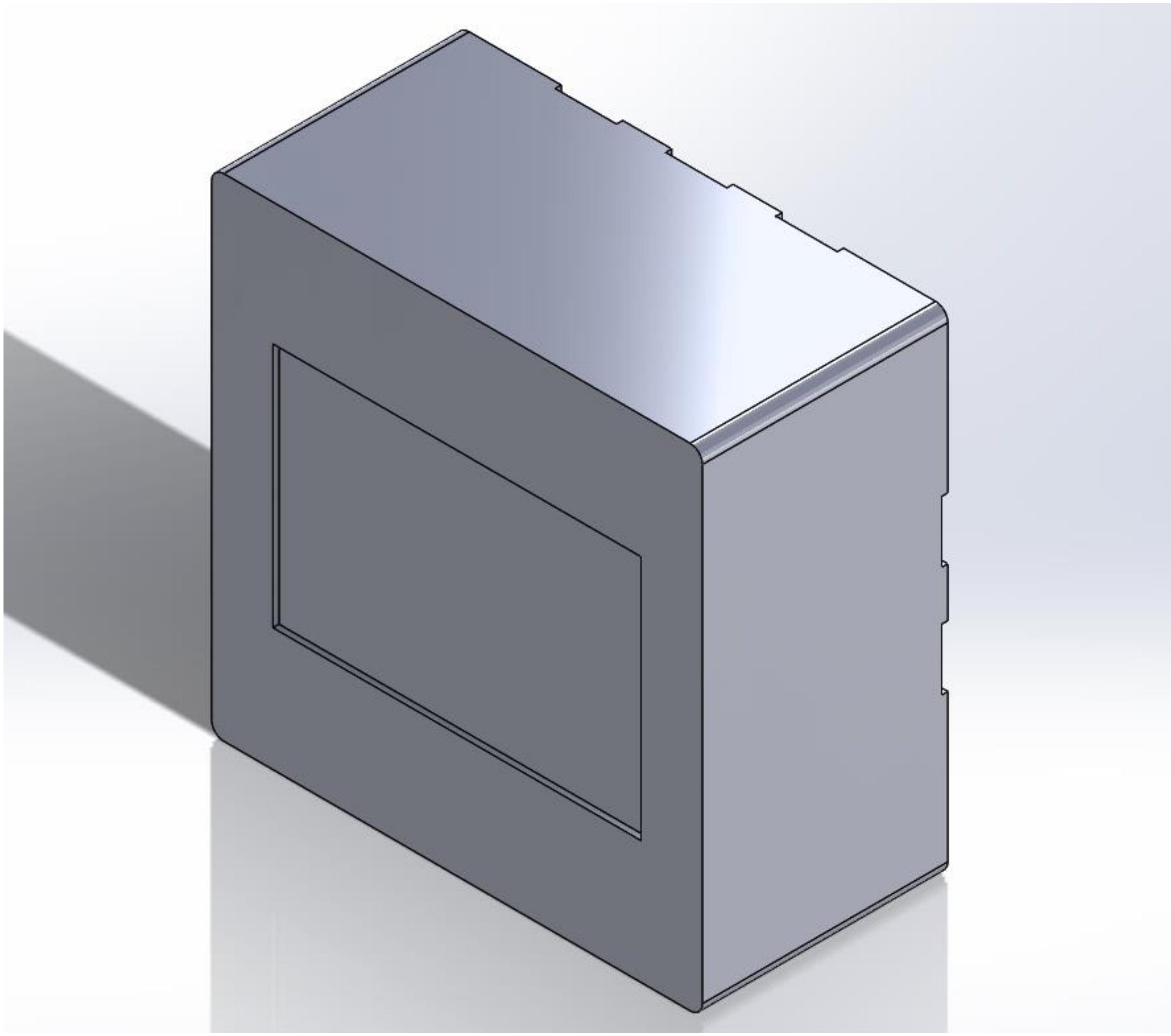

Figure 44: Part 1002 (3-Axis Digital Magnetometer IC) CAD Drawing

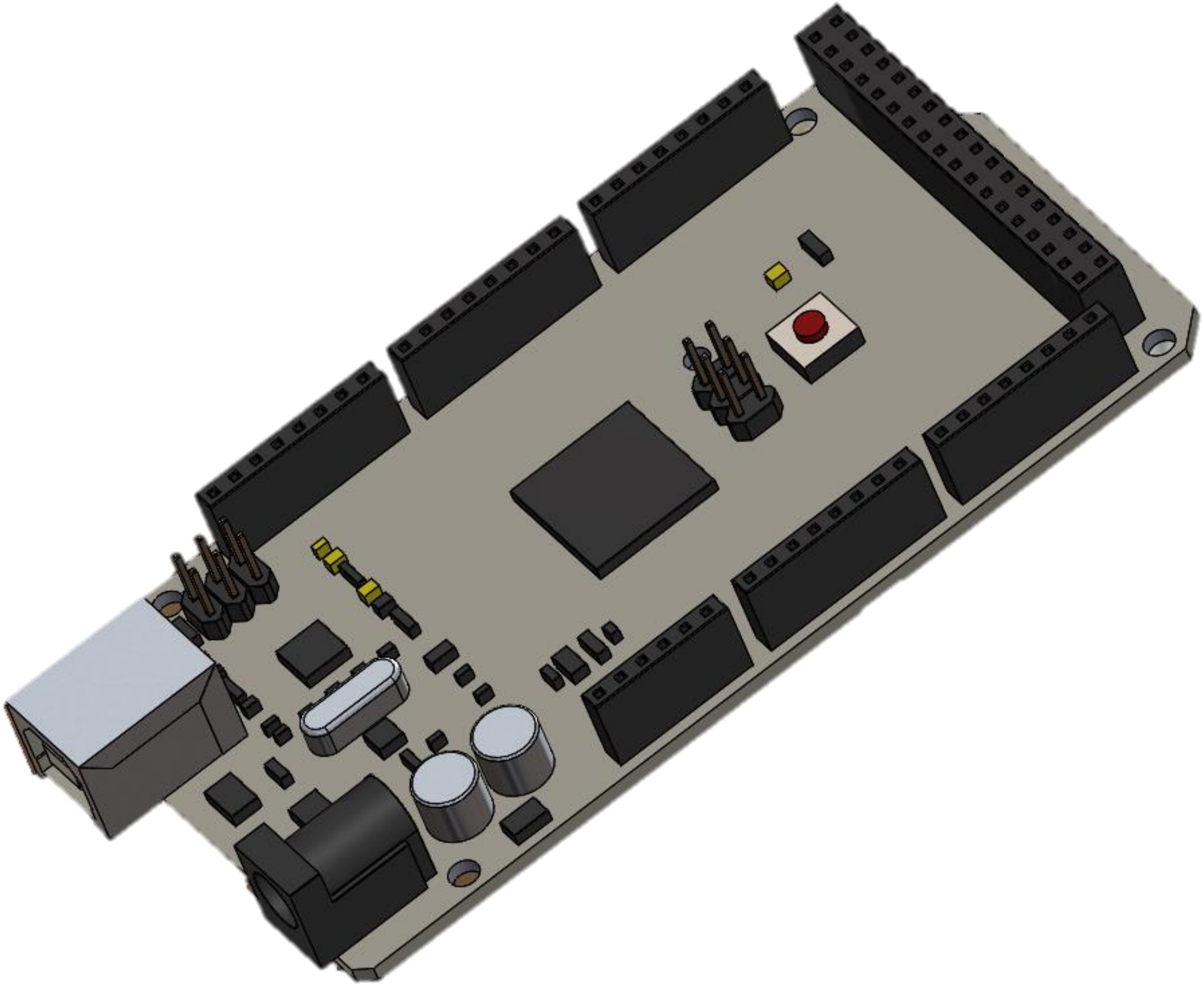

Figure 45: Part 1003 (Arduino Mega 2560 Rev3) CAD Drawing

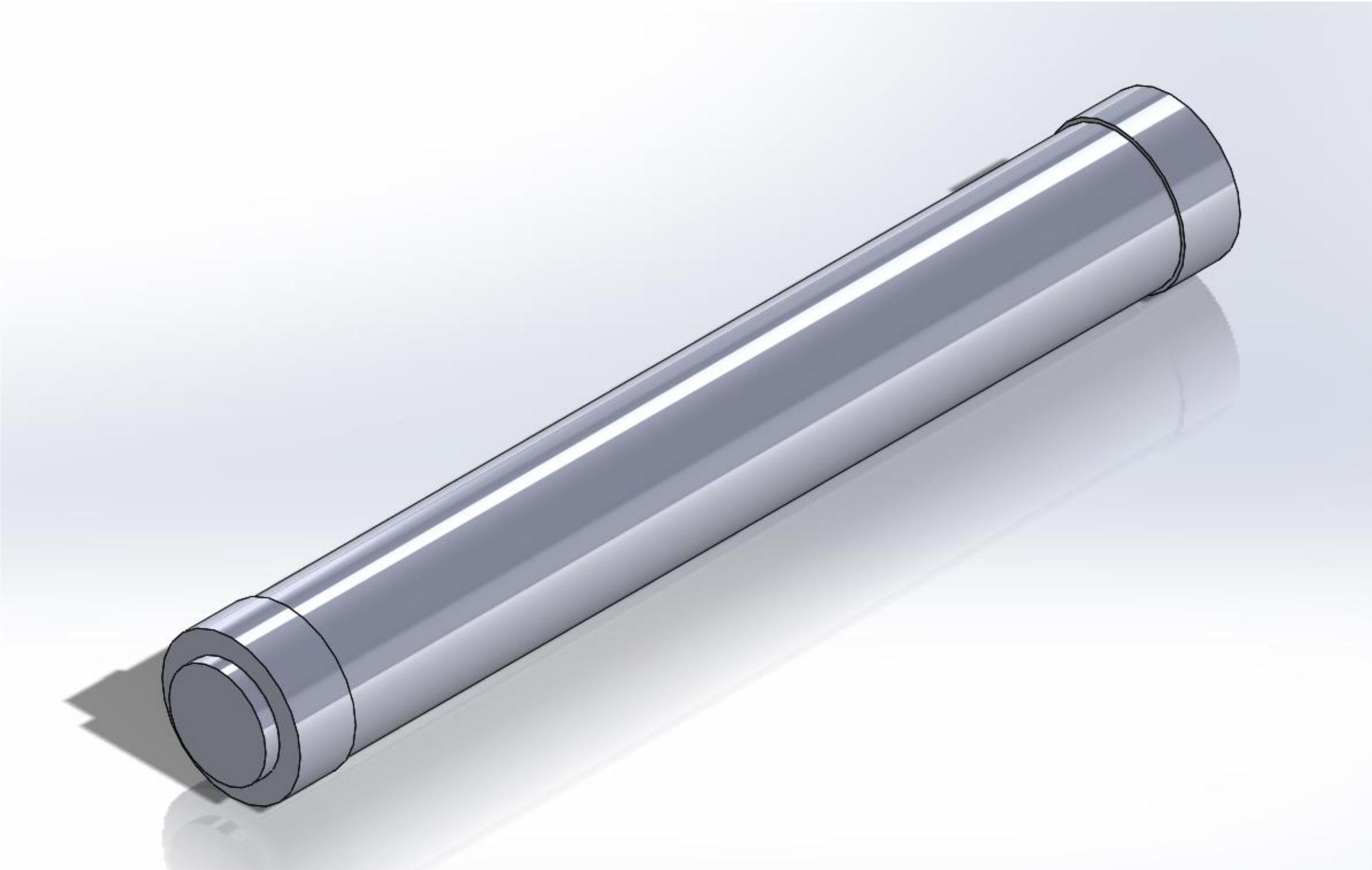

Figure 46: Part 1004 (Magnetorquer Rod) CAD Drawing

3.6. Part Drawings for Prototype

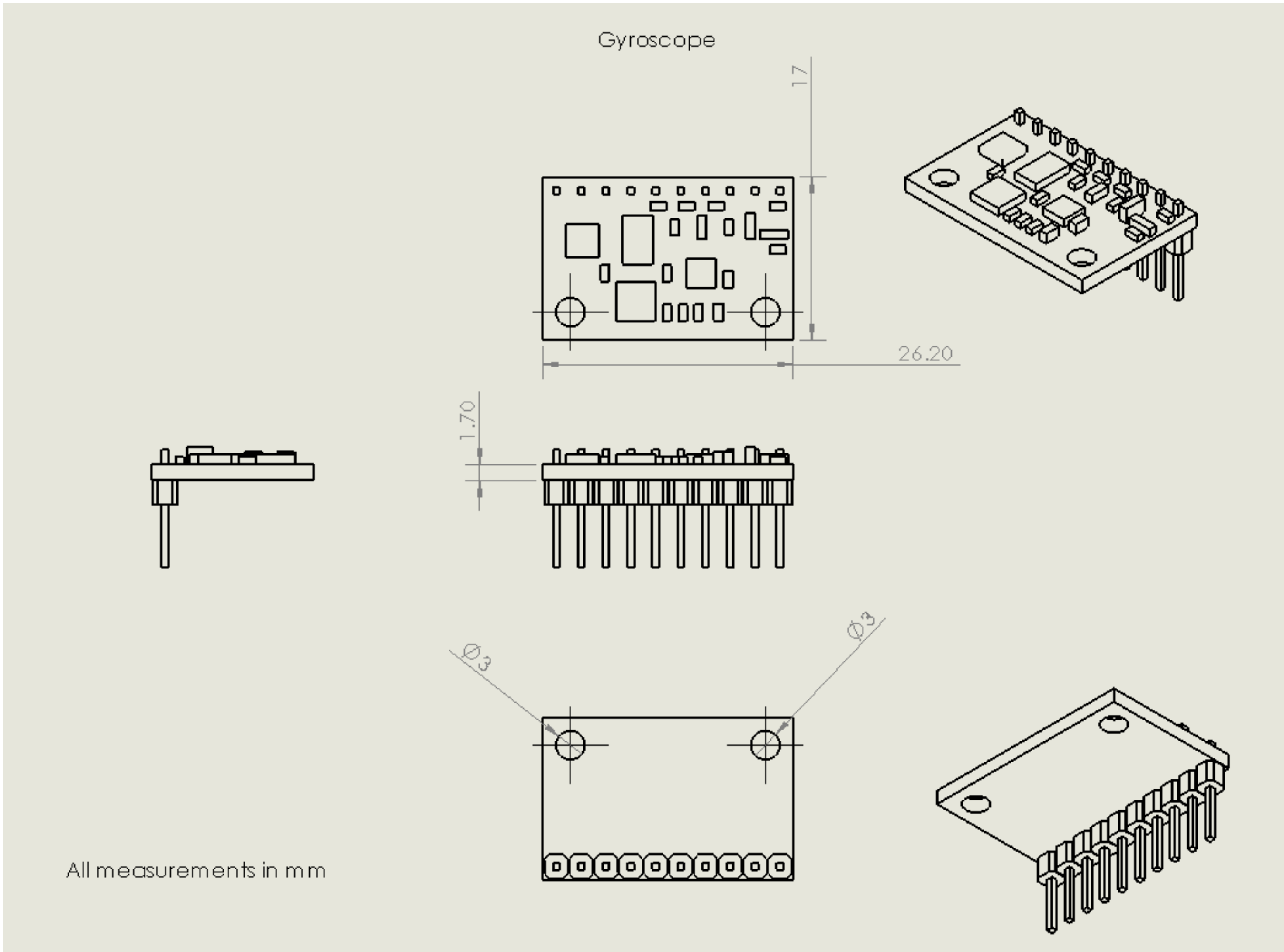

Figure 47: Part 1008 (MPU 6050 Gyroscope and Accelerometer Board) Part Drawing

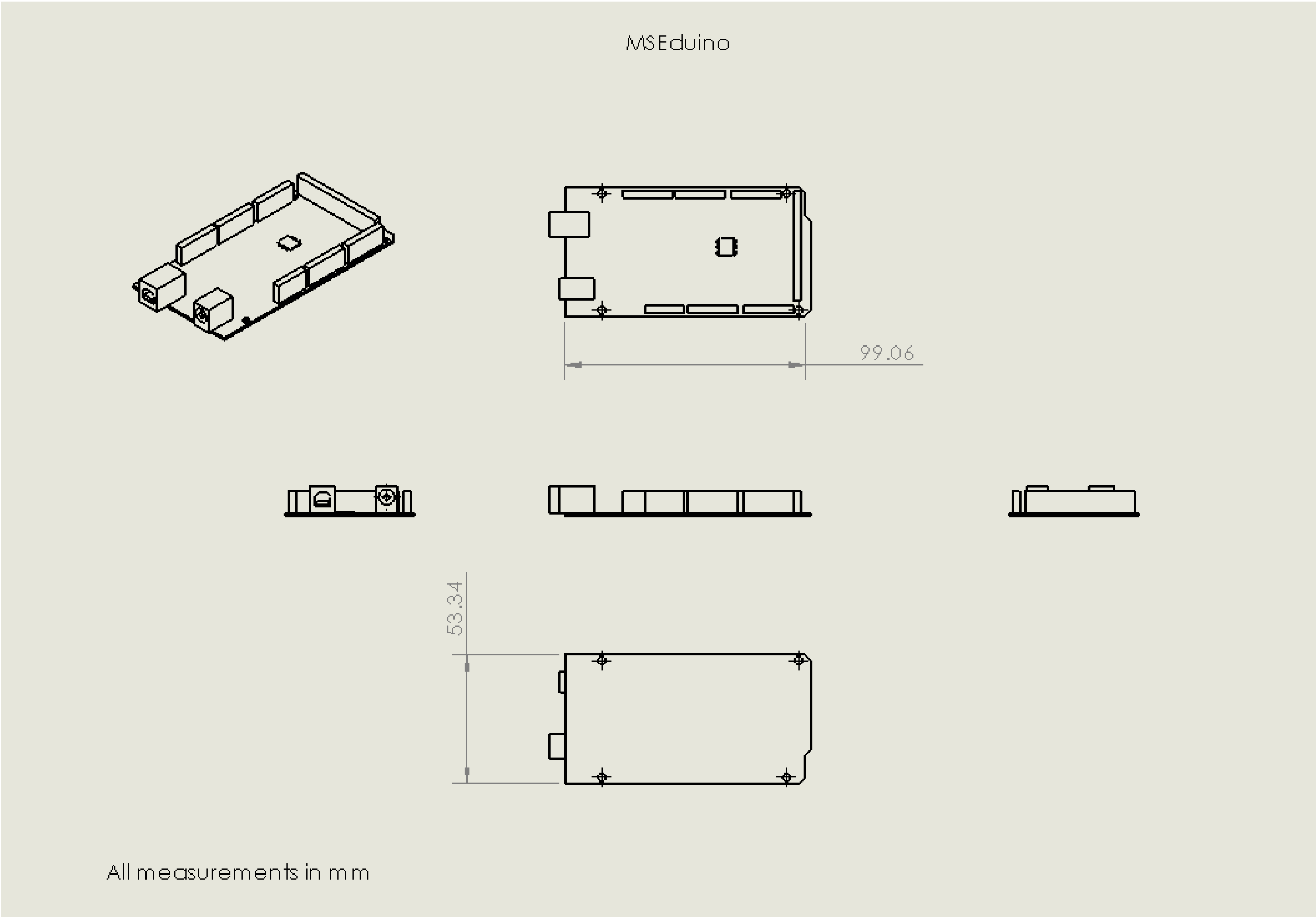

Figure 48: Part 1009 (MSEduino) Part Drawing

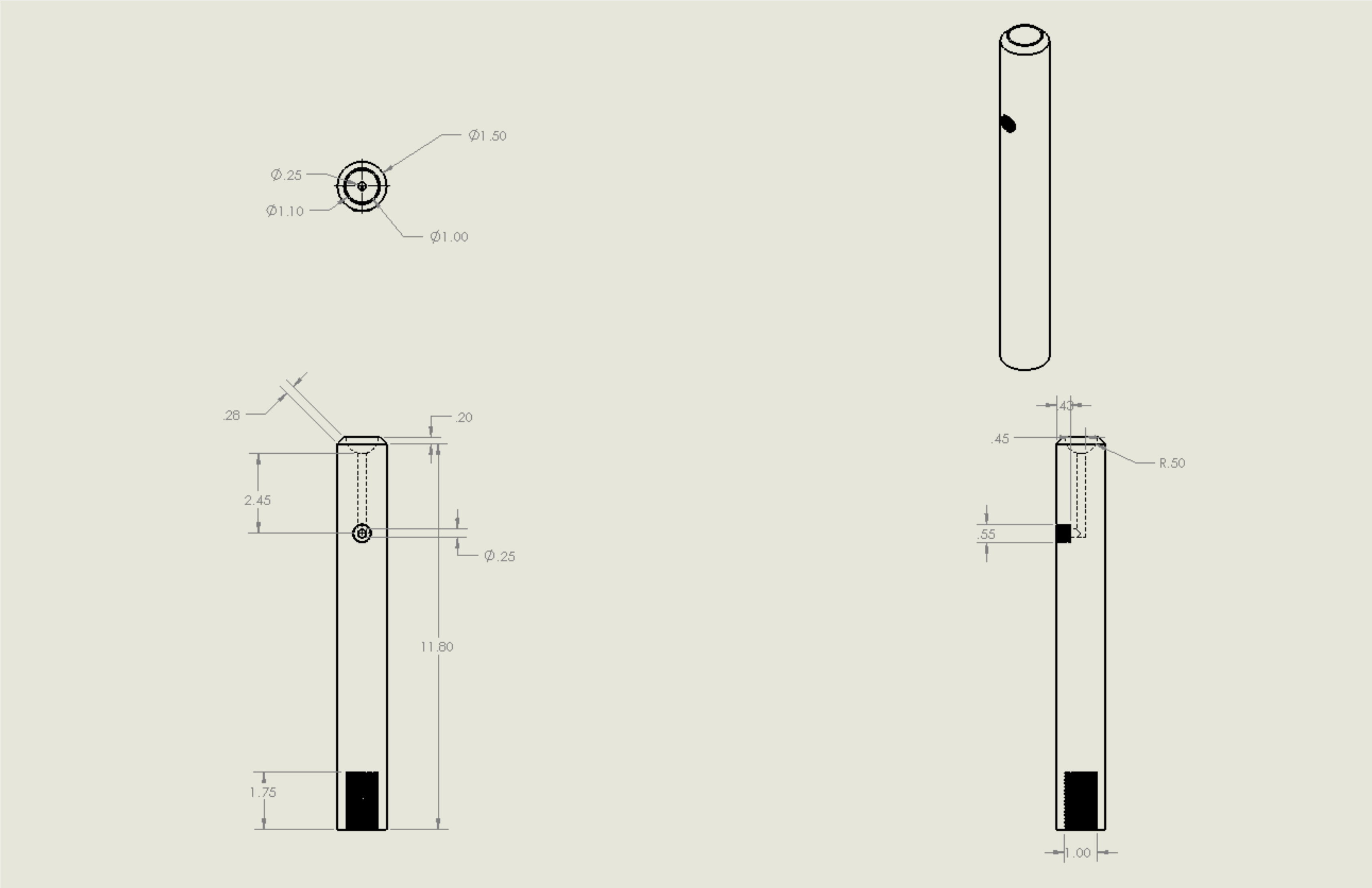

Figure 49: Part 1012 (1' Black Delrin ® Acetal Resin Rod 1-1/2" Diameter) Part Drawing

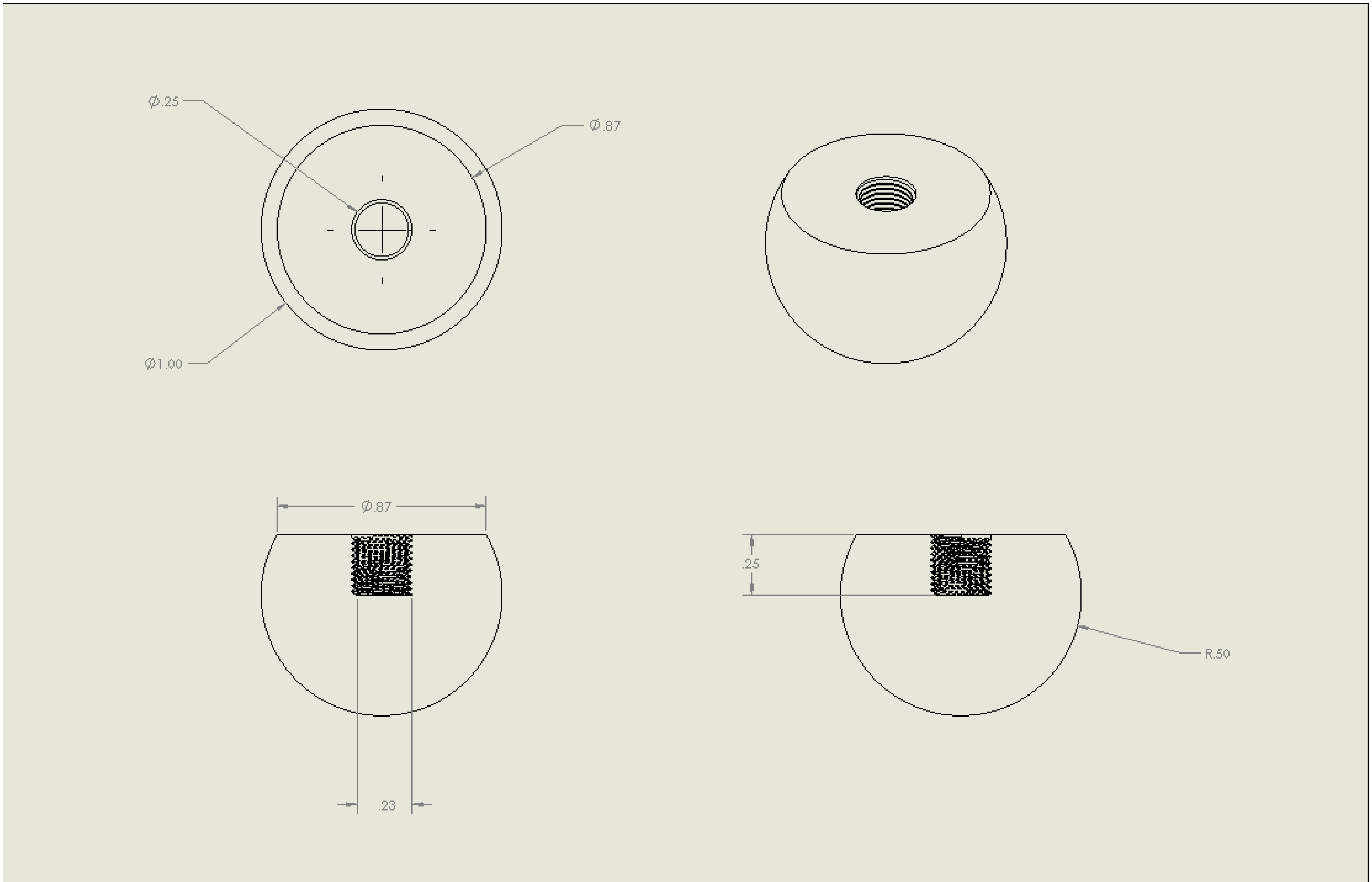

Figure 50: Part 1013 (Highly Corrosion-Resistant Stainless Steel Ball 1" Diameter) Part Drawing

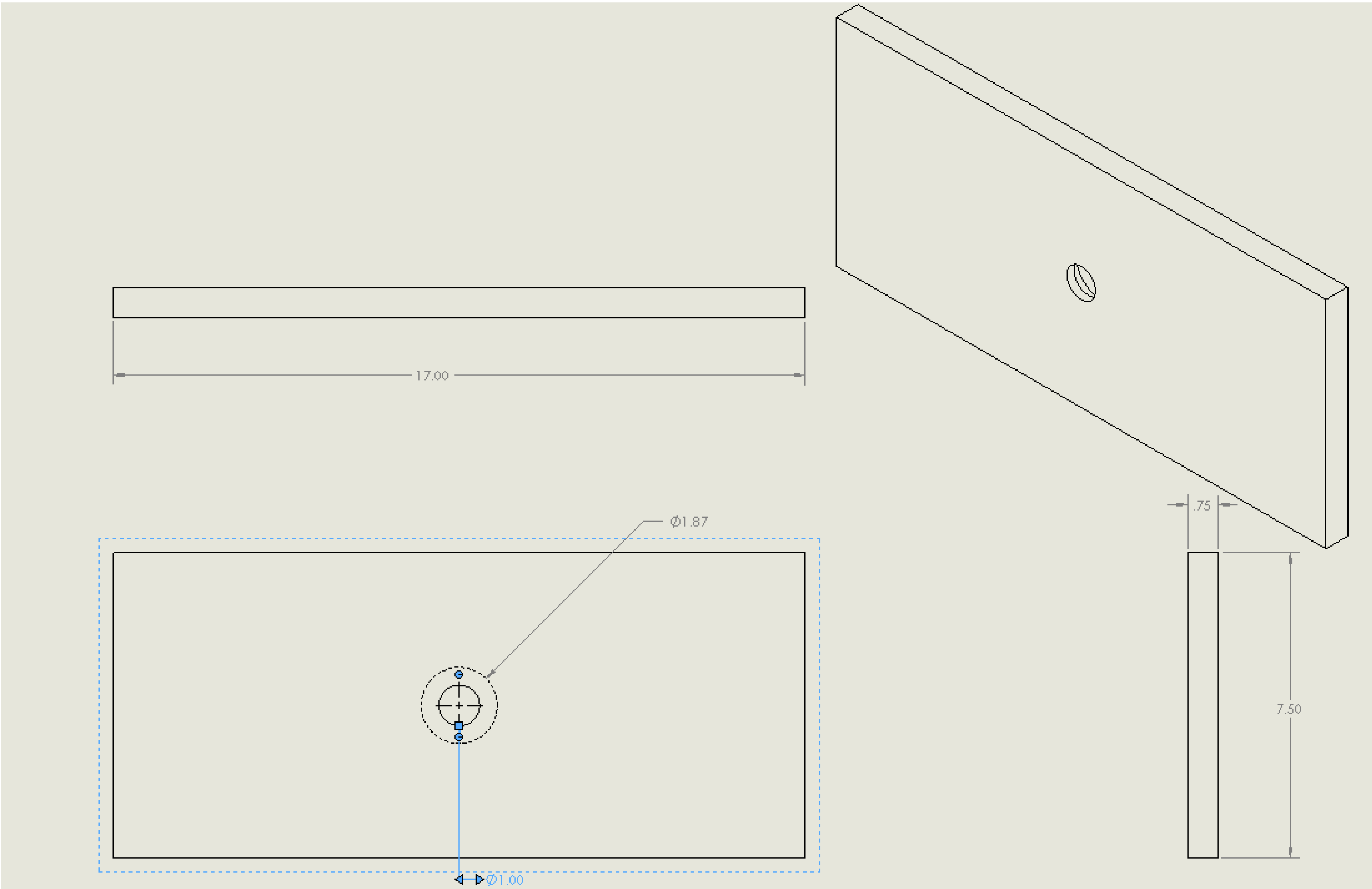

Figure 51: Part 1014 (Acrylic Sheet) Part Drawing

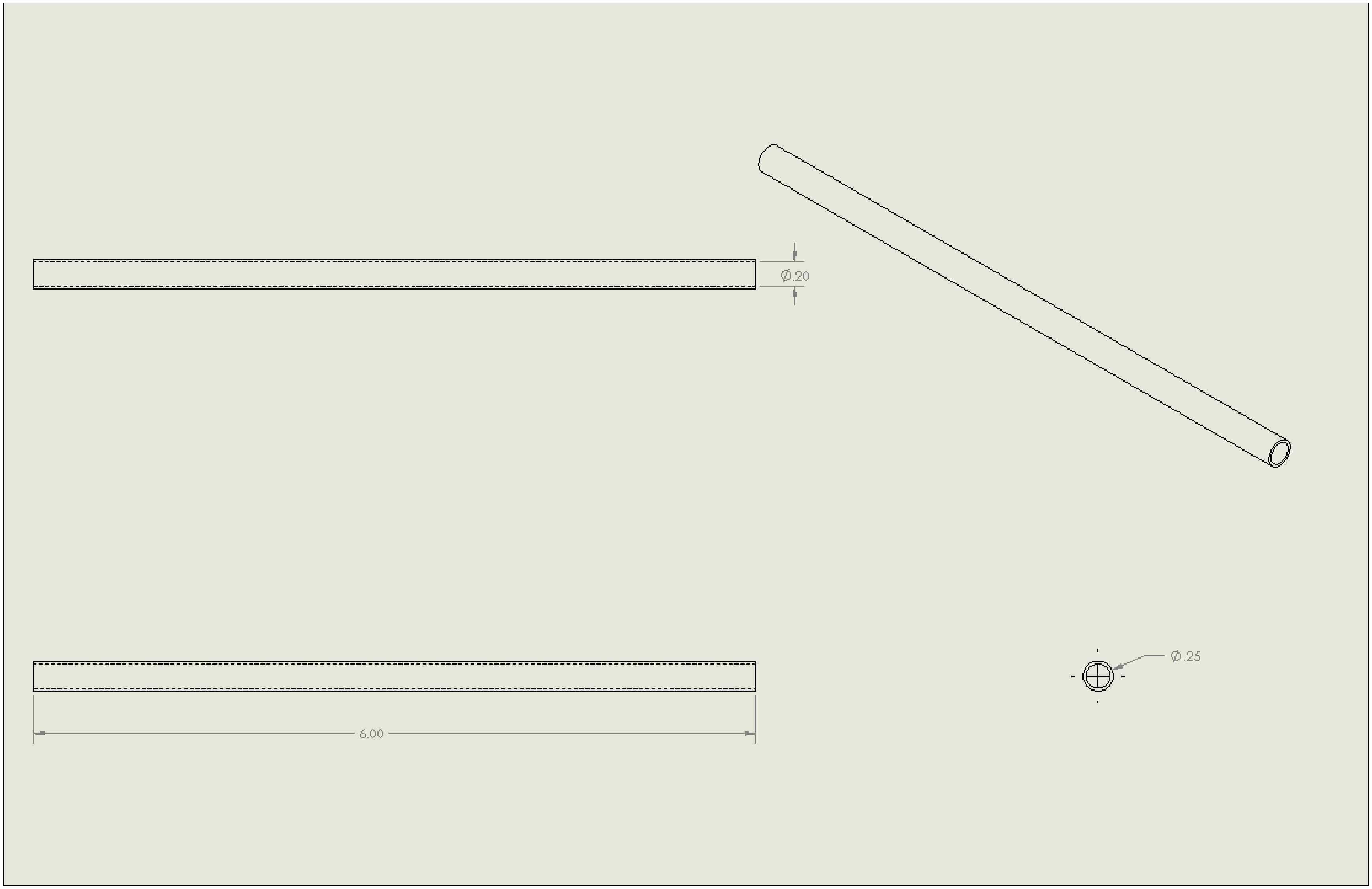

Figure 52: Part 1015 (Crack-Resist Polypropylene Semi-Clear Tubing) Part Drawing

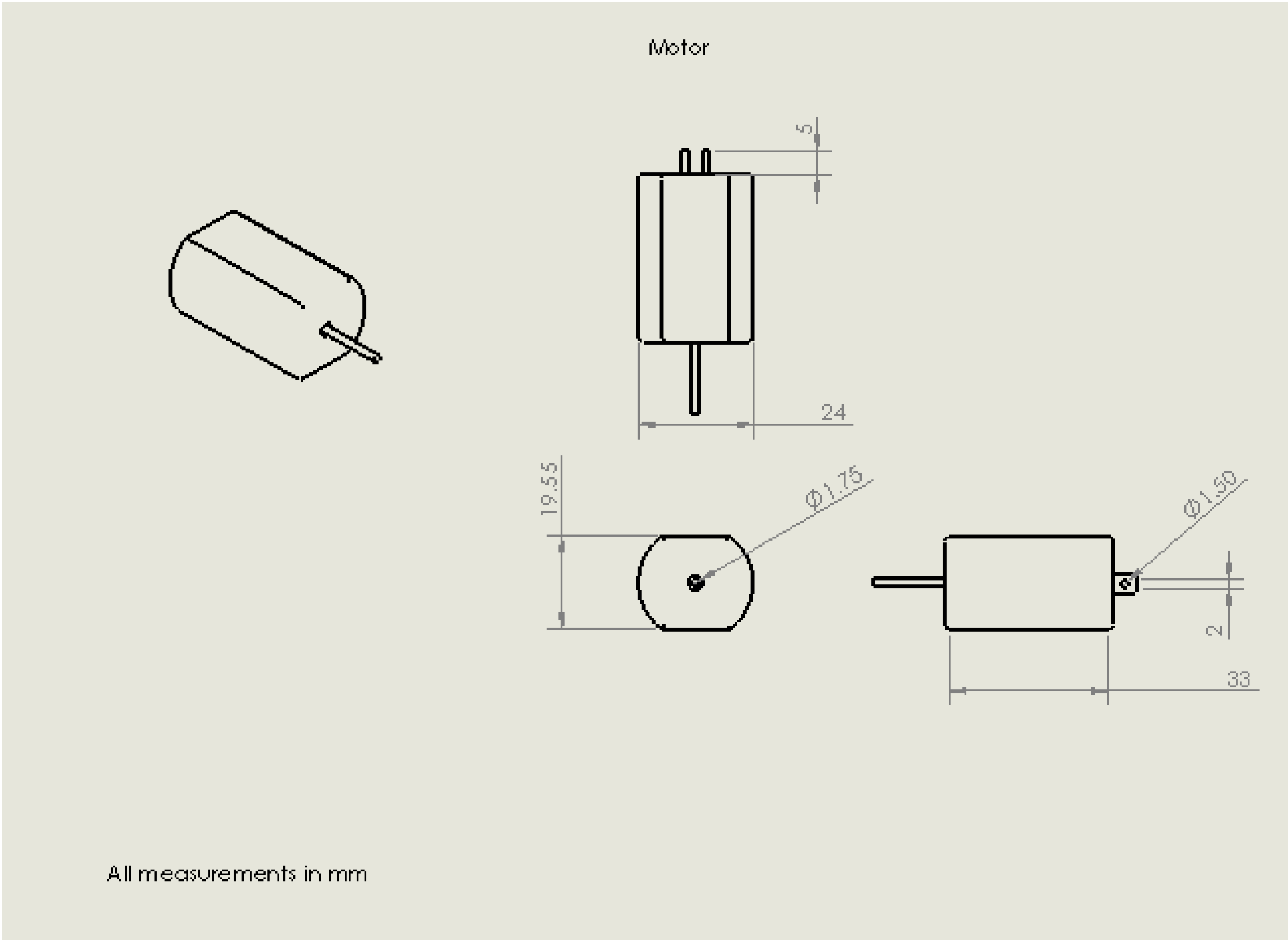

Figure 53: Part 1016 (Standard Motor 12850 rpm 12VDC) Part Drawing

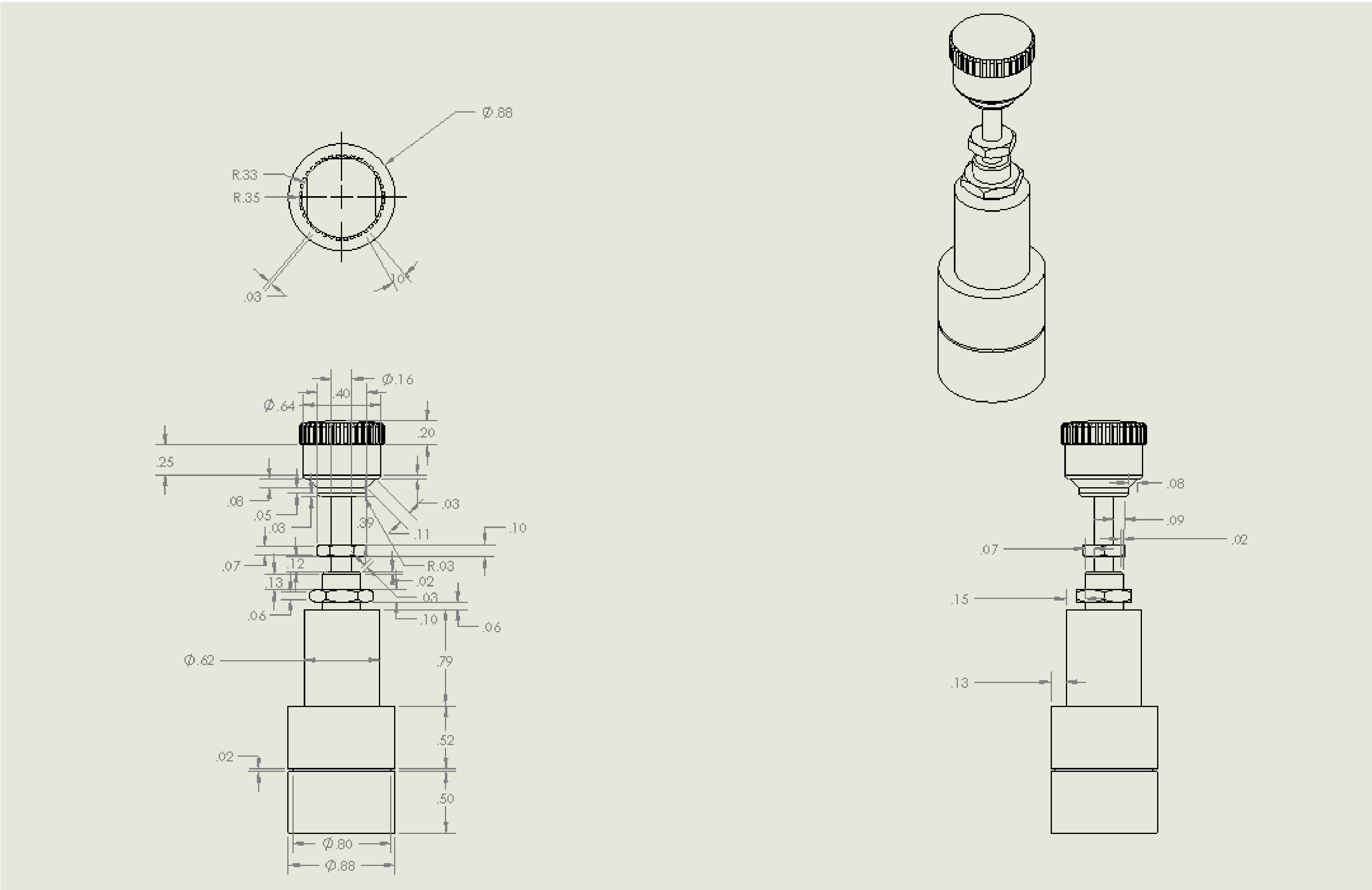

Figure 54: Part 1017 (Panel-Mount Compressed Air Regulator) Part Drawing

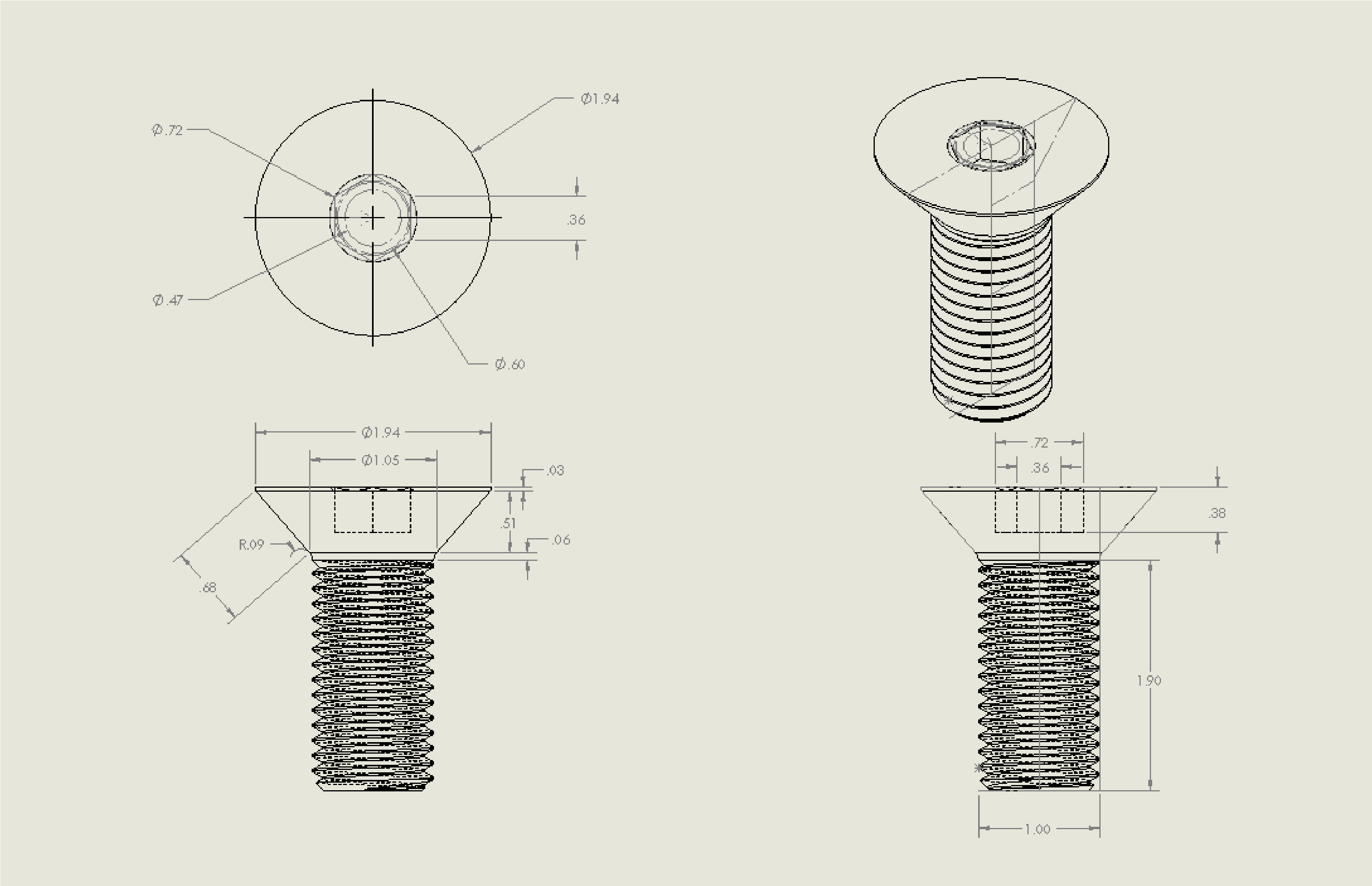

Figure 55: Part 1018 (Black-Oxide Alloy Steel Hex Drive Flat Head Screw 1”-8 Thread Size 2-1/2” Long) Part Drawing

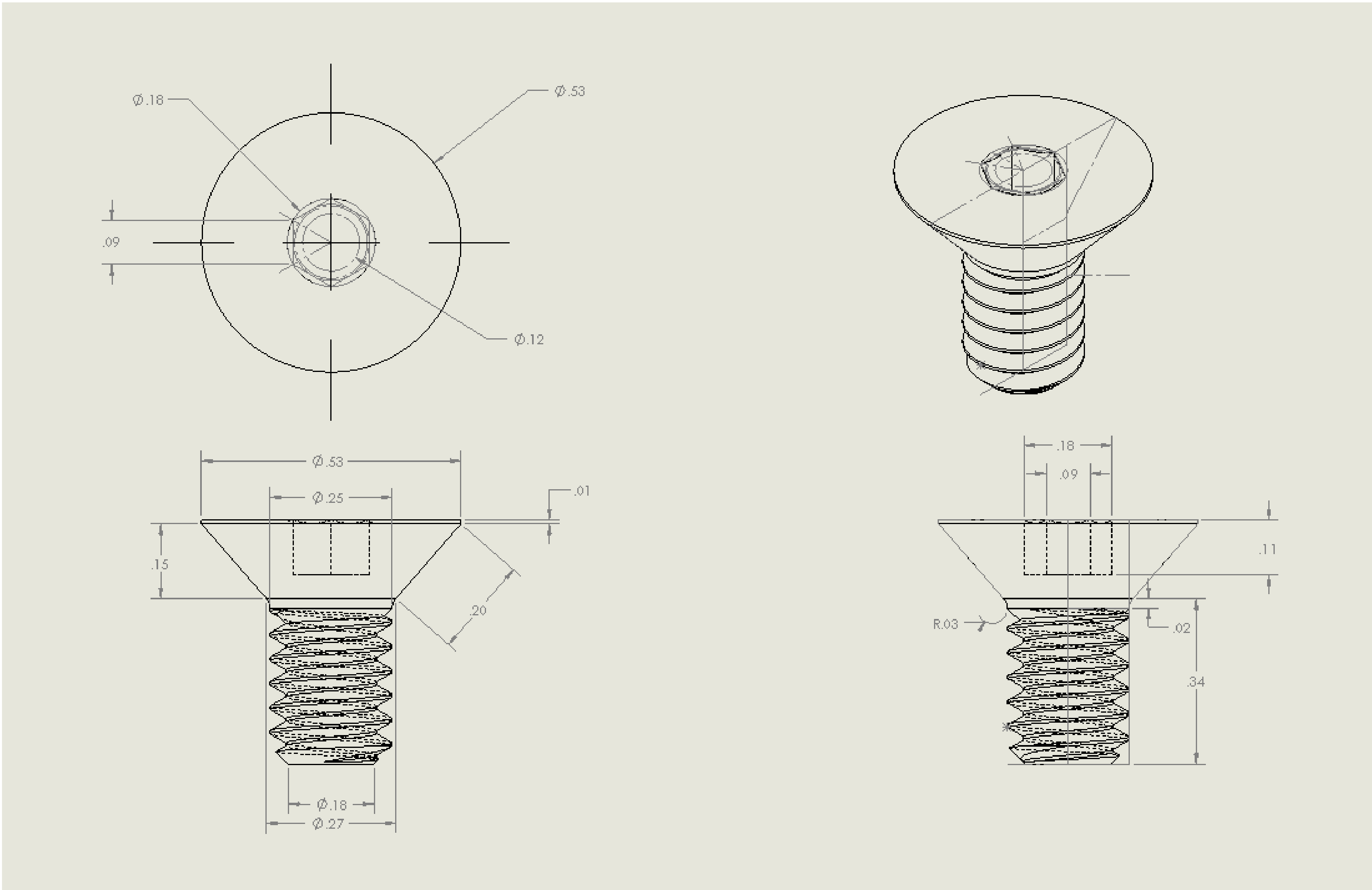

Figure 56: Part 1019 (Black-Oxide Alloy Steel Hex Drive Flat Head Screw ¼"-20 Thread Size, ½" Long) Part Drawing

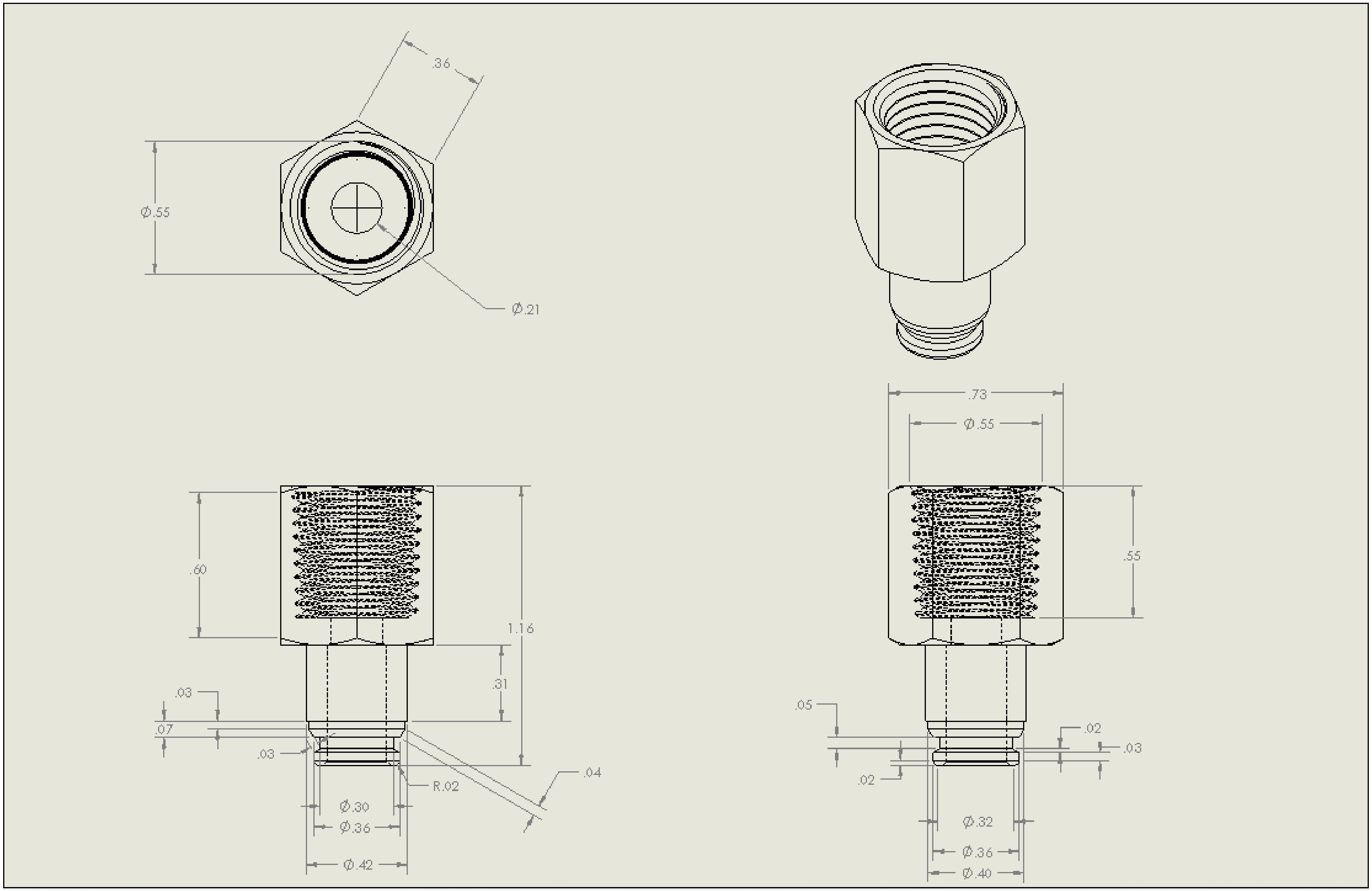

Figure 57: Part 1021 (Push-to-Connect Tube Fitting for Air) Part Drawing

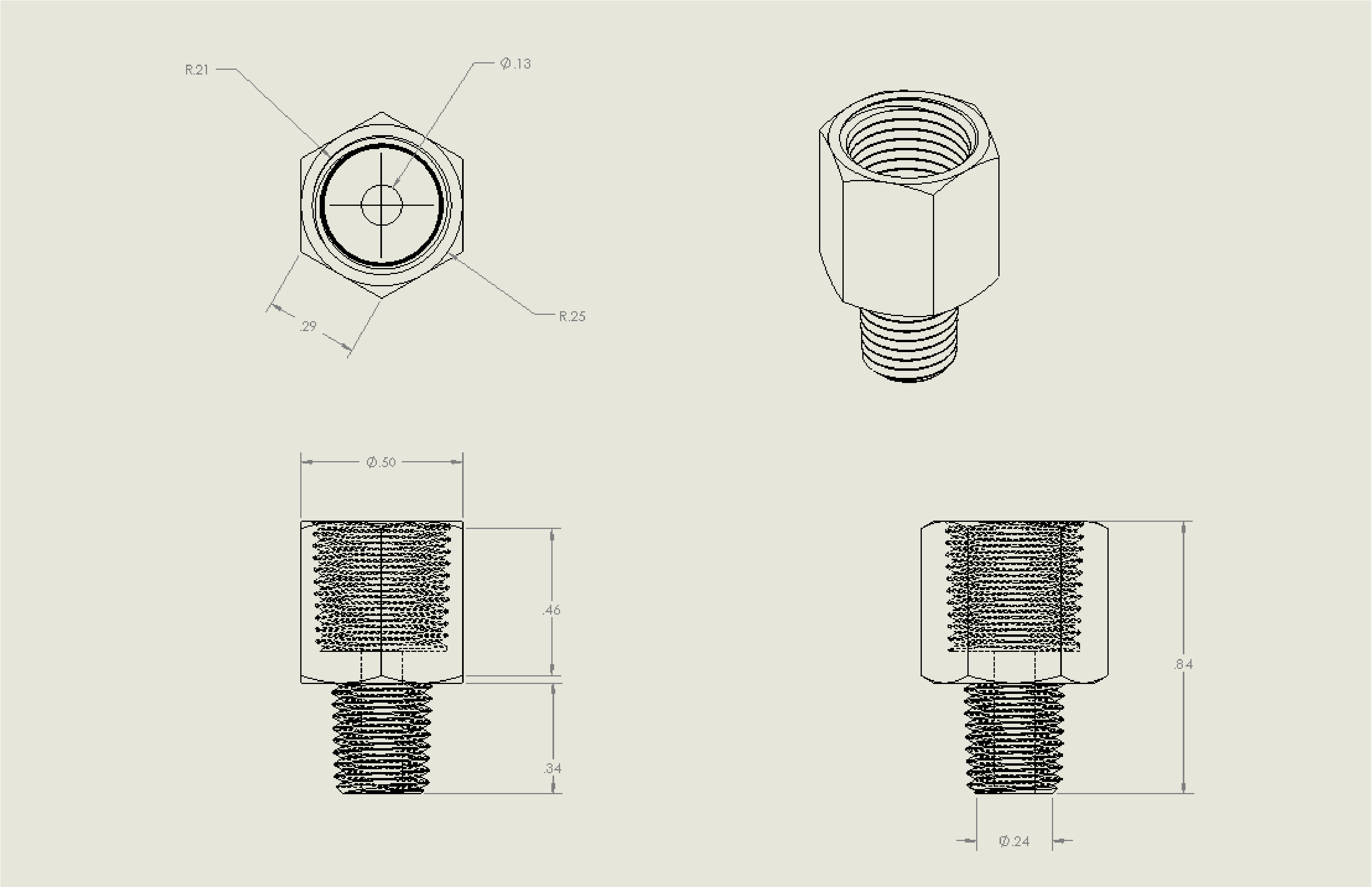

Figure 58: Part 1022 (Reducing Adapter, 1/8 NPT Female x 1/16 NPT Male) Part Drawing

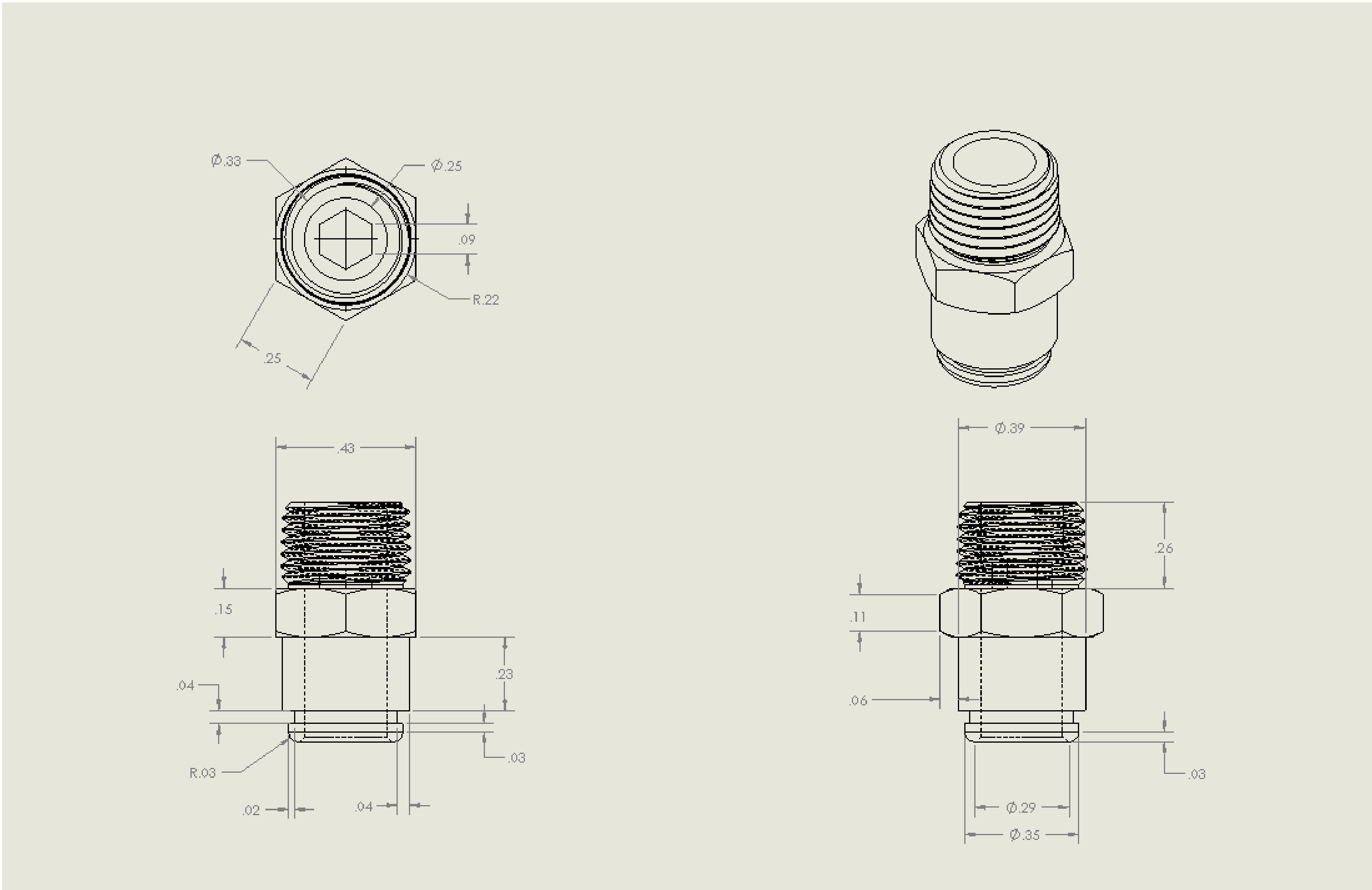

Figure 59: Part 1023 (Straight Adapter, for ¼" Tube OD x 1/8 NPT Male) Part Drawing

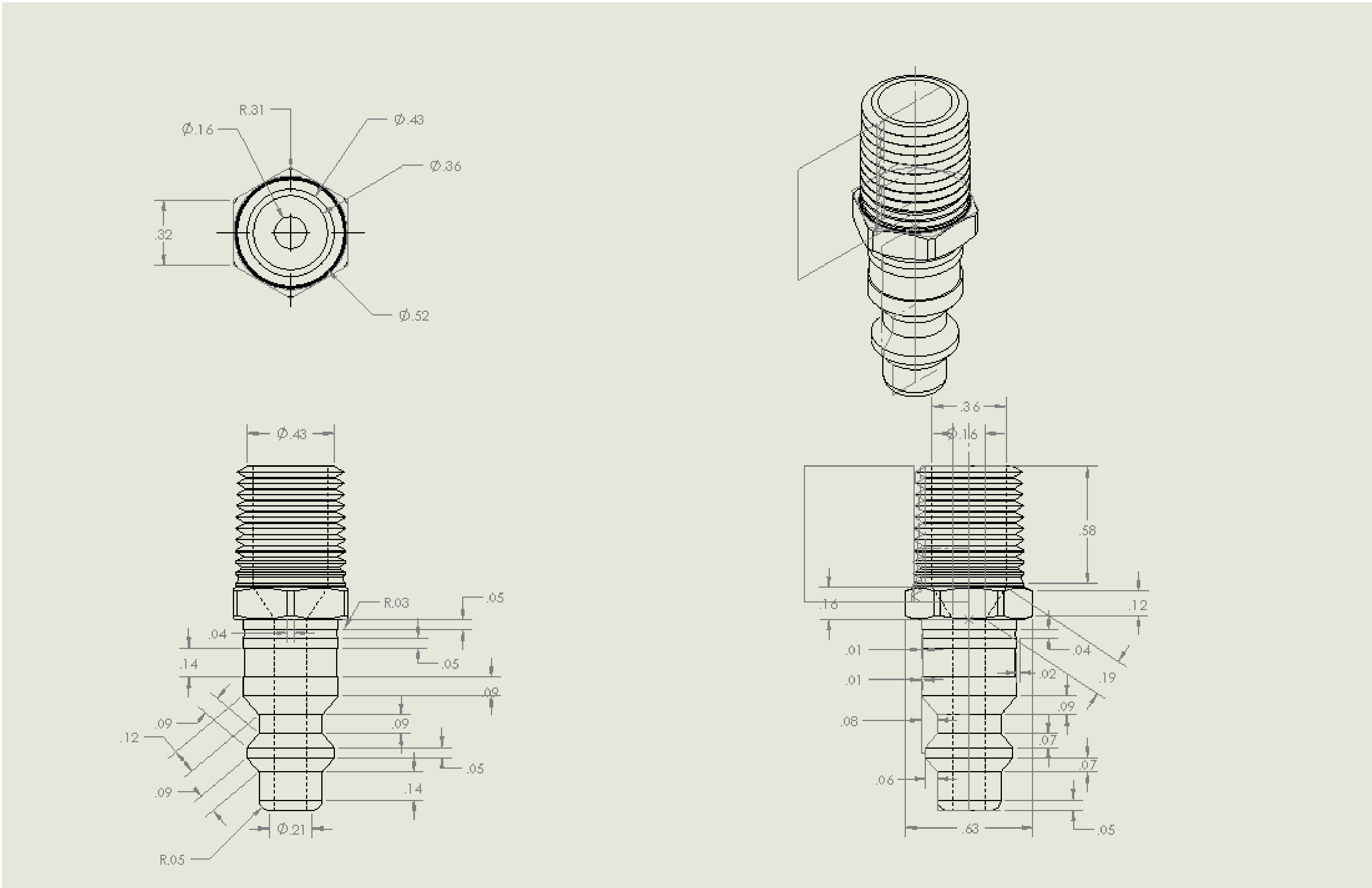

Figure 60: Part 1024 (Industrial-Shape Hose Coupling Size ¼, Zinc-Plated Steel Ply, ¼ NPTF Male End) Part Drawing

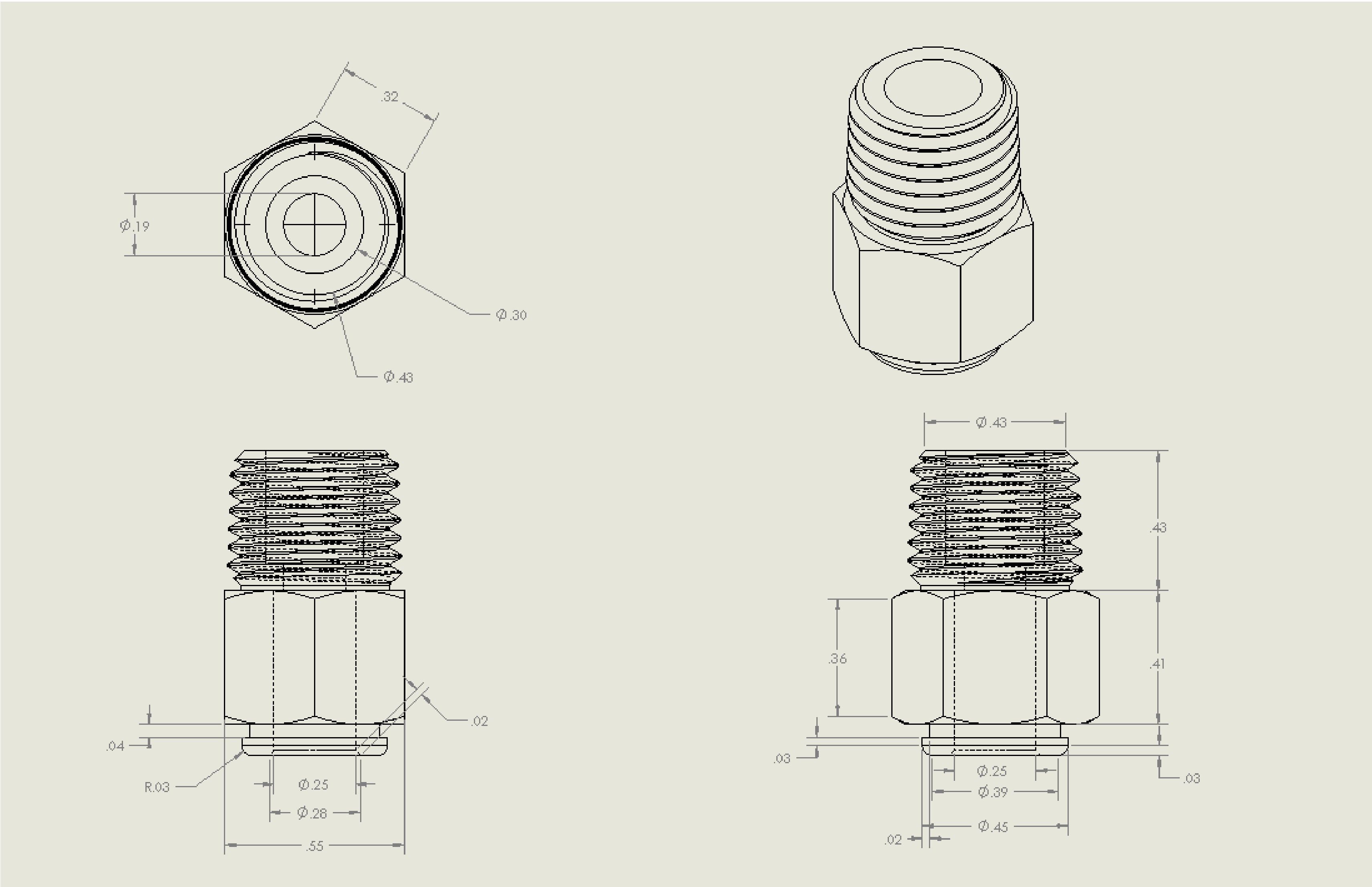

Figure 61: Part 1025 (Push-to-Connect Tube Fitting for Air, Adapter, for ¼" Tube OD, ¼ NPT Male) Part Drawing

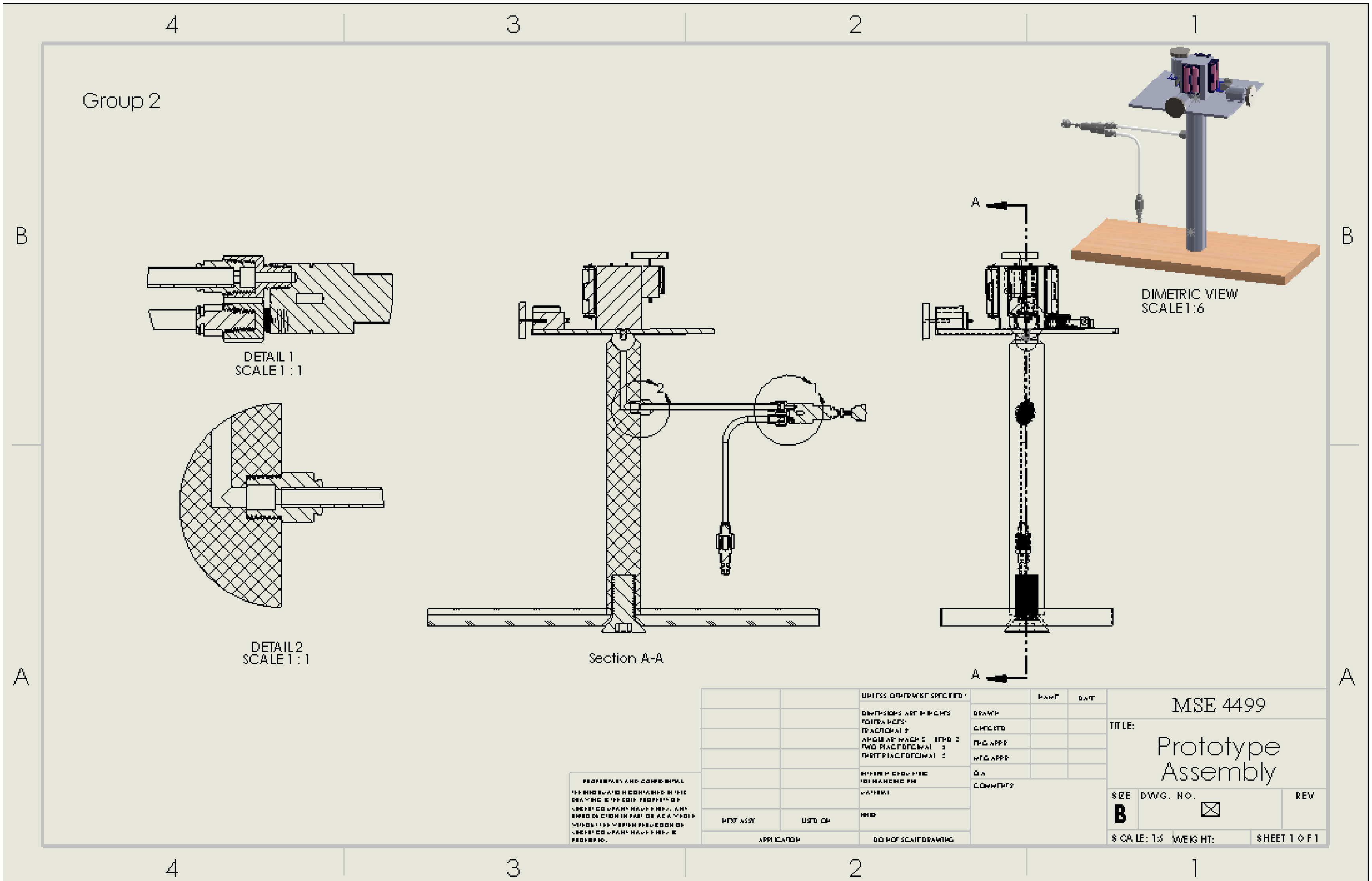

Figure 62: Full Assembly Drawing

3.7. CAD Drawings for Prototype

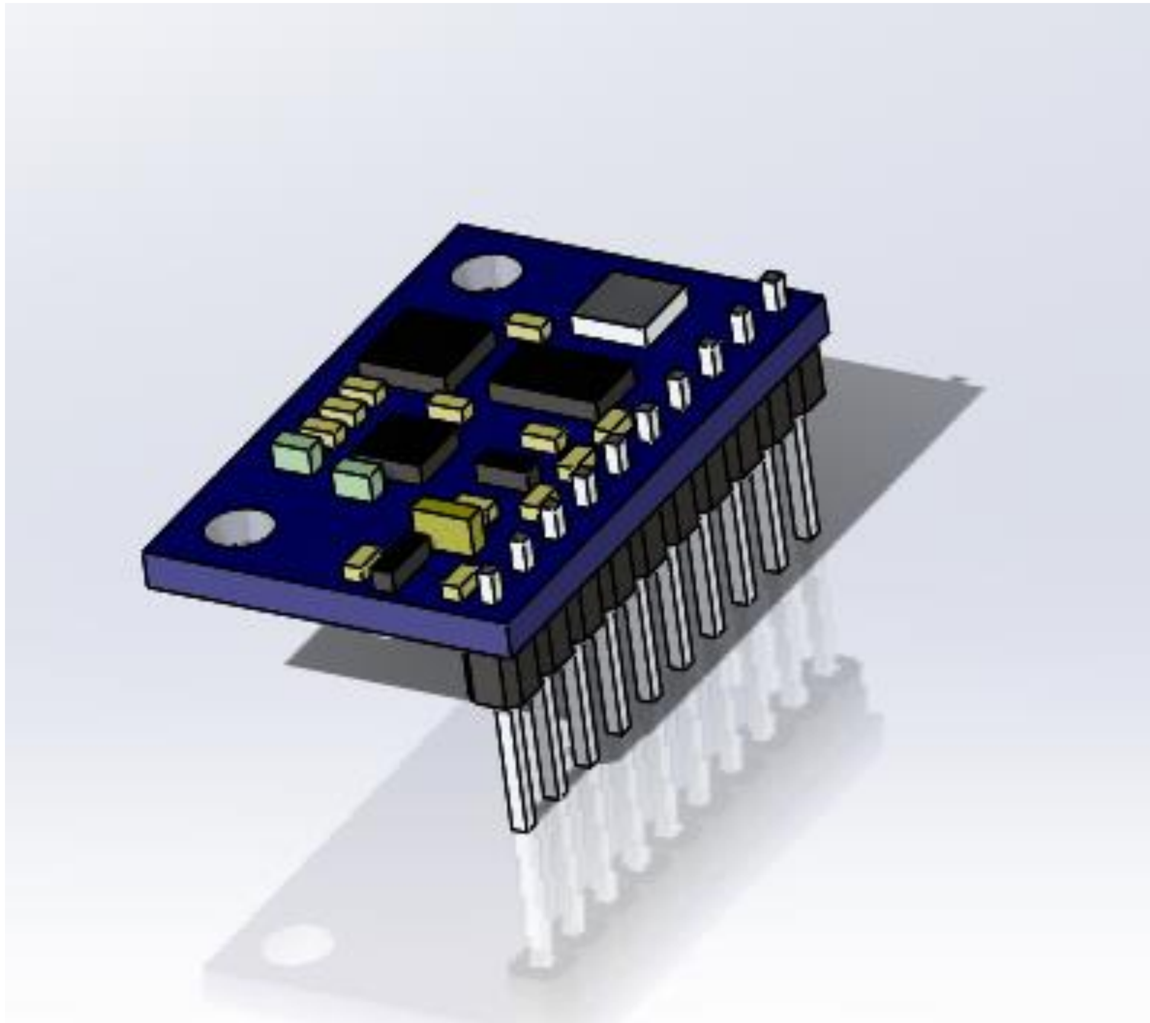

Figure 63: Part 1008 (MPU 6050 Gyroscope and Accelerometer Board) CAD Drawing

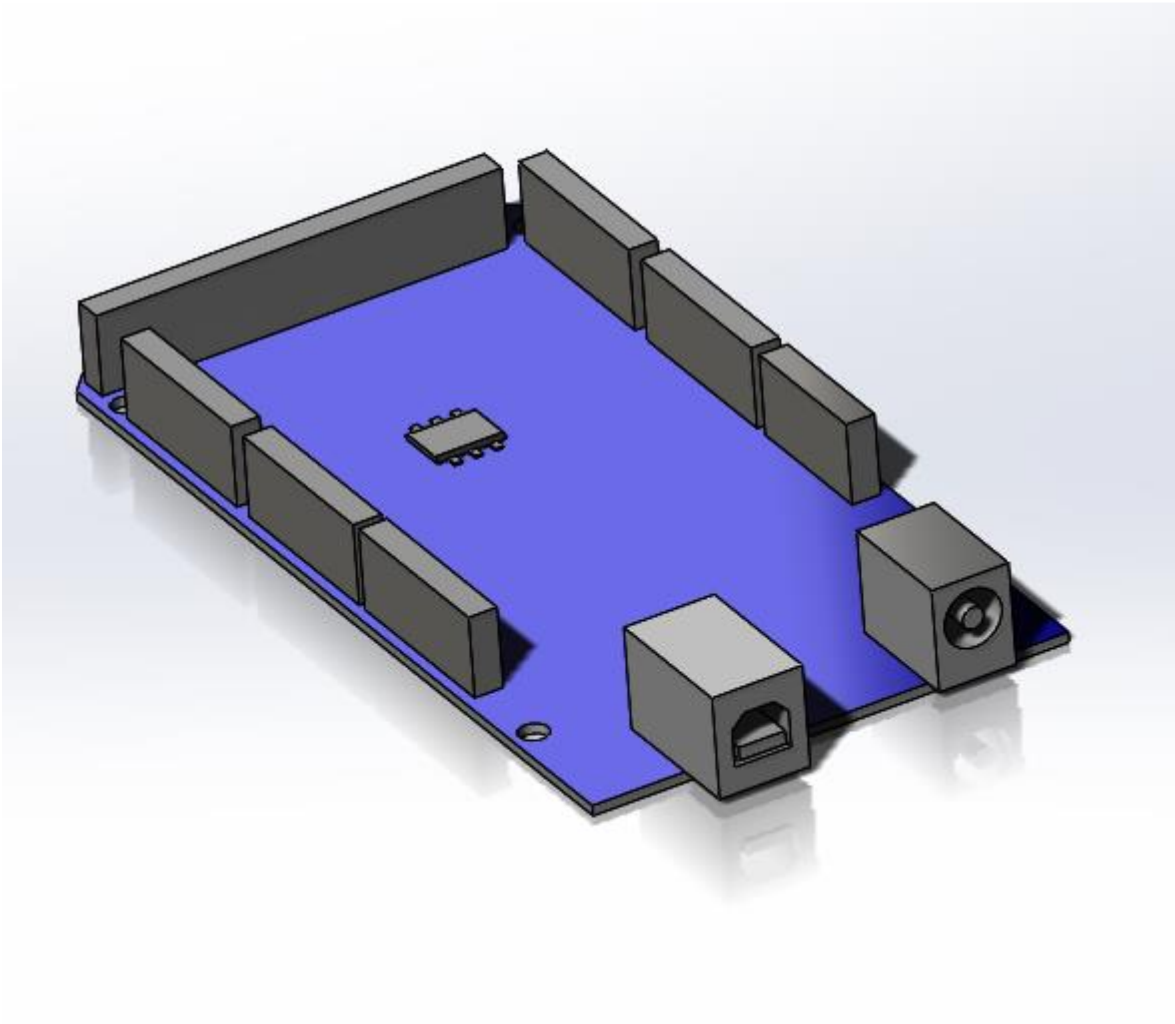

Figure 64: Part 1009 (MSEduino) CAD Drawing

Figure 65: Part 1010 (Energizer MAX AA Batteries) CAD Drawing

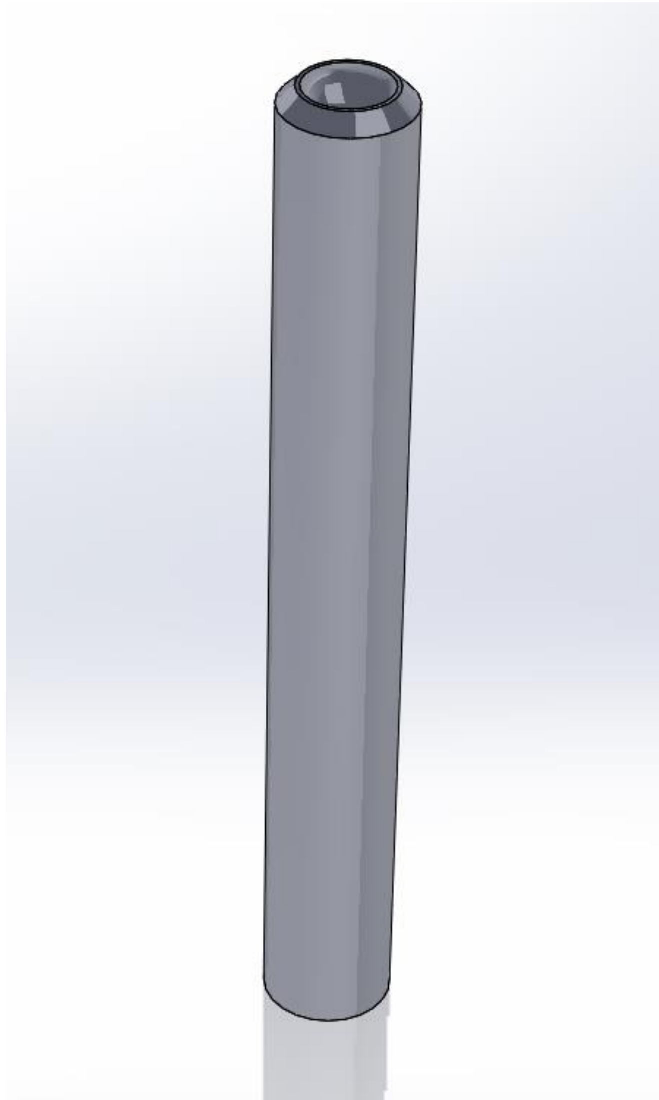

Figure 66: Part 1012 (1' Black Delrin ® Acetal Resin Rod 1-1/2" Diameter) CAD Drawing

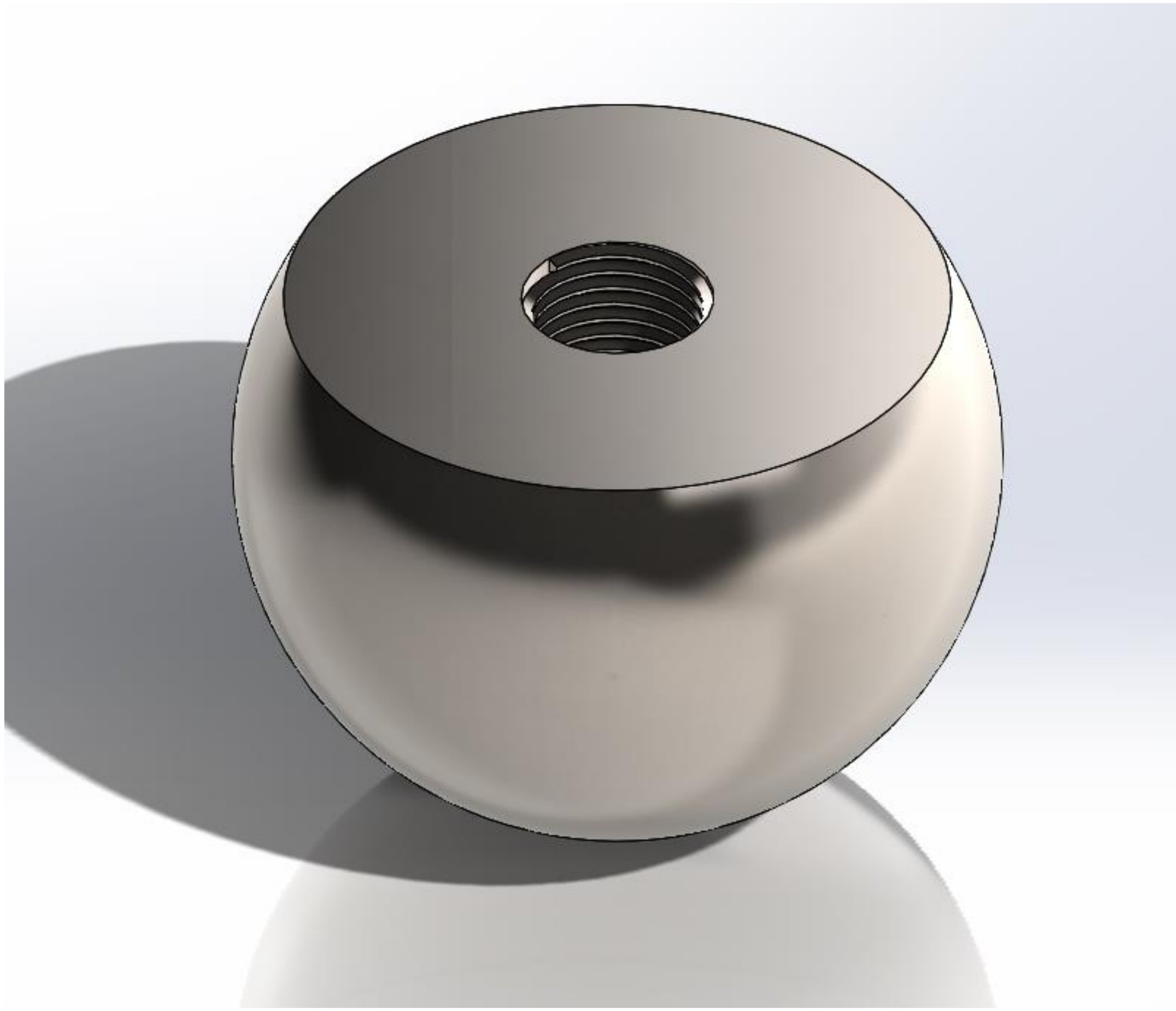

Figure 67: Part 1013 (Highly Corrosion-Resistant Stainless Steel Ball 1" Diameter) CAD Drawing

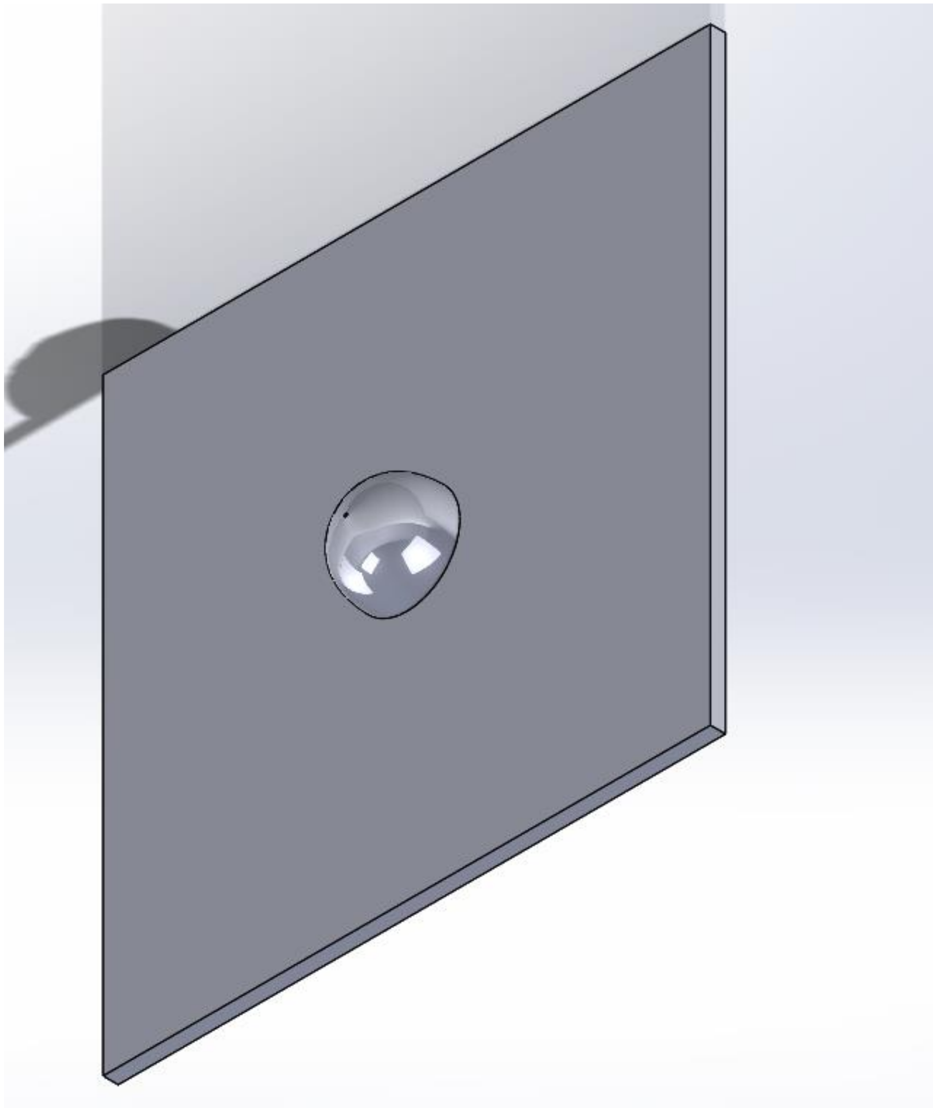

Figure 68: Part 1014 (Acrylic Sheet) CAD Drawing

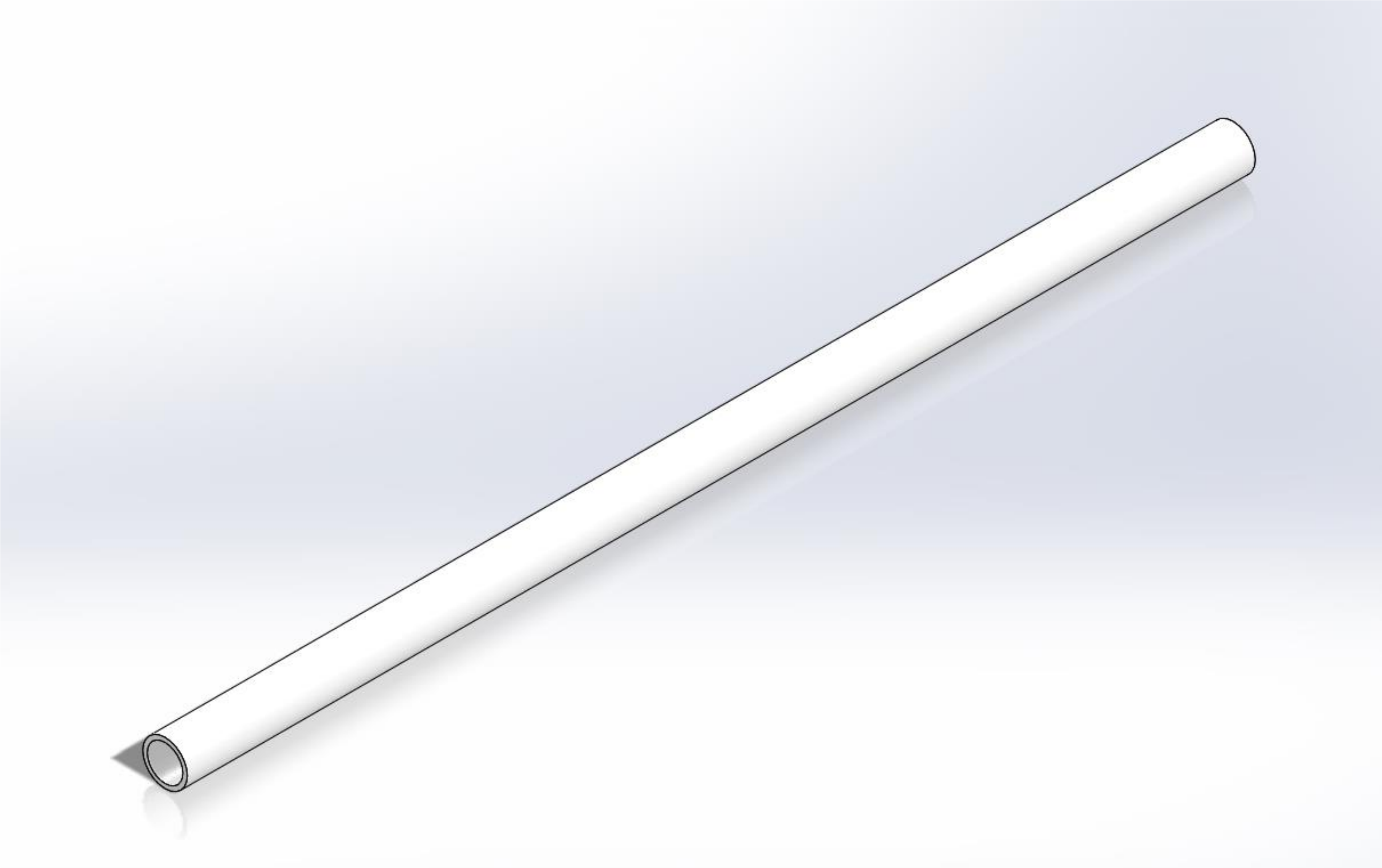

Figure 69: Part 1015 (Crack-Resist Polypropylene Semi-Clear Tubing) CAD Drawing

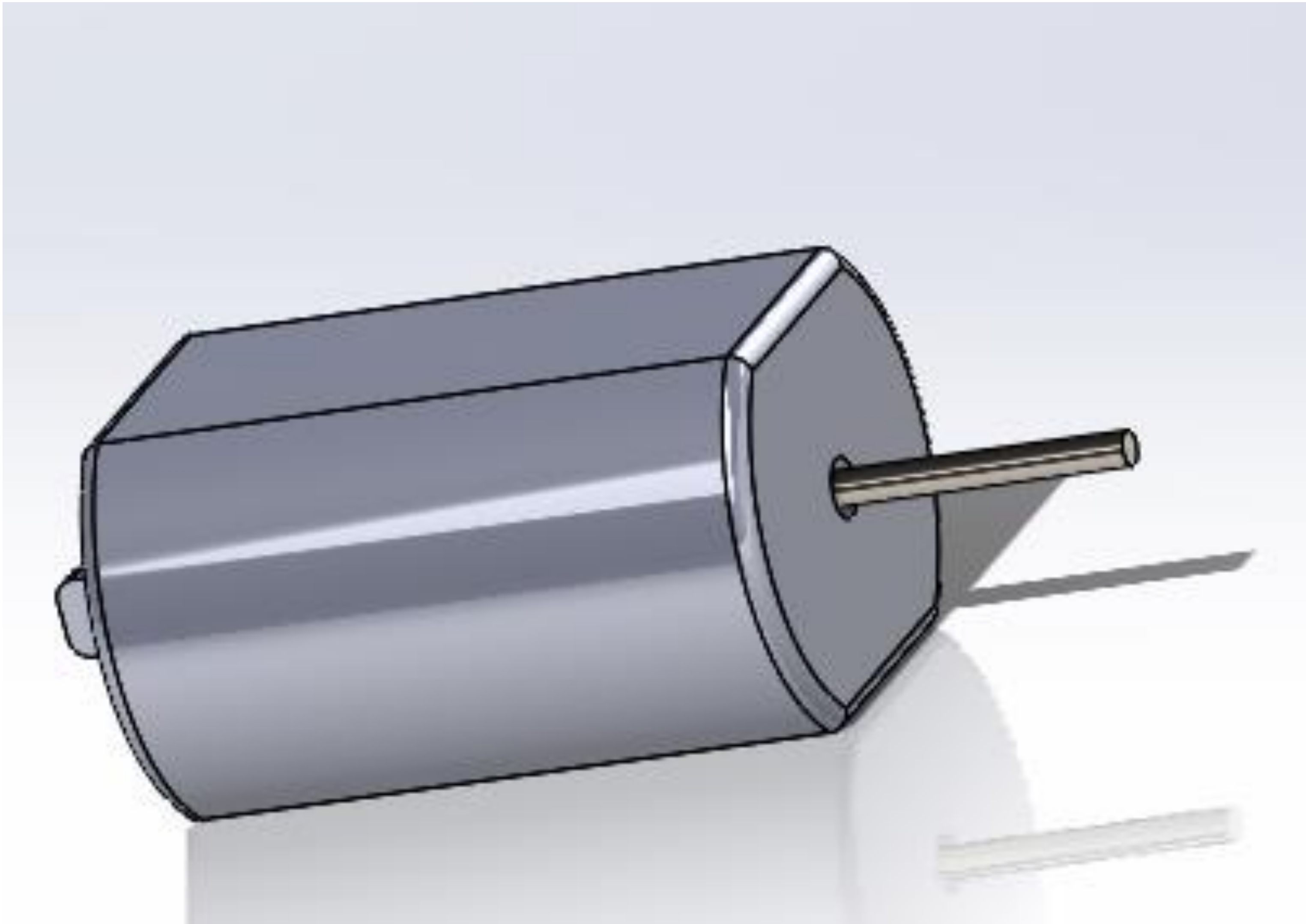

Figure 70: Part 1016 (Standard Motor 12850 rpm 12VDC) CAD Drawing

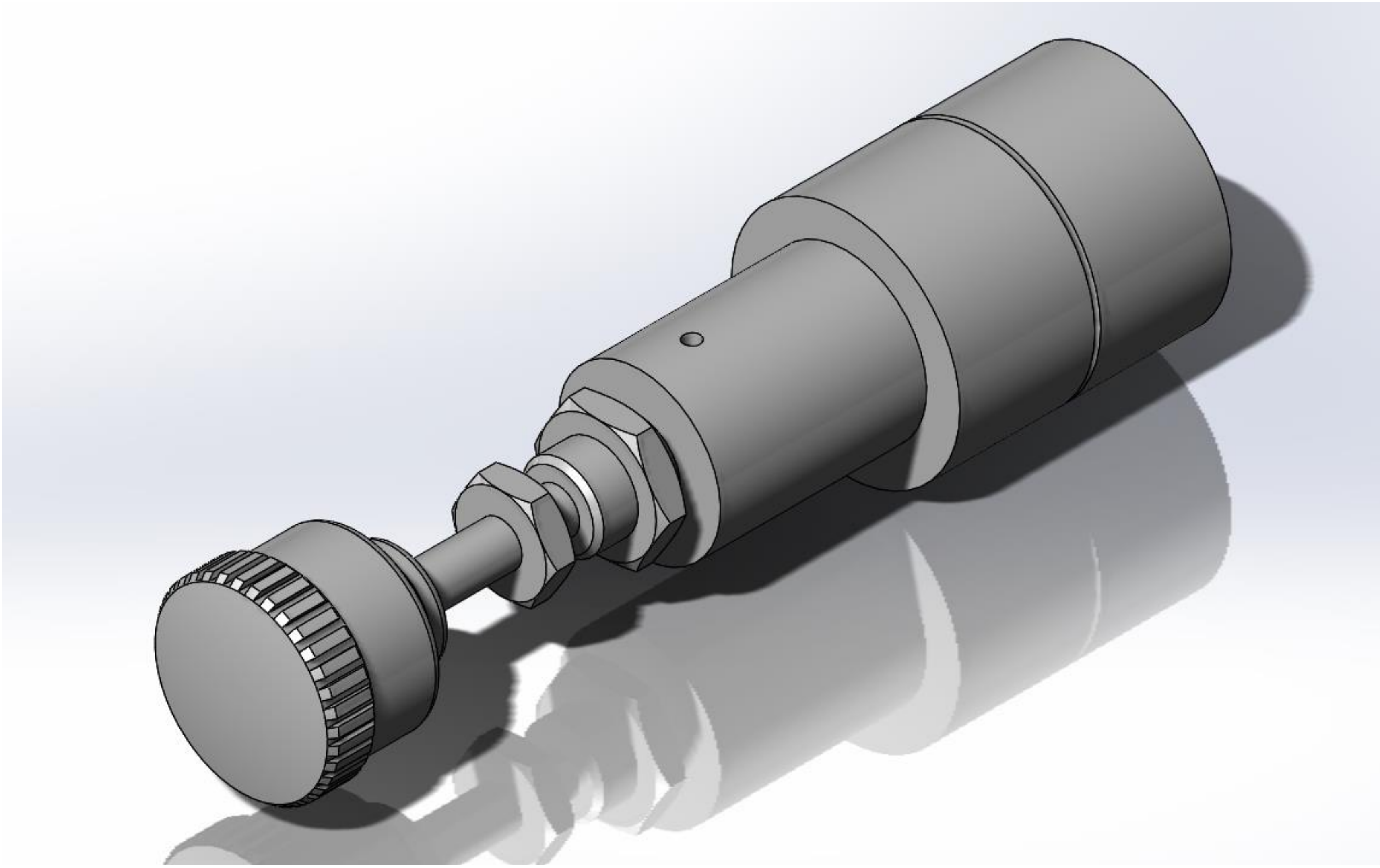

Figure 71: Part 1017 (Panel-Mount Compressed Air Regulator) CAD Drawing

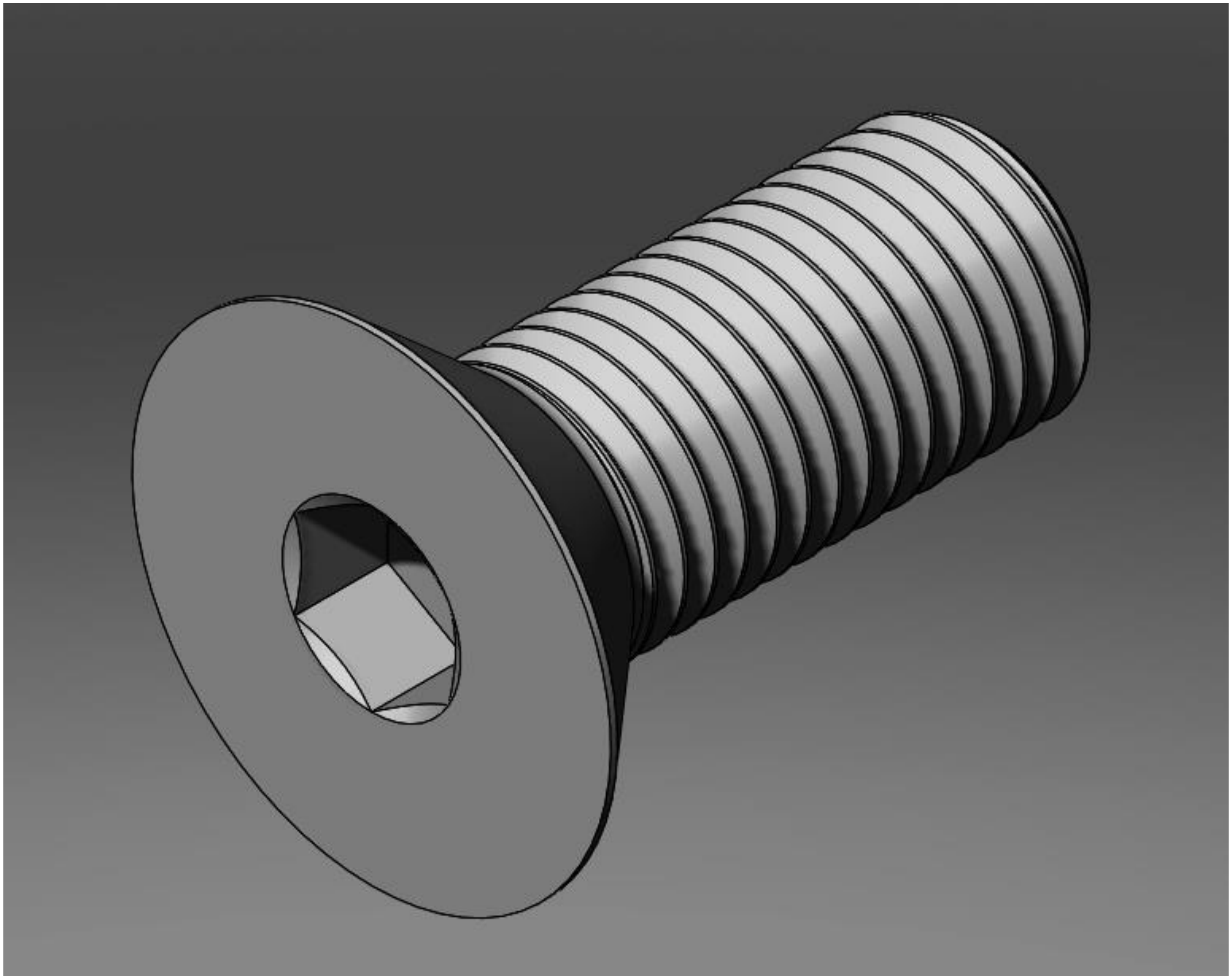

Figure 72: Part 1018 (Black-Oxide Alloy Steel Hex Drive Flat Head Screw 1”-8 Thread Size 2-1/2” Long) CAD Drawing

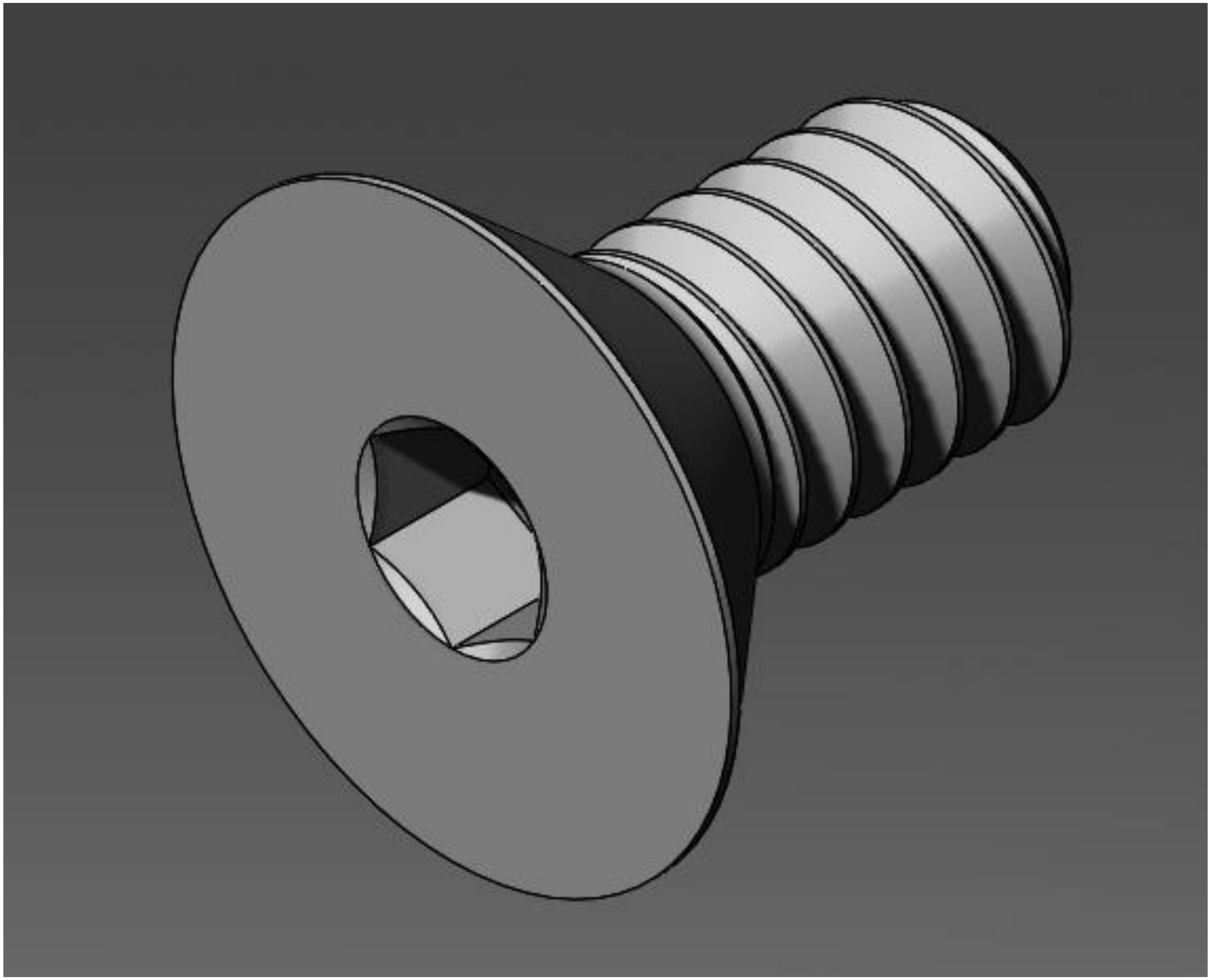

Figure 73: Part 1019 (Black-Oxide Alloy Steel Hex Drive Flat Head Screw ¼”-20 Thread Size, ½” Long) CAD Drawing

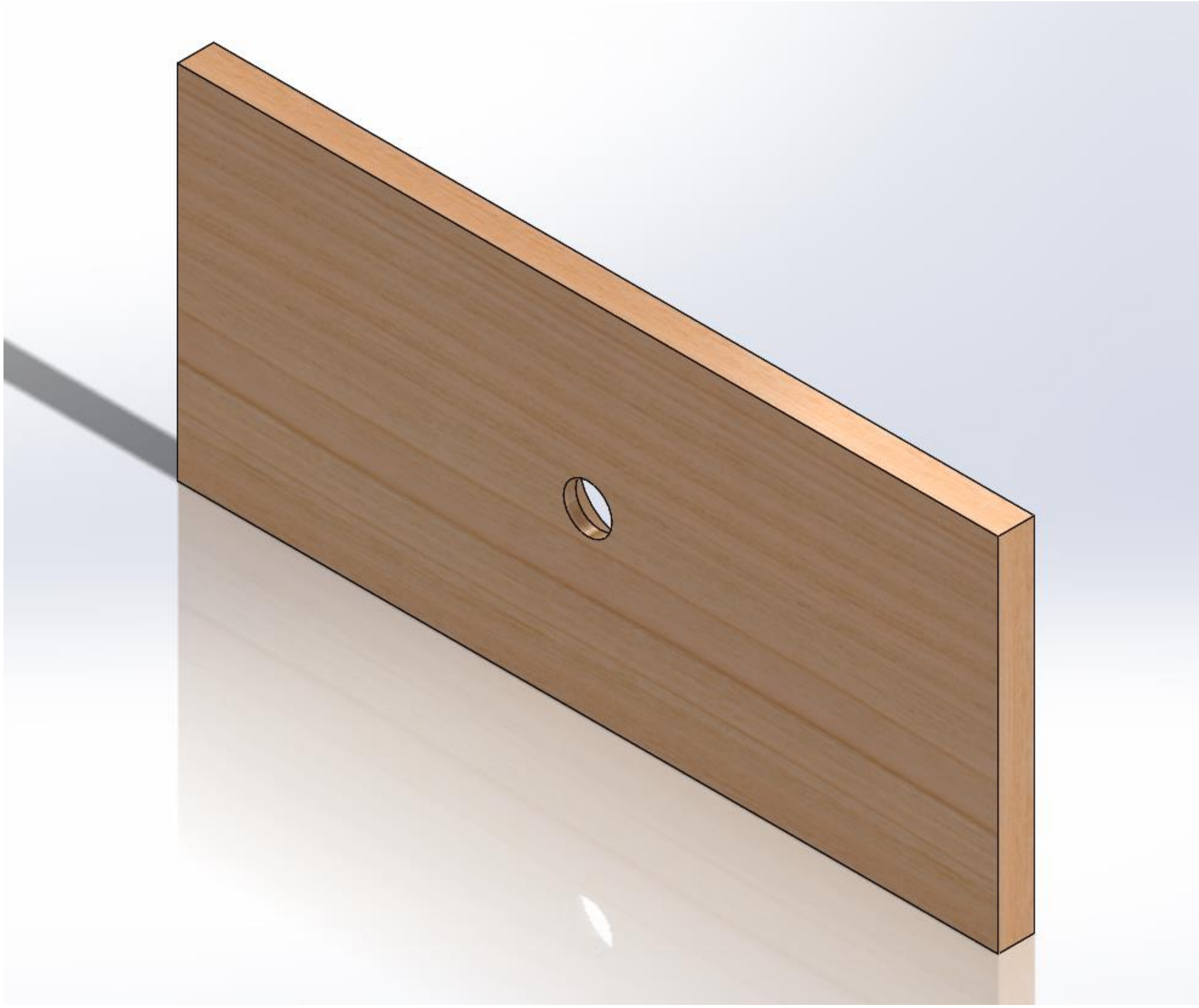

Figure 74: Part 1020 (Wooden Board) CAD Drawing

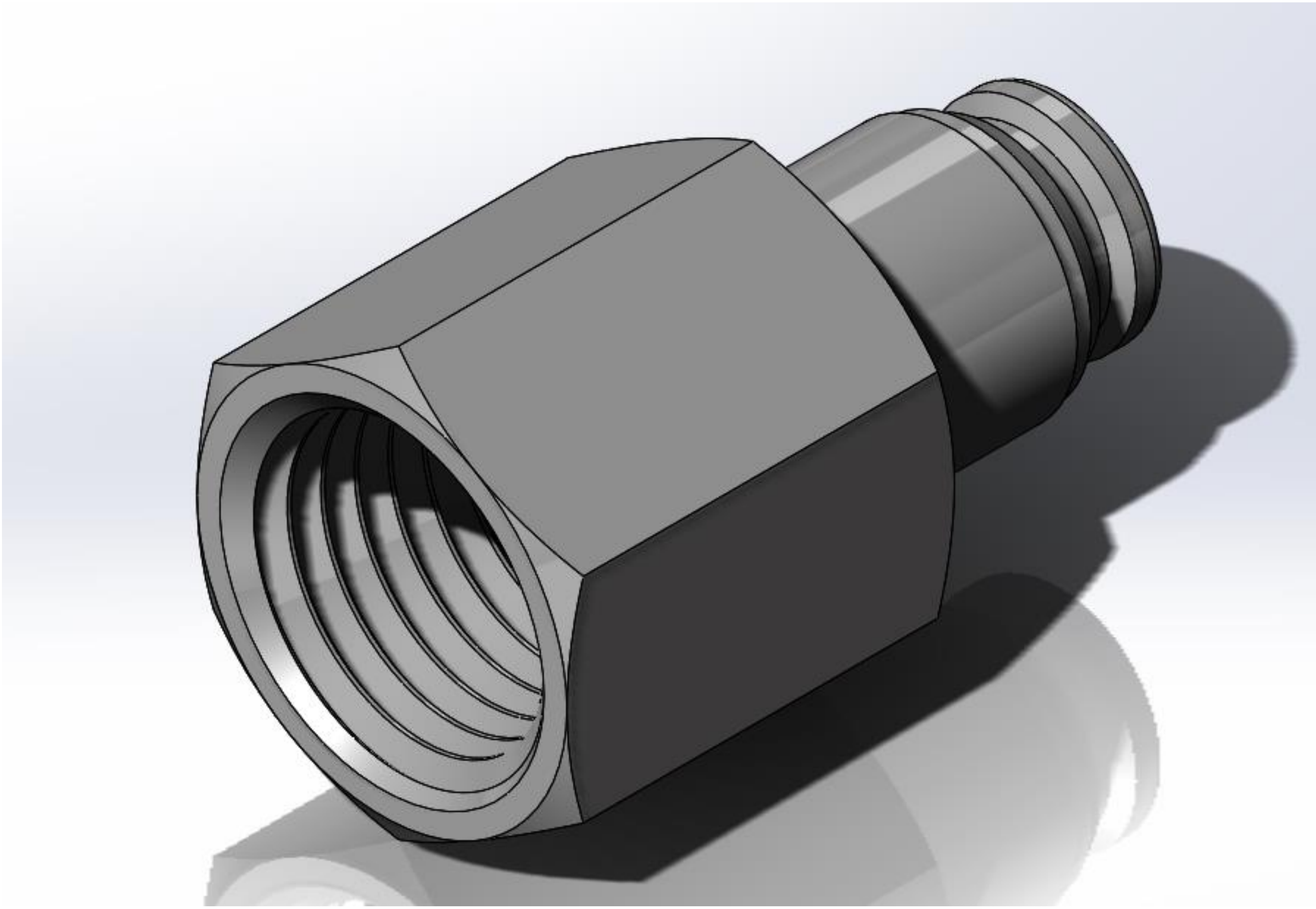

Figure 75: Part 1021 (Push-to-Connect Tube Fitting for Air) CAD Drawing

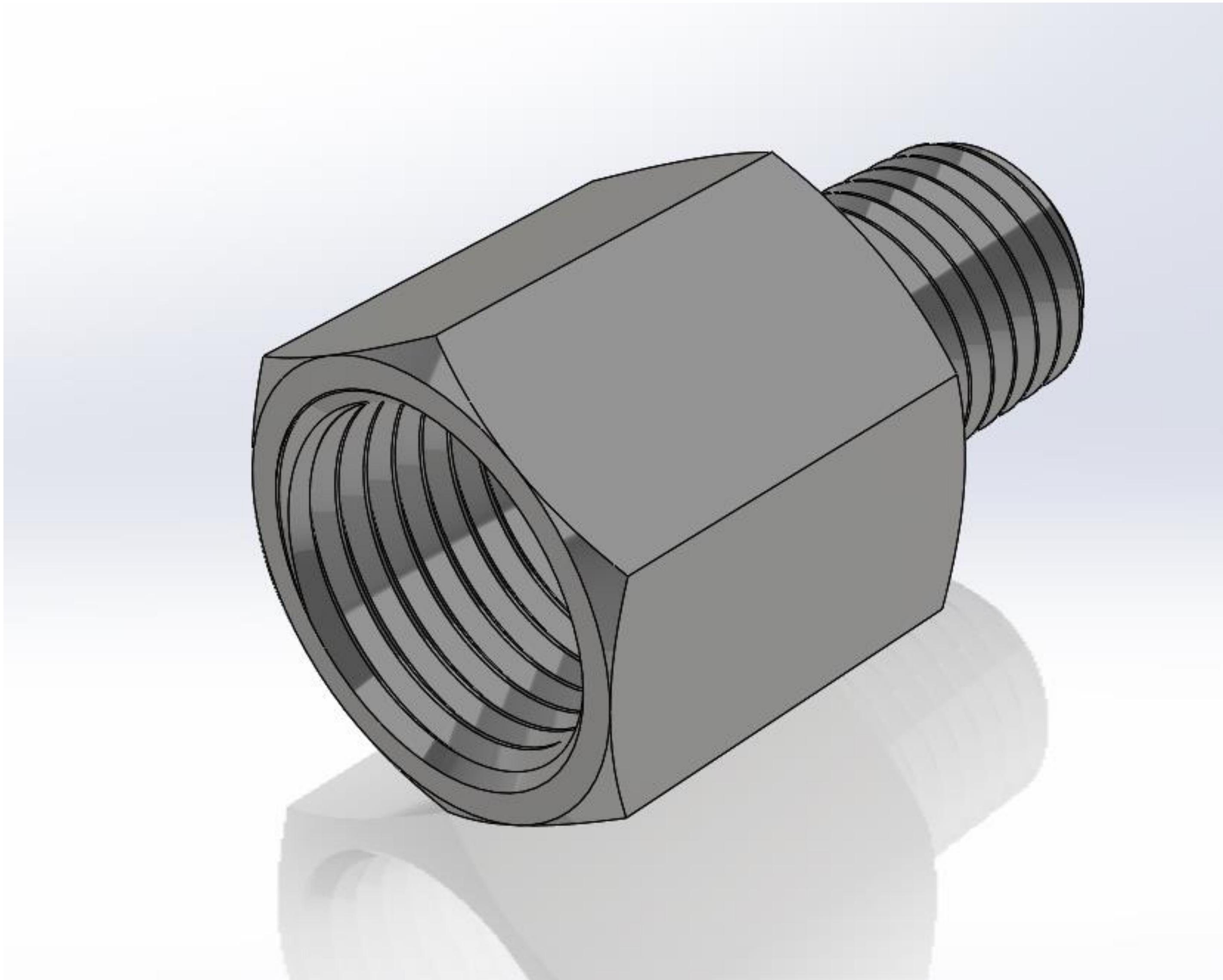

Figure 76: Part 1022 (Reducing Adapter, 1/8 NPT Female x 1/16 NPT Male) CAD Drawing

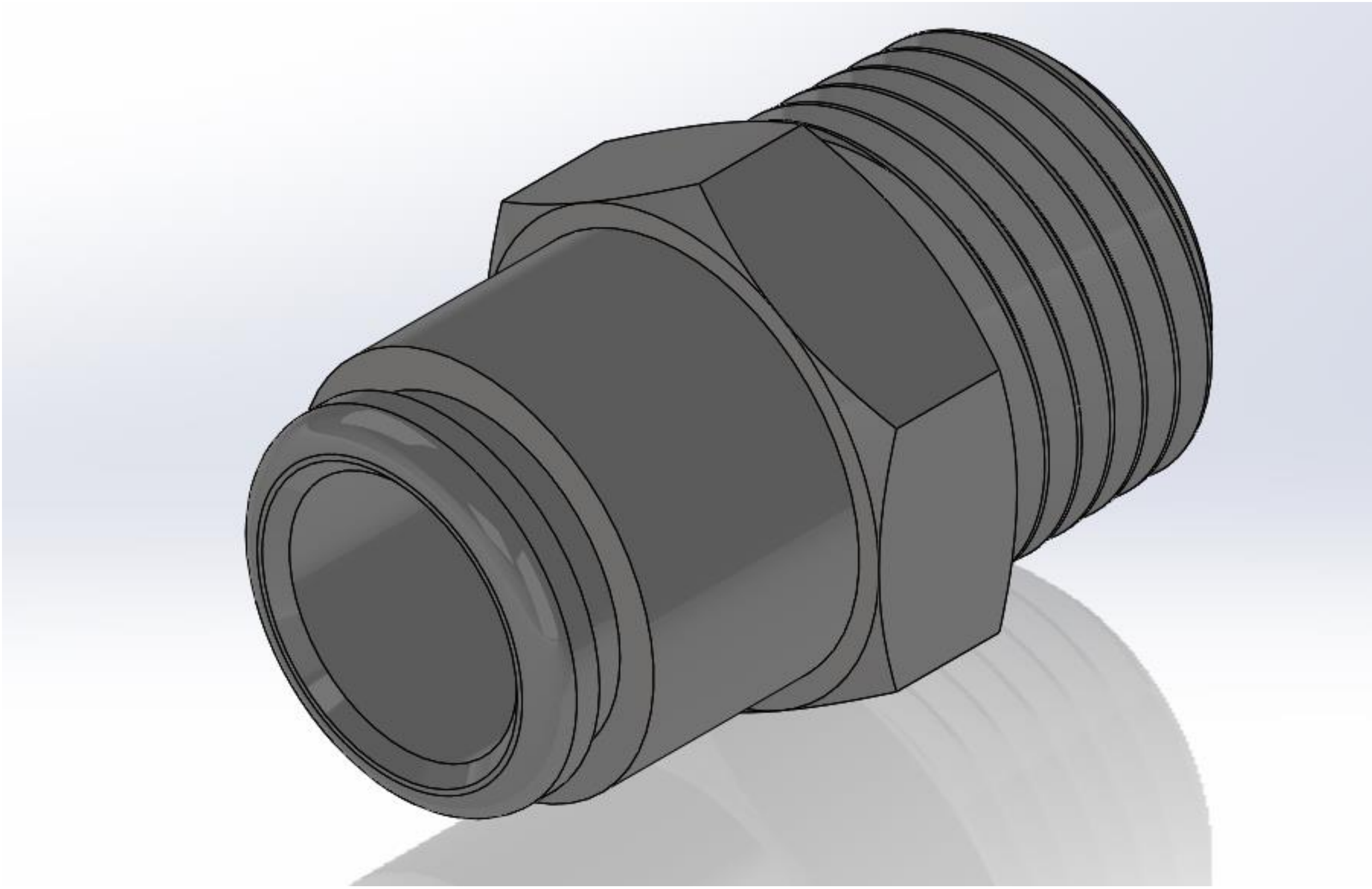

Figure 77: Part 1023 (Straight Adapter, for ¼" Tube OD x 1/8 NPT Male) CAD Drawing

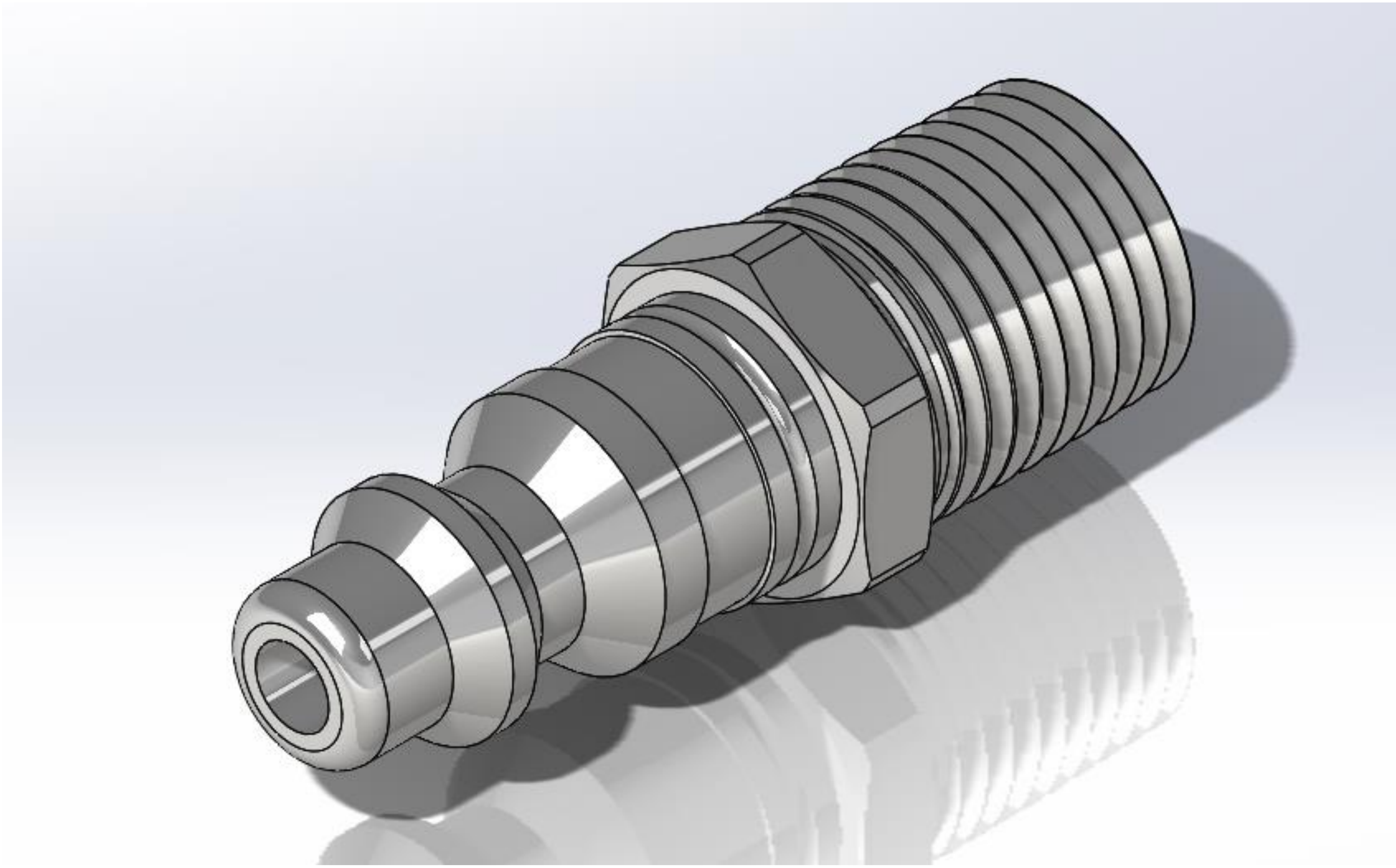

Figure 78: Part 1024 (Industrial-Shape Hose Coupling Size ¼, Zinc-Plated Steel Ply, ¼ NPTF Male End) CAD Drawing

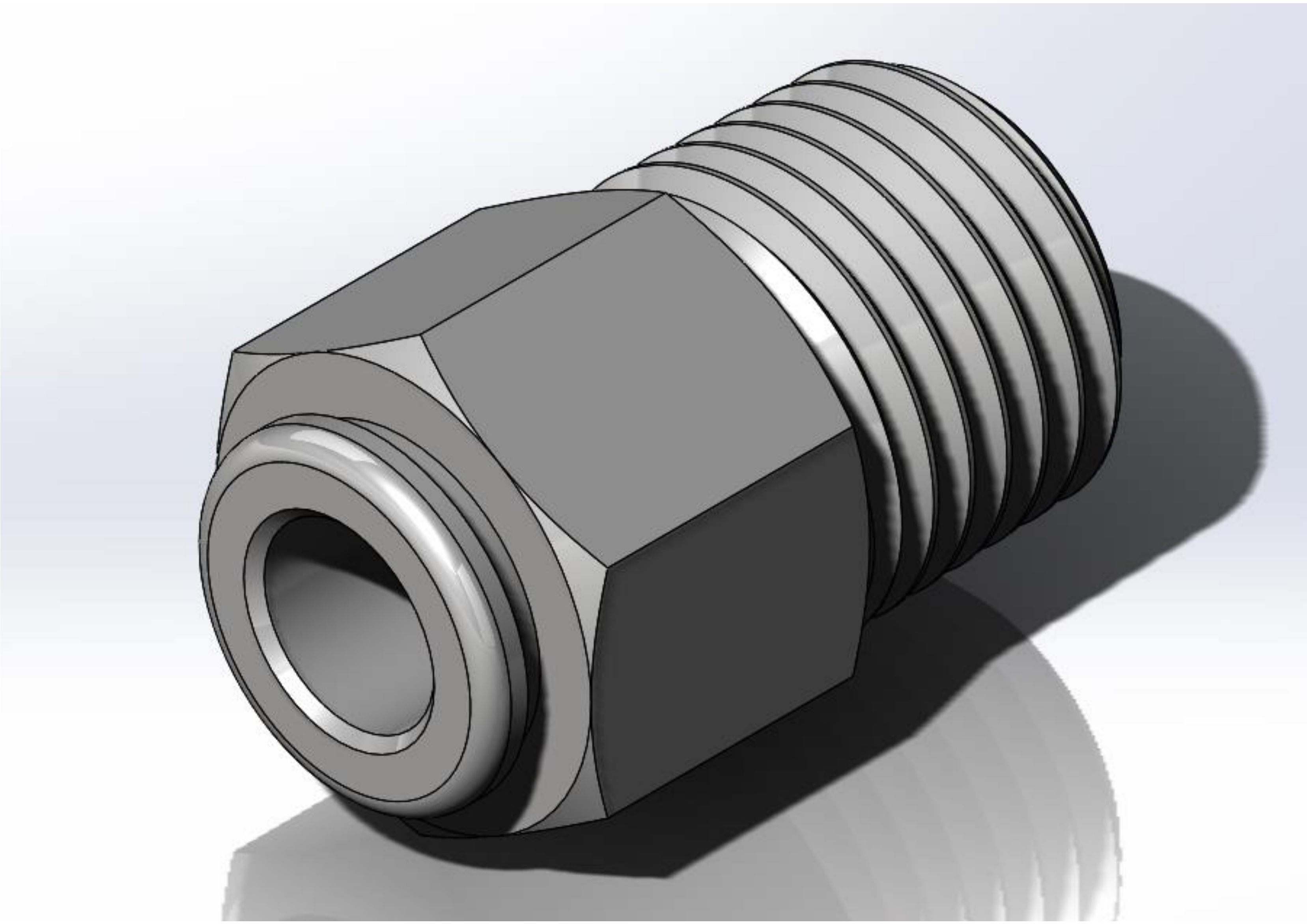

Figure 79: Part 1025 (Push-to-Connect Tube Fitting for Air, Adapter, for ¼" Tube OD, ¼ NPT Male) CAD Drawing

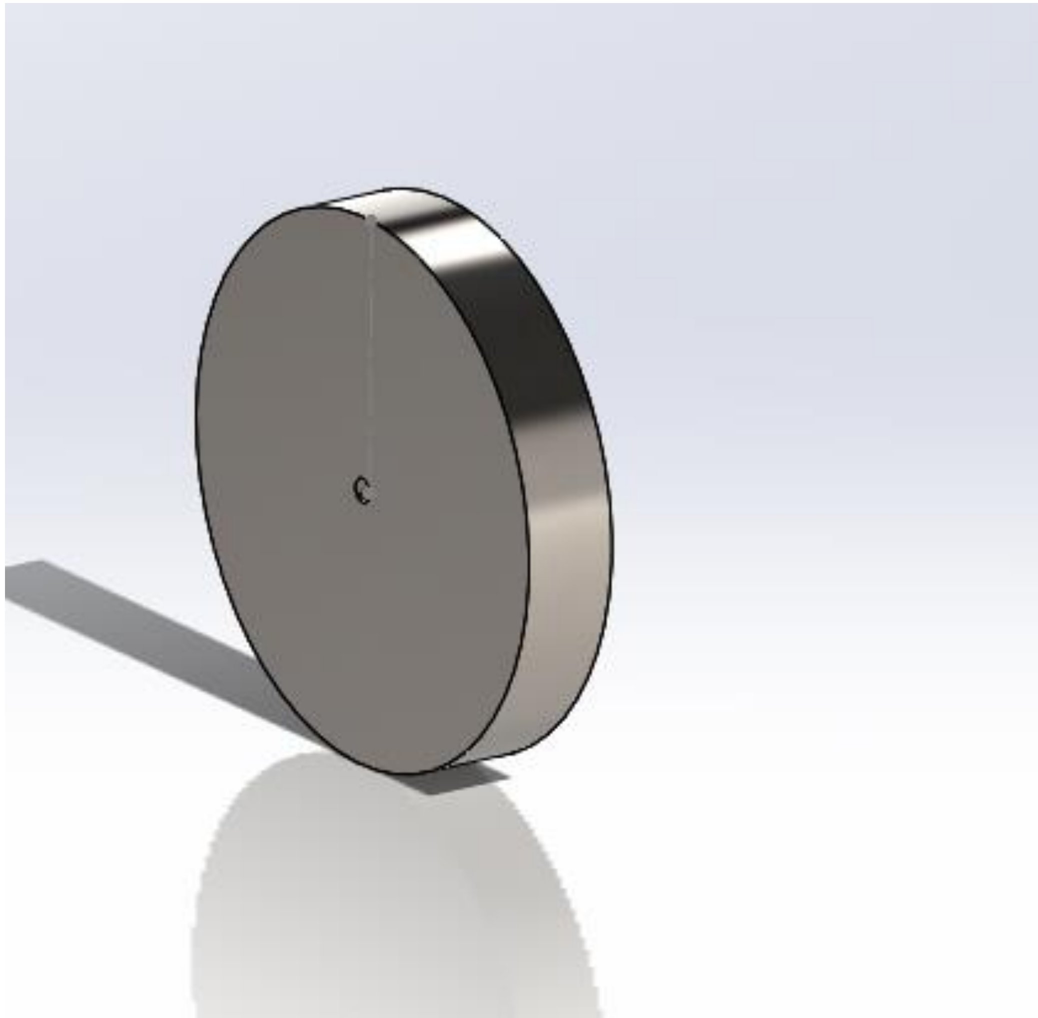

Figure 80: Part 1028 (Low-Carbon Steel Disc) CAD Drawing

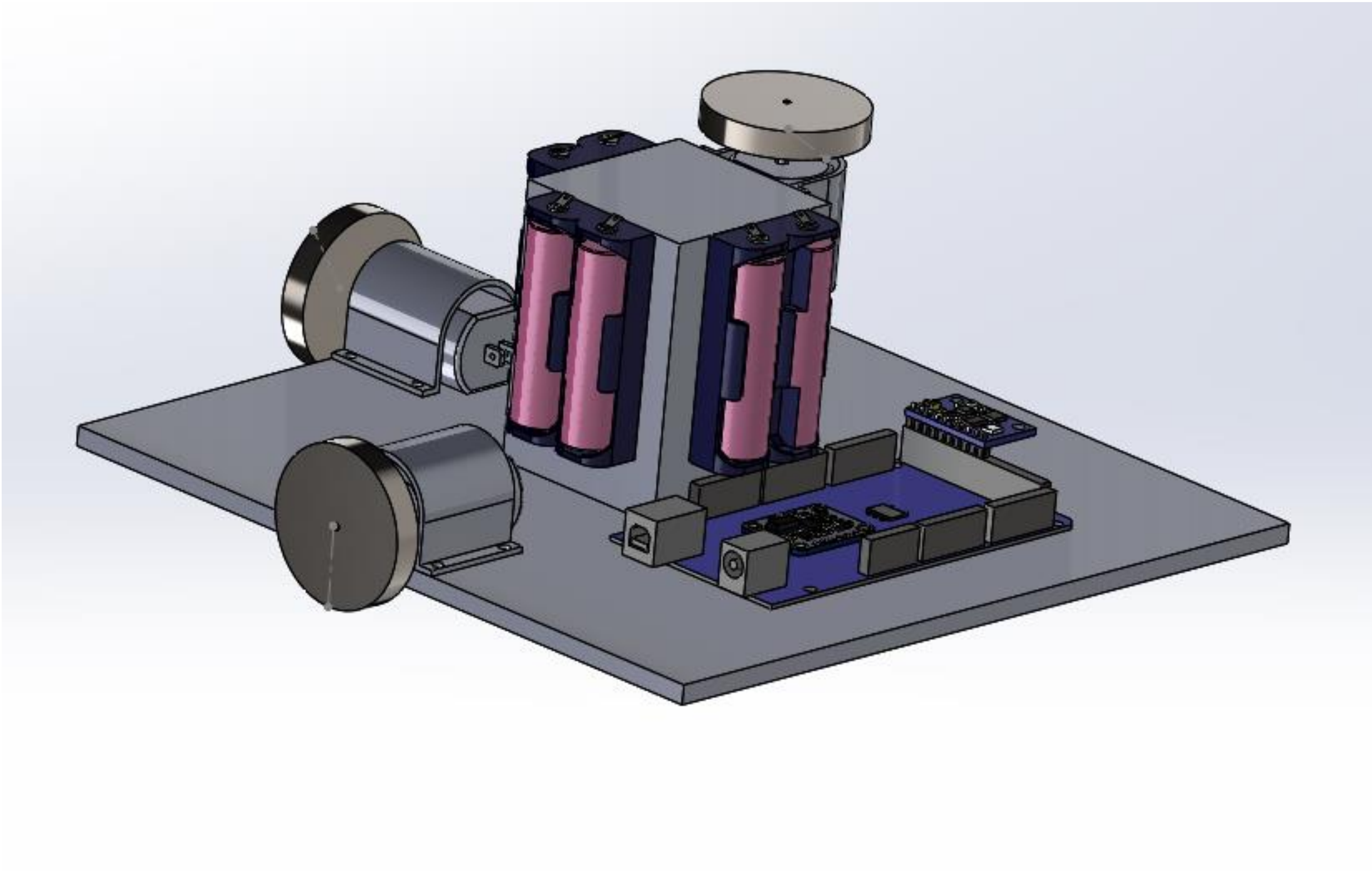

Figure 81: Prototype Assembly - CAD Drawing

3.6. Printed Circuit Board Layouts for Attitude Determination & Control System

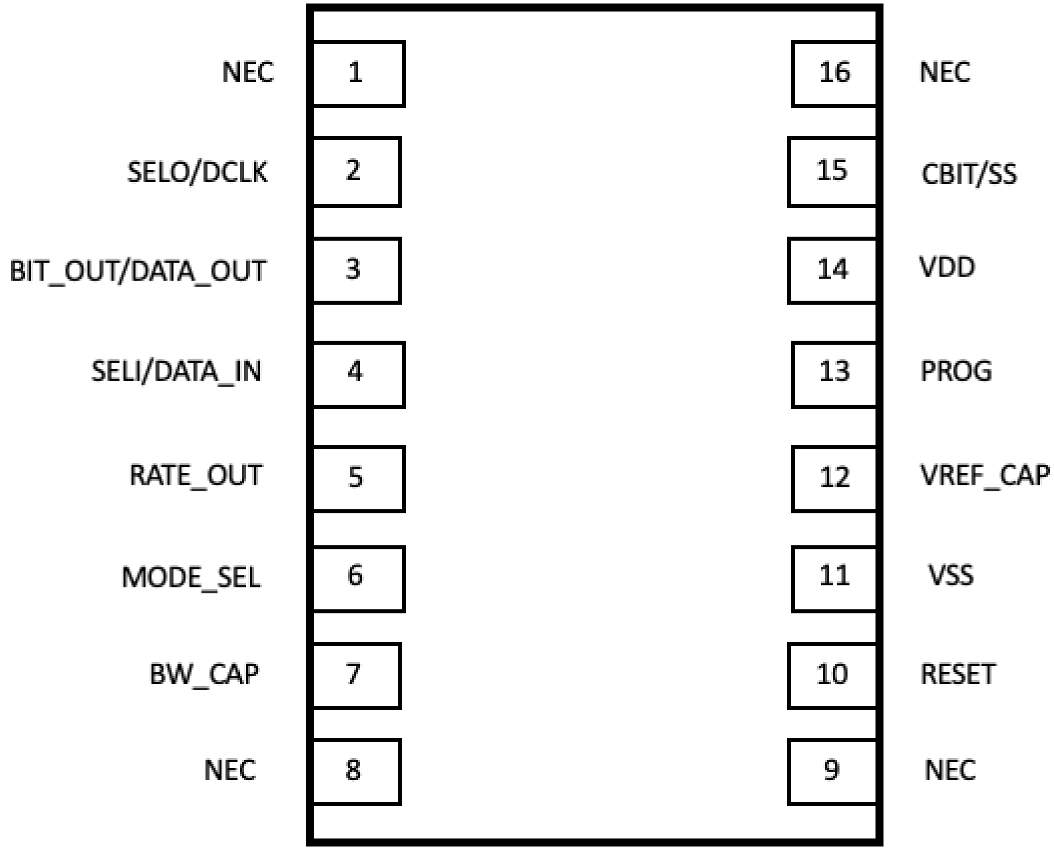

Figure 82: Part 1001 (Precision Navigation and Pointing Gyroscope) Pinout Diagram

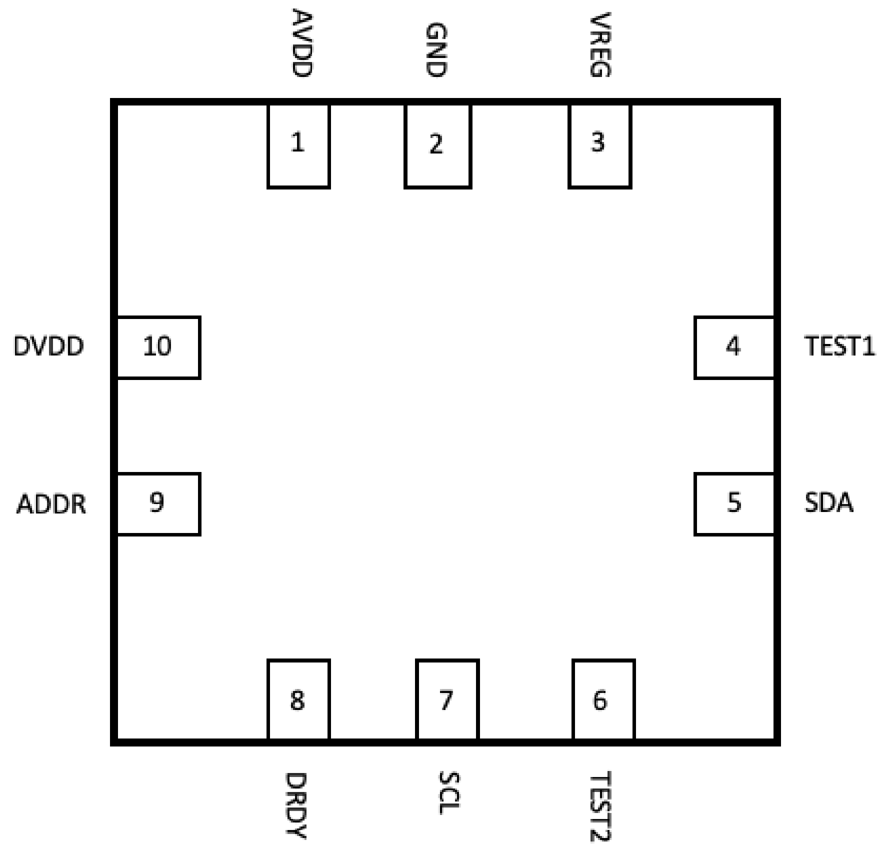

Figure 83: Part 1002 (3-Axis Digital Magnetometer IC) Pinout Diagram

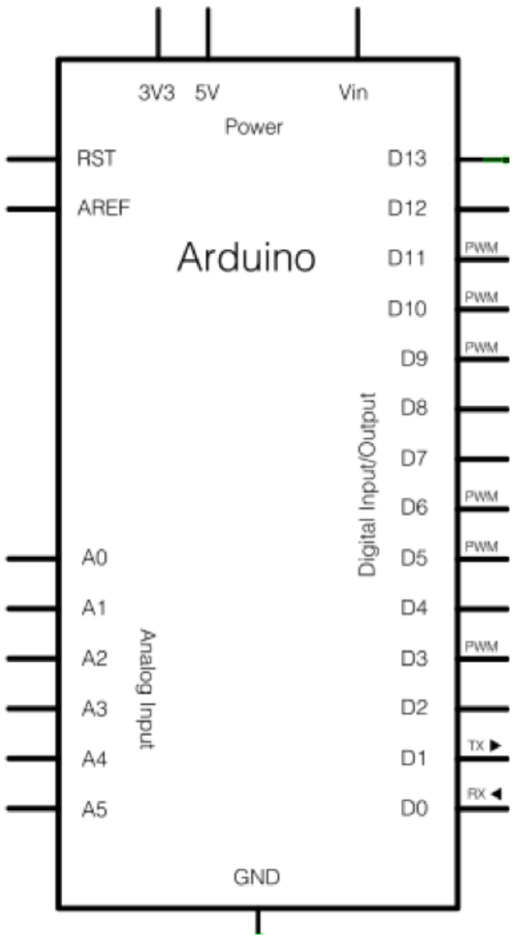

Figure 84: Part 1003 (Arduino Mega 2560 Rev3) Pinout Diagram

3.7. Printed Circuit Board Layouts for Prototype

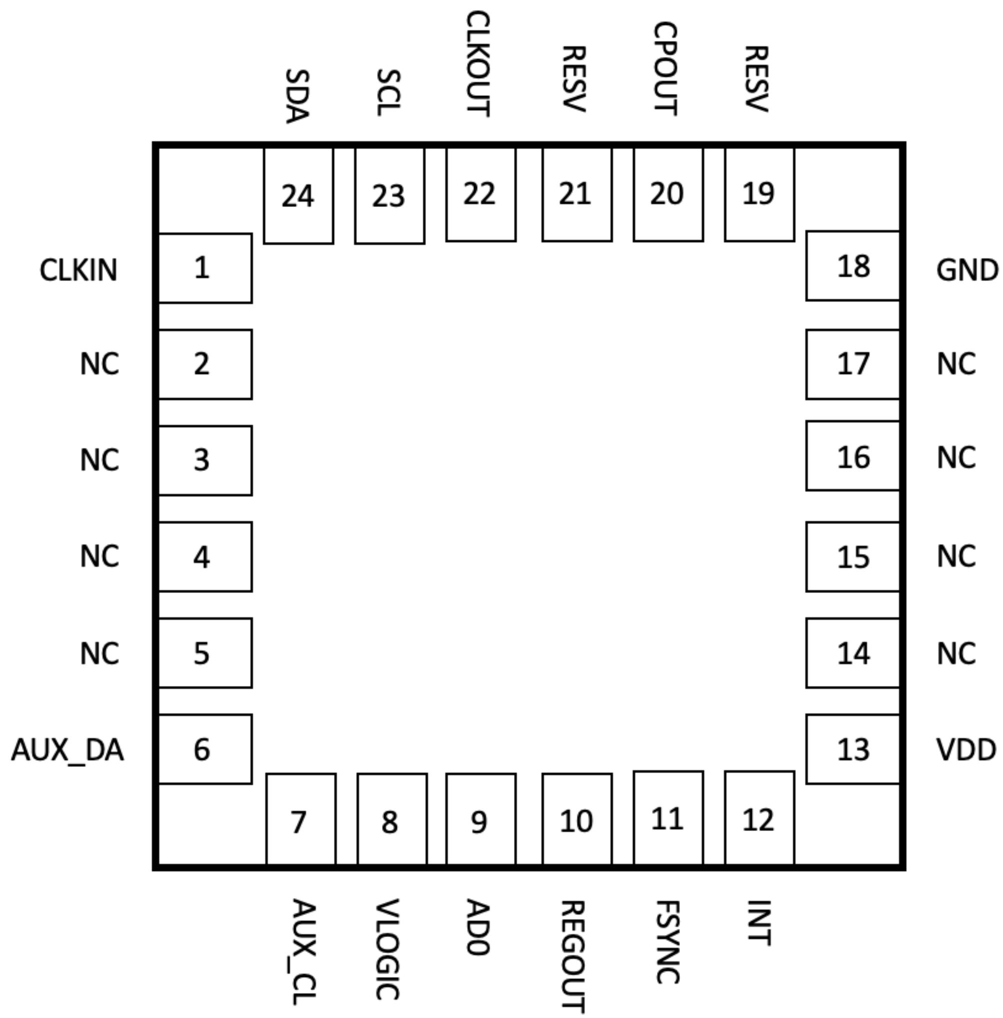

Figure 85: Sub-Component of Part 1008 (MPU 6050 Gyroscope and Accelerometer Board) Pinout Diagram

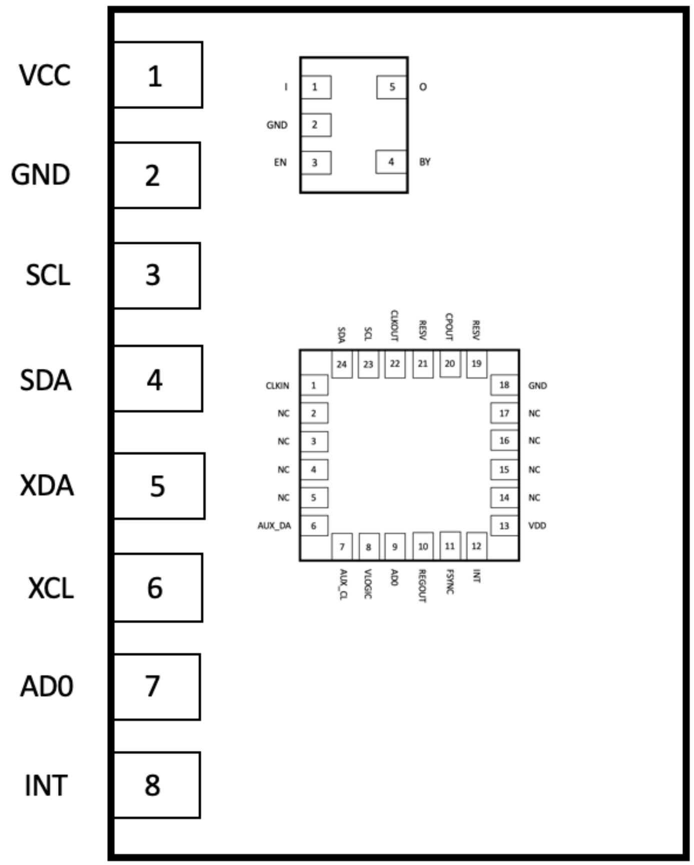

Figure 86: Part 1008 (MPU 6050 Gyroscope and Accelerometer Board) Pinout Diagram

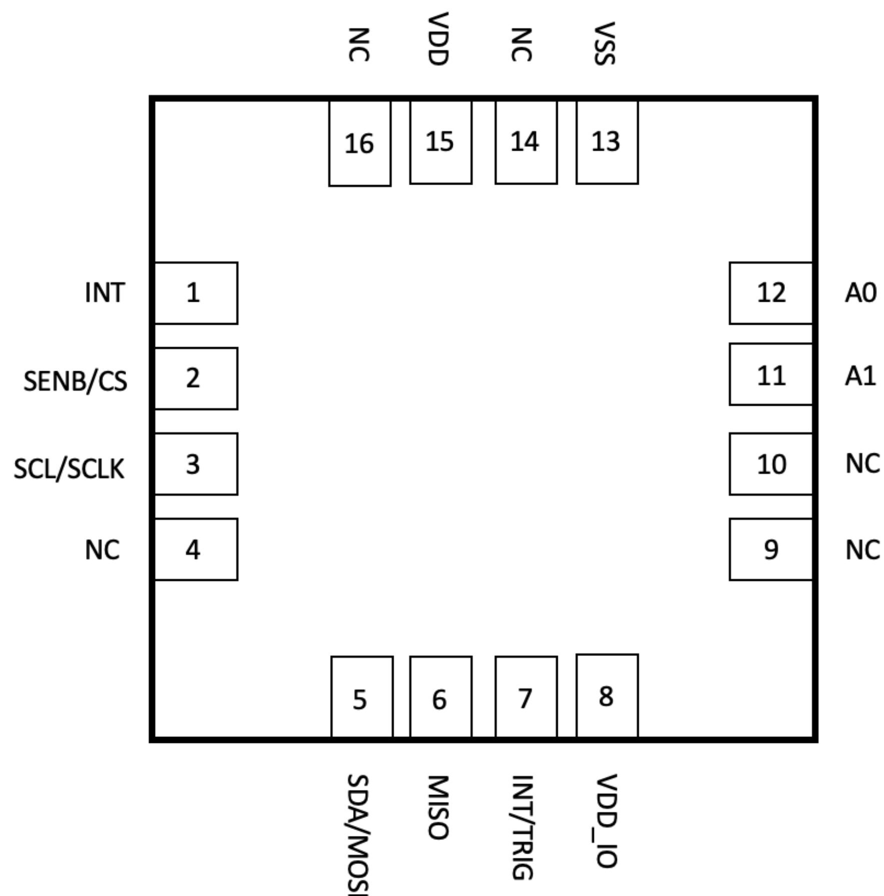

Figure 87: Sub-Component of Part 1030 (Magnetic Magnetometer Sensor Evaluation Board) Pinout Diagram

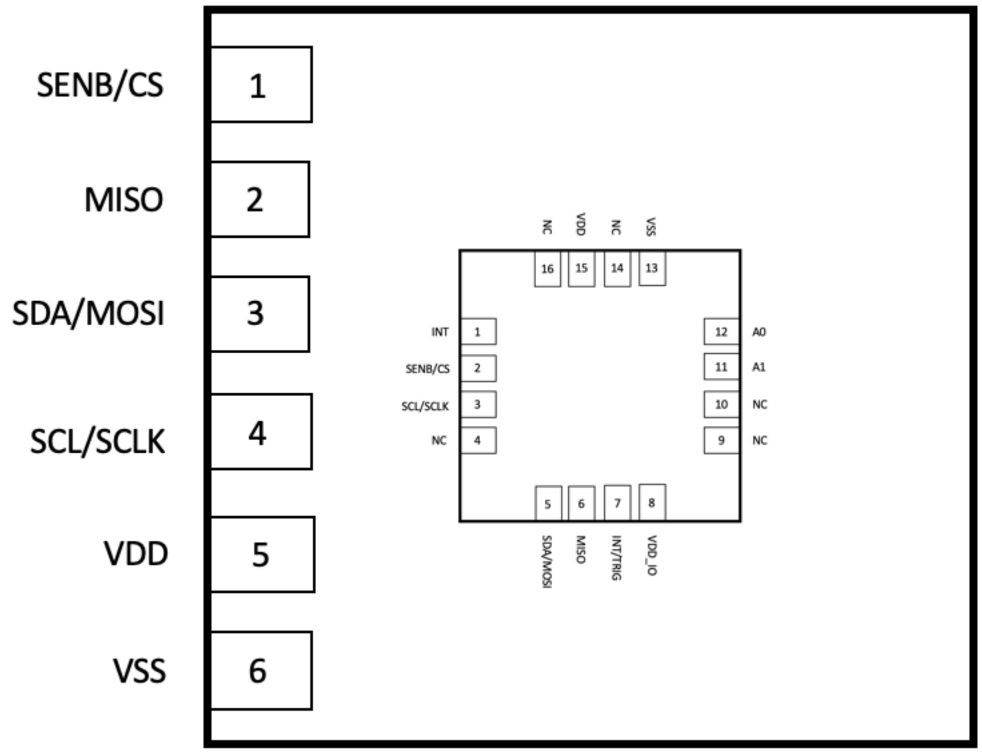

Figure 88: Part 1030 (Magnetic Magnetometer Sensor Evaluation Board) Pinout Diagram

3.8. ADCS Design Assembly Instructions

1. Take Part 1001 (Precision Navigation and Pointing Gyroscope) and using the appropriate length of Part 1005 (High Performance Wire and Cable), connect the pins of Part 1001 (Precision Navigation and Pointing Gyroscope) to the pins of Part 1003 (Arduino Mega 2560 Rev3).
    a. Connect Pin 2 (Part 1001) to Pin D5 (Part 1003).
    b. Connect Pin 4 (Part 1001) to Pin D3 (Part 1003).
    c. Connect Pin 6 (Part 1001) to GND (Part 1003).
    d. Connect Pin 7 (Part 1001) to Pin A5 (Part 1003).
    e. Connect Pin 10 (Part 1001) to Pin D0 (Part 1003).
    f. Connect Pin 11 (Part 1001) to GND (Part 1003).
    g. Connect Pin 13 (Part 1001) to 5V (Part 1003).
    h. Connect Pin 14 (Part 1001) to 5V (Part 1003).

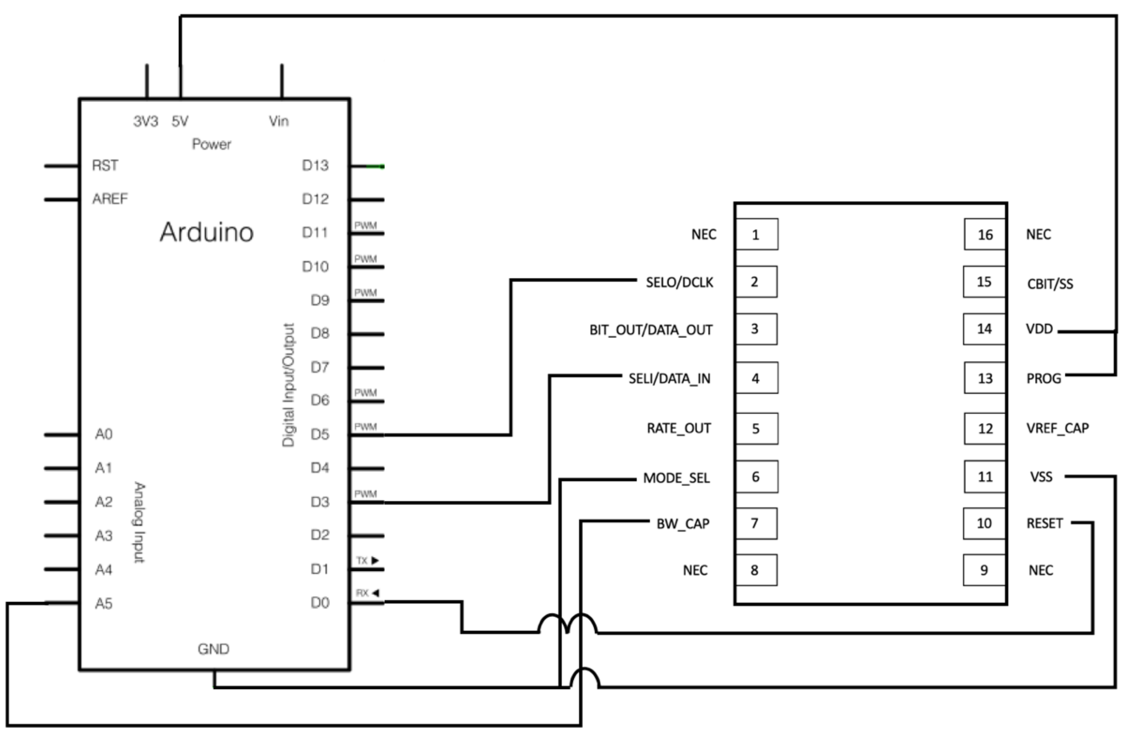

Figure 89: Pinout Diagram Connection for Part 1001 and Part 1003

2. Take Part 1002 (3-Axis Digital Magnetometer IC) and using the appropriate length of Part 1005 (High Performance Wire and Cable), connect the pins of Part 1002 (3-Axis Digital Magnetometer IC) to the pins of Part 1003 (Arduino Mega 2560 Rev3).
    a. Connect Pin 1 (Part 1002) to 5V (Part 1003).
    b. Connect Pin 2 (Part 1002) to GND (Part 1003).
    c. Connect Pin 5 (Part 1002) to Pin A4 (Part 1003).
    d. Connect Pin 7 (Part 1002) to Pin A3 (Part 1003).

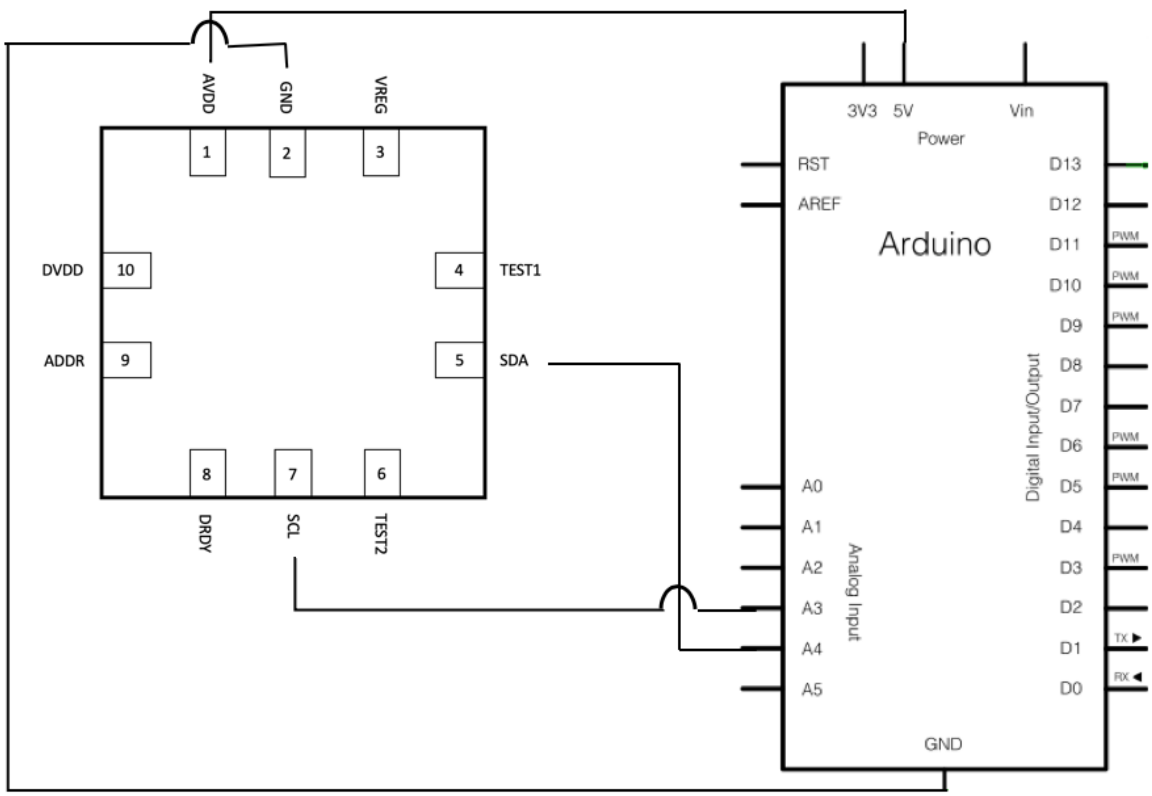

Figure 90: Pinout Diagram Connection for Part 1002 and Part 1003

3. Connect each of the six sun sensors, Part 1000 (NSS Fine Sun Sensor), to Part 1003 (Arduino Mega 2560 Rev3) using the six units of Part 1006 (Space Micro-D Connectors).

4. Mount Part 1003 (Arduino Mega 2560 Rev3) in the middle of the CubeSat using eight units of Part 1007 (M2-0.4x6 mm Phillips Pan-Head Machine Screws) until secure.

5. Mount each sun sensors, Part 1000, on each outer face of the CubeSat with Part 1007 (M2-0.4x6 mm Phillips Pan-Head Machine Screws). Each sun sensor requires three screws.

6. Connect Part 1004 (Magnetorquer Rod) to Part 1003 by soldering the wires directly to Pins 5V and GND found on Part 1003.

7. Orient each of the three units of Part 1004 perpendicular to each axis and tie them directly to Part 1003.

8. Upload the file named ADCS.ino to the Arduino using a USB connector.

3.9. Prototype Assembly Instructions

1. Attach each unit of Part 1016 (Standard Motor 12850 rpm 12VDC) to Part 1029) as shown in Figures 91 and 92.

    a. Pin In1 and In2 of one unit of Part 1029 connected to Pins 13 and 12 of one unit of Part 1016.
    b. Pin In1 and In2 of second unit of Part 1029 connected to Pins 11 and 10 of second unit of Part 1016.
    c. Pin In1 and In2 of third unit of Part 1029 connected to Pins 9 and 8 of third unit of Part 1016.

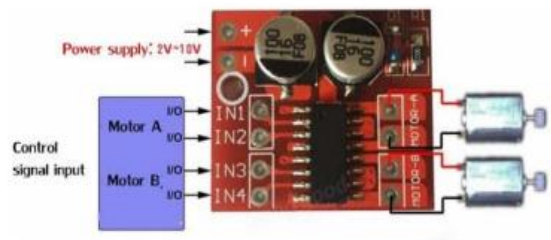

Figure 91: Part 1016 (Standard Motor) to Part 1029 Connection

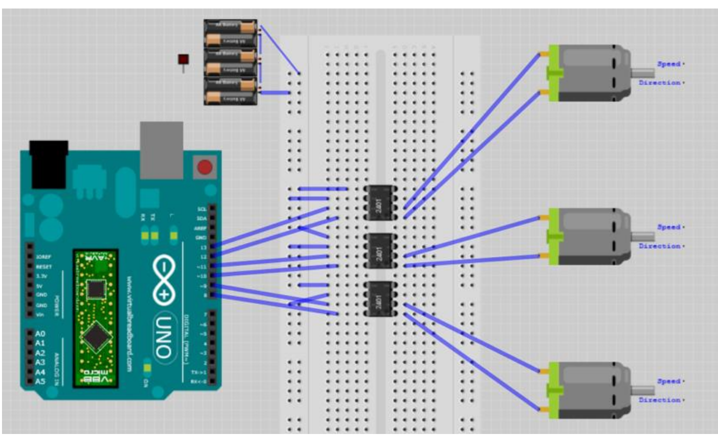

Figure 92: Part 1016 (Standard Motor) Units Interfacing with Part 1029 (Motor Driver) and Part 1009 (MSEduino)

2. Connect the six units of Part 1010 (Energizer MAX AA Batteries) in series to provide power for Part 1016 (Standard Motor 12850 rpm 12VDC).

3. Connect Part 1008 (MPU 6050 Gyroscope and Accelerometer Board) to Part 1009 (MSEduino) as shown in Figure 93 below.
    a. Connect Pin 1 of Part 1008 to 5V of Part 1009.
    b. Connect Pin 2 of Part 1008 to GND of Part 1009.
    c. Connect Pin 3 of Part 1008 to Pin A5 of Part 1009.
    d. Connect Pin 4 of Part 1008 to Pin A4 of Part 1009.
    e. Connect Pin 8 of Part 1008 to Pin D2 of Part 1009.

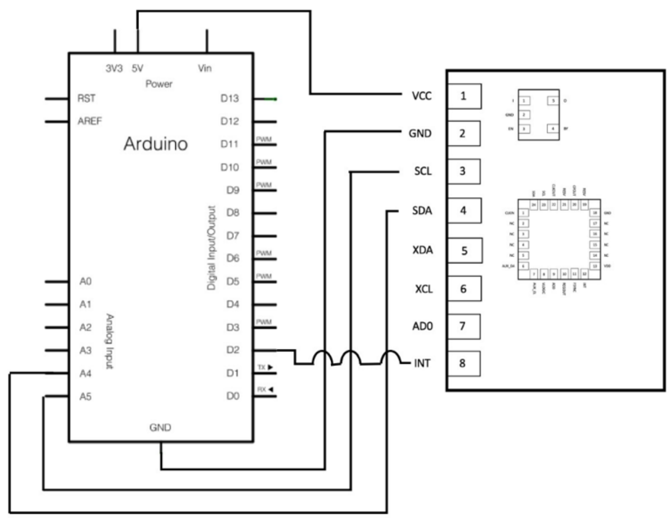

Figure 93: Pinout Diagram Connection for Part 1008 (*MPU 6050 Gyroscope and Accelerometer Board*) and Part 1009 (MSEduino)

4. Connect Part 1030 (Magnetic Magnetometer Sensor Evaluation Board) to Part 1009 (MSEduino) as shown in Figure 94 below.
    a. Connect Pin 1 of Part 1030 to 5V of Part 1009.
    b. Connect Pin 2 of Part 1030 to GND of Part 1009.
    c. Connect Pin 5 of Part 1030 to Pin A2 of Part 1009.
    d. Connect Pin 7 of Part 1030 to Pin A3 of Part 1009.

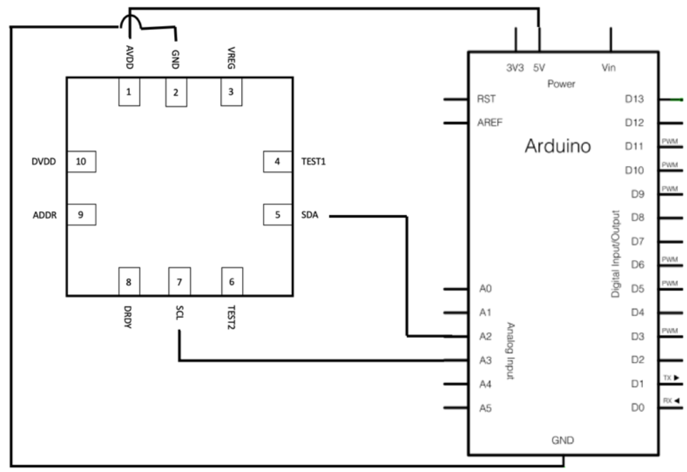

Figure 94: Pinout Diagram Connection for Part 1030 (Magnetic Magnetometer Sensor Evaluation Board) and Part 1009 (MSEduino)

5. Attach Part 1012 (1' Black Delrin ® Acetal Resin Rod 1-1/2" Diameter) to Part 1020 (Wooden Board) using Part 1018 (Black-Oxide Alloy Steel Hex Drive Flat Head Screw 1"-8 Thread Size 2-1/2" Long).

6. Attach Part 1014 (Acrylic sheet) to the levelled part of Part 1013 (Highly Corrosion-Resistant Stainless Steel Ball 1" Diameter) using Part 1019 (Black-Oxide Alloy Steel Hex Drive Flat Head Screw ¼"-20 Thread Size, ½" Long).

7. Place Part 1013 (Highly Corrosion-Resistant Stainless Steel Ball 1" Diameter) in the bowl at the top of Part 1012 (1' Black Delrin ® Acetal Resin Rod 1-1/2" Diameter) with the levelled part facing upward.

8. Attach Part 1025 (Push-to-Connect Tube Fitting for Air with Shut-Off, Adapter, for ¼" Tube OD, ¼ NPT Male) to Part 1012 (1' Black Delrin ® Acetal Resin Rod 1-1/2" Diameter) at the air inlet.

9. Attach one end each of the two Part 1023 (Straight Adapter, for ¼” Tube OD x 1/8 NPT Male) to Part 1025 (Push-to-Connect Tube Fitting for Air with Shut-Off, Adapter, for ¼” Tube OD, ¼ NPT Male).
10. Attach one of free ends of Part 1023 (Straight Adapter, for ¼” Tube OD x 1/8 NPT Male) to Part 1021 (Push-to-Connect Tube Fitting for Air) at the air inlet of Part 1012 (1’ Black Delrin ® Acetal Resin Rod 1-1/2” Diameter).
11. Attach the other free end of the second Part 1023 (Straight Adapter, for ¼” Tube OD x 1/8 NPT Male) to Part 1024 (Industrial-Shape Hose Coupling Size ¼, Zinc-Plated Steel Ply, ¼ NPTF Male End).
12. Apply Part 1026 (PTFE Tape) to all areas where Part 1023 (Straight Adapter, for ¼” Tube OD x 1/8 NPT Male) is connected to Part 1024 (Industrial-Shape Hose Coupling Size ¼, Zinc-Plated Steel Ply, ¼ NPTF Male End) to ensure no air will escape.
13. Attach the floating Part 1025 (Push-to-Connect Tube Fitting for Air with Shut-Off, Adapter, for ¼” Tube OD, ¼ NPT Male) to both units of Part 1022 (Reducing Adapter, 1/8 NPT Female x 1/16 NPT Male).
14. Attach both units of Part 1022 (Reducing Adapter, 1/8 NPT Female x 1/16 NPT Male) to Part 1017 (Panel-Mount Compressed Air Regulator).
15. Attach Part 1024 (Industrial-Shape Hose Coupling Size ¼, Zinc-Plated Steel Ply, ¼ NPTF Male End) to an air supply.

3.10. Program Flow Charts for Arduino Code

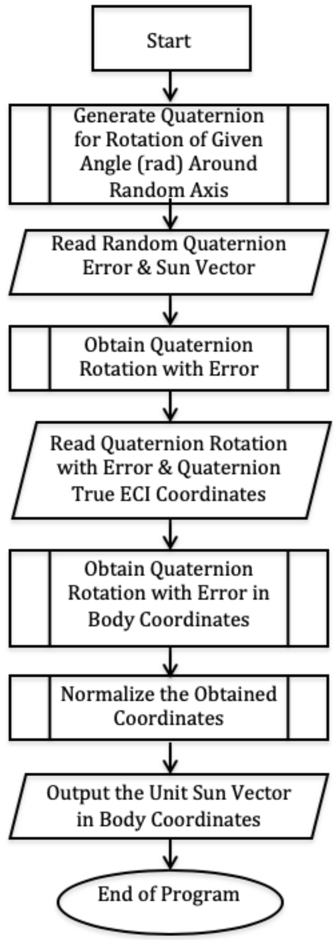

Figure 95: Flowchart for Sun Sensor

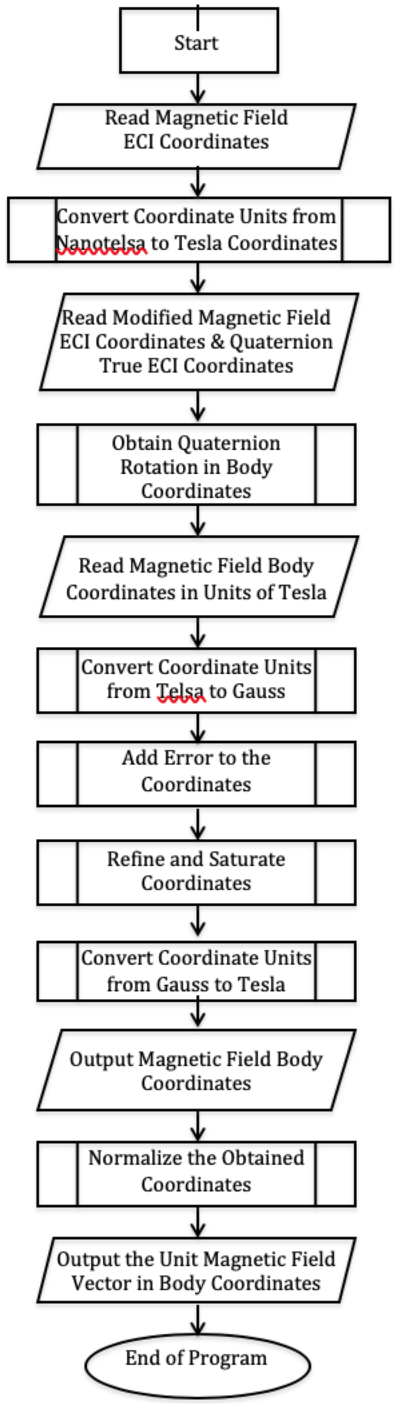

Figure 96: Flowchart for Magnetometer

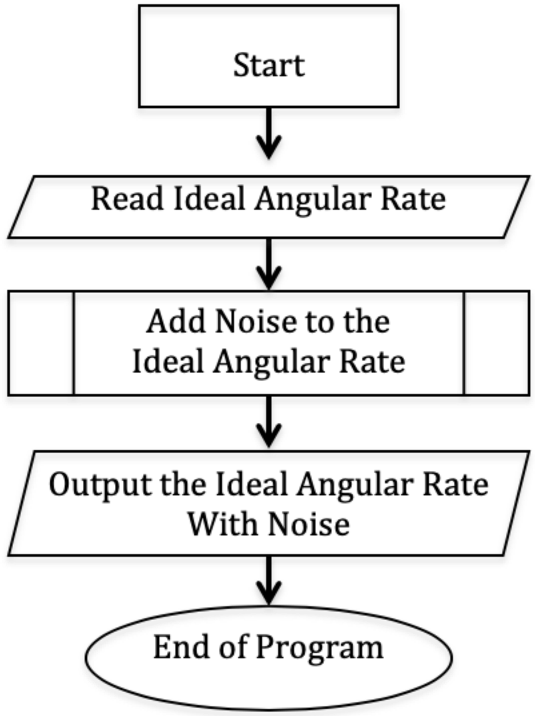

Figure 97: Flowchart for Gyroscope

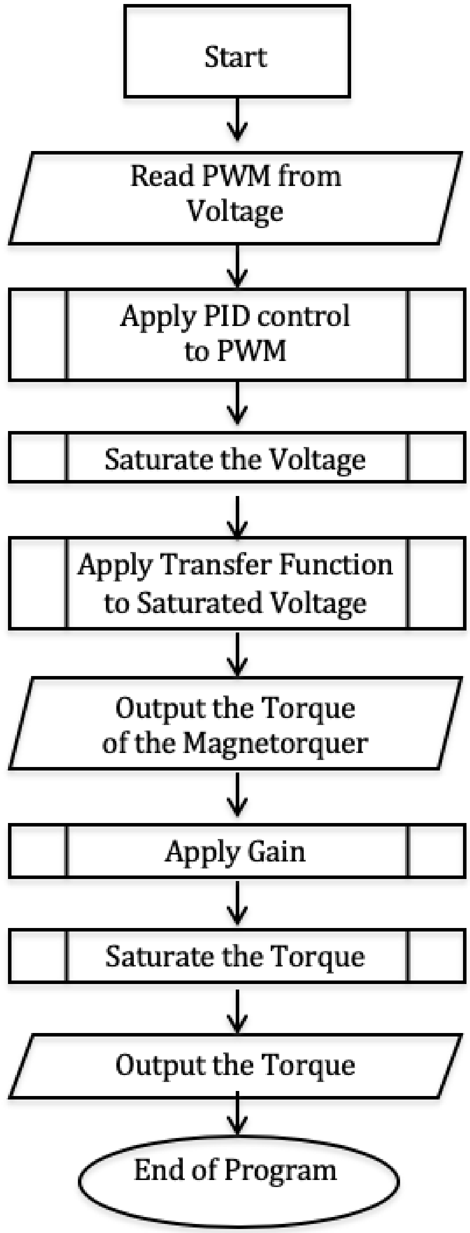

Figure 98: Flowchart for Magnetorquer

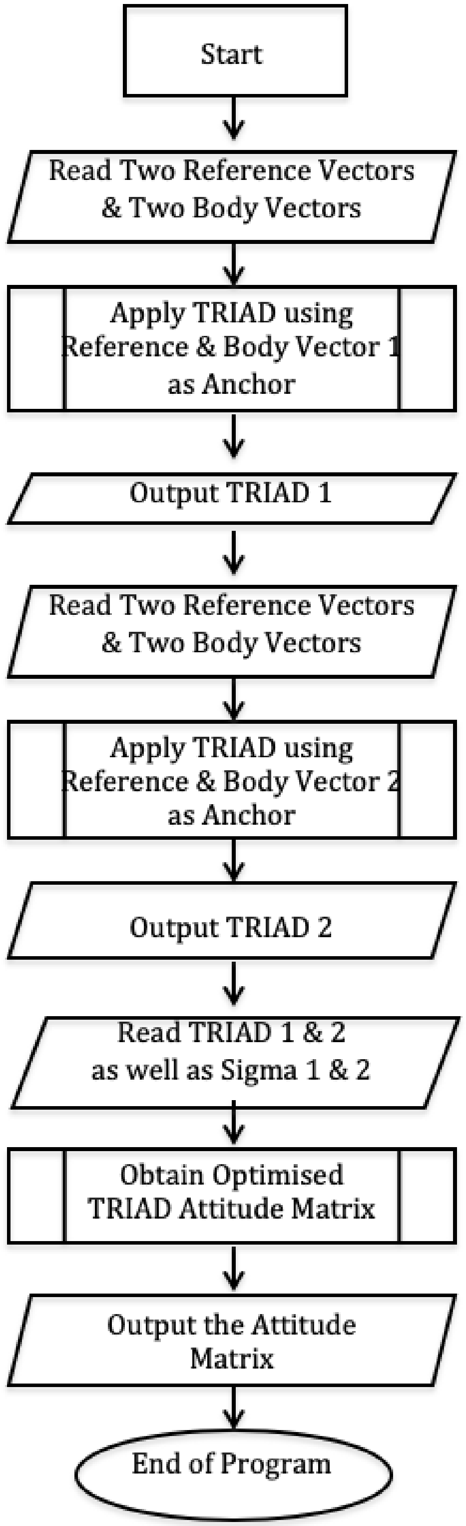

Figure 99: Flowchart for TRIAD

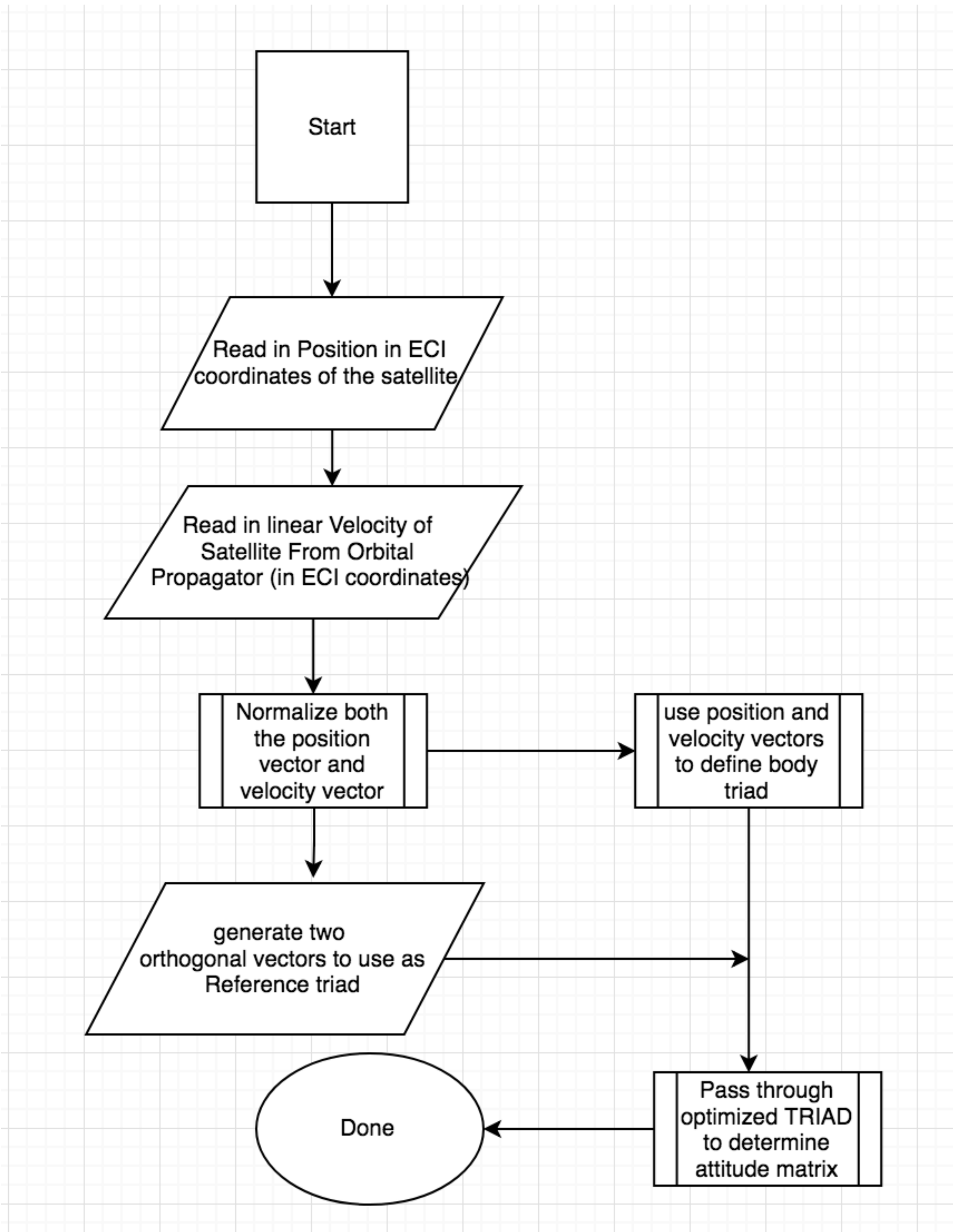

Figure 100: Flowchart for Attitude Propagator

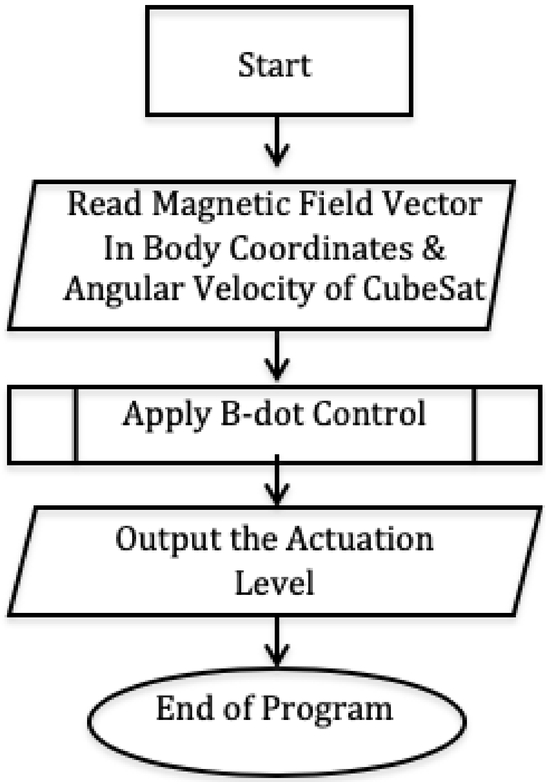

Figure 101: Flowchart for Control Law

3.11. Bill of Materials

Part Number	Name	Description	Supplier	Supplier Part	Order Quantity	Unit Price	Lead Time
1000 [5]	NSS Fine Sun Sensor	Sun sensor	New Space Systems	NCSS-SA05	6	$3,300.00	4 weeks
1001 [6]	Precision Navigation and Pointing Gyroscope	Gyroscope	Silicon Sensing	CRM200	2	$20.00	10 weeks
1002 [7]	3-Axis Digital Magnetometer IC	Three-axis magnetometer	ROHM Semiconductor	BM1422AGMV	2	$8.00	5 weeks
1003 [8]	Arduino Mega 2560 Rev3	Microprocessor	Arduino	A000067	1	$38.50	1 week
1004 [9]	Magnetorquer Rod	Magnetorquer	New Space Systems	NCTR-M002	4	$1,200.00	4 weeks
1005 [10]	High Performance Wire and Cable	Space-grade wires	TE Connectivity	55	1	$42.90	6 weeks
1006 [11]	Space Micro-D Connectors	Nano-D female connectors	Axon Cable	AWG28	6	$12.34	8 weeks
1007 [12]	M2-0.4x6 mm Phillips Pan-Head Machine Screws	M2 threaded screws	Crown Bolt	11828	30	$0.46	1 week
Total for ADCS: $24,825.24							
1008[P] [13]	MPU 6050 Gyroscope and Accelerometer Board	Three-axis gyroscope	Sunfounder	ARD001	1	$10.23	1 week

1009[P] [14]	MSEduino	Microprocessor	Arduino	A000067	1	$38.50	1 week
1010[P] [15]	Energizer MAX AA Batteries	Battery	Energizer	E92BP4	6	$1.36	1 week
1011[P] [16]	Wire Wrap	Wires	Adafruit Industries LLC	1446	1	$10.64	1 week
1012[P] [17]	1’ Black Delrin ® Acetal Resin Rod 1-1/2” Diameter	Resin rod	McMaster-Carr	8497K313	1	$5.13	1 week
1013[P] [18]	Highly Corrosion-Resistant Stainless Steel Ball 1” Diameter	Stainless steel ball	McMaster-Carr	96415K82	1	$19.43	1 week
1014[P] [19]	Acrylic sheet	Acrylic sheet	Plaskolite	1X09241A	1	$3.28	1 week
1015[P] [20]	Crack-Resist Polypropylene Semi-Clear Tubing	Clear tubing	McMaster-Carr	1979T2	1	$7.50	1 week
1016[P] [21]	Standard Motor 12850 RPM 12VDC	Motor	NMB Technologies Corporation	PAN14EE12AA1	3	$21.12	14 weeks
1017[P] [22]	Panel-Mount Compressed Air Regulator	Air regulator	McMaster-Carr	41795K3	1	$52.22	1 week
1018[P] [23]	Black-Oxide Alloy Steel Hex Drive Flat	Flat head screw (1”-8 thread size, 2-1/2” long)	McMaster-Carr	91253A914	1	$15.21	1 week

	Head Screw 1”-8 Thread Size 2-1/2” Long						
1019P [24]	Black-Oxide Alloy Steel Hex Drive Flat Head Screw ¼”-20 Thread Size, ½” Long	Flat head screw (1/4”-20 thread size, 1/2” long)	McMaster-Carr	91253A537	1	$0.22	1 week
1020P [25]	Wooden board	Wooden board	Irving	228288	1	$12.98	1 week
1021P [26]	Push-to-Connect Tube Fitting for Air	Tube fitting to air	McMaster-Carr	5779K131	1	$5.85	1 week
1022P [27]	Reducing Adapter, 1/8 NPT Female x 1/16 NPT Male	Reducing adapter	McMaster-Carr	2684K21	2	$9.93	1 week
1023P [28]	Straight Adapter, for ¼” Tube OD x 1/8 NPT Male	Straight adapter	McMaster-Carr	5779K108	2	$3.16	1 week
1024P [29]	Industrial-Shape Hose Coupling Size ¼, Zinc-Plated Steel Ply, ¼ NPTF Male End	Industrial-shape hose	McMaster-Carr	6534K46	1	$1.18	1 week
1025P [30]	Push-to-Connect Tube	Tube fitting for air with shut-off adapter	McMaster-Carr	5779K417	1	$15.53	1 week

	Fitting for Air with Shut-Off, Adapter, for ¼” Tube OD, ¼ NPT Male						
1026P [31]	PTFE Tape	PTFE tape	Dixon Valve & Coupling	TTB75	1	$0.05	1 week
1027P [32]	18.9L Max 125 PSI Portable Air Tank	Air Compressor	Speedway	7296	1	$68.95	1 week
1028P [33]	Low-Carbon Steel Disc	Reaction Wheels	McMaster-Carr	7786T12	3	$10.32	2 weeks
1029P [34]	1.5A 2-Way MX1508 DC Motor Driver Module, PWM Speed control	Motor Driver	HobbyTronics	MOT-01940	3	$0.47	3 weeks
1030P [35]	Magnetic Magnetometer Sensor Evaluation Board	Three-Axis Magnetometer	Melexis	MLX90393	1	$29.77	1 week
Total for ADCS Prototype: $356.19							

Table 2: Bill of Materials

4. Prototype Feasibility

4.1. Description of Prototype

The prototype will be used to demonstrate the effectiveness of our ADCS design. The prototype will show the actuation capabilities of the ADCS. The prototype will consist of a gyroscope and magnetometer that will act as sensors, the MSEduino, which will be the microprocessor board holding the determination algorithm and control law, and three reaction wheels that will act as our actuators. The testbed will allow the ADCS to orient itself in three-axes with very little resistance, similar to the conditions the ADCS will experience in space.

4.2. Rationale for Prototype

Due to the limited budget currently available for the Western CubeSat project, the prototype will not include flight-level hardware such as magnetorquers or sun sensors. Each unit of these components individually cost over $1000 each. To combat this issue, the model of the magnetorquer was used in conjunction with the model of the satellite's orbital path to determine the effective dipole moment that the magnetorquer would be able to generate at any point during its orbit. With this knowledge, a less expensive non-flight certified reaction wheel will be used on the prototype to provide the same dipole moment that would be provided by the magnetorquer as determined through simulations in MATLAB. Although this is not ideal, the integrity of the prototype test results will be preserved and the prototype will still be able to effectively demonstrate the feasibility of the control law and the resultant actuation.

In addition, since sun sensors cannot be purchased, there will be no second vector input reading for the system. Although there are still two sensors being used for the prototype, a magnetometer and a gyroscope, only the magnetometer will provide an input vector of the Earth's magnetic field. The gyroscope is normally used to integrate a vector over a limited time period; a vector in which would have been provided by the sun sensor. For the purposes of the prototype, the gyroscope will be given the initial frame of the ADCS, and then integrate and update the position of the ADCS. These two vectors will then be used as inputs for the ADCS, go through our control law and allow for the actuation of the reaction wheels. Mechanically, the prototype will consist of the magnetometer, gyroscope and three reaction wheels. These will all be connected to the microprocessor board, the MSEduino, and all mounted on a structure representative of the true size of the weight of the CubeSat.

4.3. Cost Analysis of Prototype

Item	**Cost**
Engineering Hours ($80/hr)	$76,800.00
MATLAB Education License [36]	$665.14
Fundamentals of Spacecraft ADCS Textbook [37]	$107.00
Materials and Components	$356.19
Laser Cutter [38]	$15.00
Air Compressor [39]	$68.95
University Machine Services Fees ($64.35/hr) [40]	$128.70
Simulink Education License [36]	$665.14
	Total $78,806.12

Table 3: CubeSat ADCS Prototype Budget

Part Number	Name	Order Status	Order Quantity	Unit Price
1008^{P}	MPU 6050 Gyroscope and Accelerometer Board	Received	1	$10.23
1009^{P}	MSEduino	Received	1	$38.50
1010^{P}	Energizer MAX AA Batteries	Received	6	$1.36
1011^{P}	Wire Wrap	Received	1	$10.64
1012^{P}	1’ Black Delrin ® Acetal Resin Rod 1-1/2” Diameter	Received	1	$5.13
1013^{P}	Highly Corrosion-Resistant Stainless Steel Ball 1” Diameter	Received	1	$19.43
1014^{P}	Acrylic sheet	Received	1	$3.28
1015^{P}	Crack-Resist Polypropylene Semi-Clear Tubing	Received	1	$7.50
1016^{P}	Standard Motor 12850 RPM 12VDC	Received	3	$21.12
1017^{P}	Panel-Mount Compressed Air Regulator	Received	1	$52.22
1018^{P}	Black-Oxide Alloy Steel Hex Drive Flat Head Screw 1”-8 Thread Size 2-1/2” Long	Received	1	$15.21
1019^{P}	Black-Oxide Alloy Steel Hex Drive Flat Head Screw ¼”-20 Thread Size, ½” Long	Received	1	$0.22
1020^{P}	Wooden board	Received	1	$12.98
1021^{P}	Push-to-Connect Tube Fitting for Air	Received	1	$5.85
1022^{P}	Reducing Adapter, 1/8 NPT Female x 1/16 NPT Male	Received	2	$9.93
1023^{P}	Straight Adapter, for ¼” Tube OD x 1/8 NPT Male	Received	2	$3.16
1024^{P}	Industrial-Shape Hose Coupling Size ¼, Zinc-Plated Steel Ply, ¼ NPTF Male End	Received	1	$1.18
1025^{P}	Push-to-Connect Tube Fitting for Air with Shut-Off, Adapter, for ¼” Tube OD, ¼ NPT Male	Received	1	$15.53
1026^{P}	PTFE Tape	Received	1	$0.05
1027^{P}	18.9L Max 125 PSI Portable Air Tank	Received	1	$68.95
1028^{P}	Low-Carbon Steel Disc	Received	3	$10.32
1029^{P}	1.5A 2-Way MX1508 DC Motor Driver Module, PWM Speed control	Received	3	$0.47
1030^{P}	Magnetic Magnetometer Sensor Evaluation Board	Received	1	$29.77
				Total: $356.19

Table 4: CubeSat ADCS Real-Cost Budget

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