1.0 Introduction

This document outlines the development of a robotics cinematography assistance tool catered towards beginner filmmakers who are looking to improve their cinematic, moving-camera shots at a low cost [1]. Current entry-level cinematography-oriented robot arm designs tend to average around $30 000 USD [Appendix A], with higher end arms exceeding $70 000 USD, being an order of magnitude out of budget for beginners who spend, at most, thousands on filling out their cinematography kit [2][3].

This document investigates the specific scoping and requirements of this market gap, as well as the ideation and selection of designs. Specifically, this report presents, using Solidworks CAD [4], and evaluates three alternative concepts: the Scissor Lift Cart, Tracked Cart, and Linear Track designs, on their ability to meet the engineering specifications, and their respective tradeoffs.

2.0 Problem Statement

The design project addresses the need for a low cost and long reach camera mount for cinematography, specifically for beginner cinematographers and advanced hobbyists. Specifically, the framings, angles, and camera movements must tailor to the needs of the intended audience as the associated motion should be smooth and easily repeatable.

The design scope involves the entirety of a machine that will be used to assist in cinematography in locations including but not limited to the University of Toronto King's College Circle, in the Myhal Arena, and in an enclosed studio room. The influence of codes such as the Canadian Electrical Code (CEC), and the limits of modern manufacturing also generally constrain the design space. Furthermore, the design should easily integrate with any equipment the basic intended user may already possess.

3.0 Stakeholders

This section highlights the key stakeholders and their roles in this project. The stakeholders in this project mainly revolve around external organizations, and the target intended users of the product, both displayed below in Table 1 and Table 2.

Table 1. Focus external stakeholders for this design.

Priority	Stakeholder	Interest/Influence
1	Government of Canada	• Canadian Electrical Code (CEC) [5] • Canadian Safety Regulations

2	Third-Party Manufacturers	• Manufacturing robot arm components
		  ○ 3D printing
		  ○ CNC Machining
		  ○ Welding
		  ○ More as needed

Table 2. Focus intended users for this design, ranked by priority from top to bottom.

Priority	Intended User	Interest/Influence	Camera Zooms & Shots [Appendix B.1]
1	Beginner Professional	Owns multiple cameras Experience in cinematography Contracting work Outdoors and indoors work	Extreme wide shot, full shot, medium shot, close-ups Over-the-shoulder/POV shots (rotation) High/low angle shots (linear, vertical) Tracking/Dolly shots (linear, horizontal) Pan (yaw movement, left/right) Tilt (pitch movement, up/down)
2	Advanced Hobbyist	Owns few cameras Limited experience in cinematography Indoors work	Medium shot, full shot, close-ups Over-the-shoulder/POV shots (rotation) High/low angle shots (linear, vertical) Pan (yaw movement, left/right) Tilt (pitch movement, up/down)
3	Beginner cinematographer	Owns a camera Limited cinematography experience Outdoor work	Extreme wide shot, full shot, medium shot High/low angle shots (linear, vertical) Pan (yaw movement, left/right) Tilt (pitch movement, up/down)

4.0 Service Environment

As defined above, the intended users of our product consist of individuals who have experience with and own at least one beginner to intermediate camera. As such, the payload specification was built around the mass of these beginner cameras and associated lenses.

Through research of online sources that one may take advice from when searching to purchase a starter camera, beginner equipment totals to about 5 kg in payload mass, accounting for a 2.5 safety factor [Appendix B.2, Table B.2.1]. This allocation accounts for the camera, lens, and potentially a larger zoom focused lens.

Table 3. Typical conditions of common service locations [Appendix B.3]

Parameters:	Outdoors (King's College Circle)	Open Indoors (Myhal Arena)	Enclosed Indoors (Studio Room)
Exposure	Fully Outdoors	Indoor, Large Volume:	Indoor, Small Volume:

	• Rain • Water splashes • Dust • Human Traffic • Mud/grass	• Dust from foot traffic • Water from janitorial activities • HVAC airflow • Spectator noise	• Minimal dust • No water • Controlled lighting • Conversational noise • Controlled HVAC
Recommended IP	IP66 - IP67	IP64 - IP66	IP60 - IP64
Wind Considerations	12.0 km/h - 21.0 km/h [10]	Negligible air speeds Note: Winds from doors opening can cause temporary gusts	Negligible air speeds
Power Access	No available sources of power	Outlets on walls offer 120V	Outlets on walls offer 120V 3 outlets
Recommended Power Source	Battery Box or Portable Generator	Battery Box or Outlets	Outlets
Internet Access	No reliable WiFi Nearby Bell and Rogers cellular towers offer cellular data [11]	Reliable WiFi 6 Nearby Bell and Rogers cellular towers offer cellular data	Reliable WiFi 6 Nearby Bell and Rogers cellular towers offer cellular data
Ambient Temperature	-8°C - 25°C [12]	18°C - 25°C [13]	18°C - 25°C [13]

5.0 Engineering Specifications

This section outlines the major engineering specifications and requirements that our final design must meet. A concrete Requirements Traceability Matrix was also developed with all considered engineering specifications [Appendix B.4].

Table 4. Major engineering specifications, with evaluation details.

#	Engineering Specification	Impact
1*	Design shall support a payload of no less than 5 kg	High
2	Design shall not overheat	High

3*	Design shall have a sufficient IP rating	High
4	Design shall not have sharp edges/parts poking out	High
5*	Design shall be stable	High
6	Design shall be operable by one operator	High
7	Design shall be able to reach within the range of its work envelope easily	Medium
8	Design shall be able to move relative to surroundings at speeds of no more than X m/s	Medium
9	Design shall have a minimum clearance of 0.01 m from the ground (if wheeled)	Medium
10	Design shall offer modularity with a standard camera	Medium
11*	Design shall have sufficient degrees of freedom (DoF)	Low
12*	Design shall move in both linear and circular rotational ways (pan, tilt)	Low
13	Design shall be able to move the payload at a max speed no less than X m/s	Low
14*	Design shall be able to do a horizontal and vertical 180 degrees in X s in any configuration	Low
15	Design shall have repeatability up to X meters	Low
16	Design shall be wired with minimum 7+ m cord length to a standard NA 120V outlet if wired	Low
17	Must be 3D printable or Low-cost CNC	Low
18	Design shall be open-source	Low
19*	Design shall be affordable for intended users	Low

* Major Engineering Specifications.

For each engineering specification, its respective impact on the overall design was ranked on a low, medium, high scale, where low impact referred to no safety or operational risk, medium impact referred to minimal safety and operational risk, and high impact referred to a present safety and operational risk. Please refer to Appendix B.4 for information on validation methods and acceptance criteria for each specification.

6.0 Generation, Selection, Description of Alternative Designs

This section outlines idea generation, selection, and details of the alternative designs.

6.1 Idea Generation

With a fully realized set of engineering specifications, eight unique full designs were conceptualized, using a Morph chart to organize DoF functions and describing how each design fulfills the major engineering specifications and creating designs by linking these methodologies together [Appendix C.1].

These designs were constructed based on market research into current robotic cinematography aids [Appendix A], as well as intuition through the Minimal Viable Design method of thinking.

The ideas are designated A1, A2, J1, J2, M1, M2, L1, and L2, and upon evaluation, demonstrated some shared methods of tackling specifications, shown below in Table 5.

Table 8. Common themes from idea generation [Appendix B.4]

Specification (Shortened)	Common Ways of Solving
Linear and rotational Movement	Linear ● Wheels ● Tracks and V-slot wheels ● Telescoping/scissoring lifts Rotational ● High-torque gearbox ● Large motor size allocation
5kg Payload	● Gas springs ● Large bases ● Low centre of gravity
Reasonably affordable	● CNC aluminum ● 3D printed plastic parts ● Few custom parts ● Highly modular and accessible

6.2 Idea Selection

The eight conceptual ideas, after being thoroughly described by the Morph chart, were subject to a two step process to focus to a singular final design.

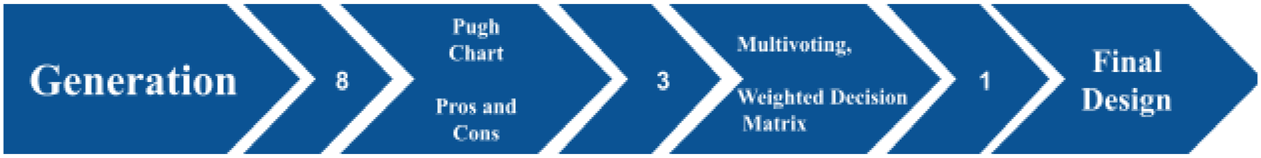

Figure 1. Idea generation and selection timeline

With eight full designs in the morph chart, advantages and tradeoffs of each DoF function were noted, and a Pugh Chart was constructed with design L1 as the datum, due to its similarity to most existing solutions [Appendix C.2]. From this process, three alternate designs were consolidated.

Upon expanding more on the alternative designs selected with more detailed and pragmatic-focused advantages and tradeoffs, as well as possible iterative solutions, multivoting between the four project members was conducted. Refer to section 6.3 Candidate Designs for details. Additionally, a Weighted Decision Matrix (WDM) was constructed with major engineering specifications and a specific rating system to further justify idea selection [Appendix C.3]. The two methods converged, and the chosen design was candidate design 3, the Linear Track design.

6.3 Candidate Design Descriptions

This section outlines the three candidate solutions, describing how each meets the major engineering specifications, as well as the general design philosophy and core mechanisms of each design.

It is worthwhile to also acknowledge the terminology used to describe rotational motion. Consistent with camera and videography, the rotational axes will be referred to as pitch, roll and yaw, visualized below in Figure 2.

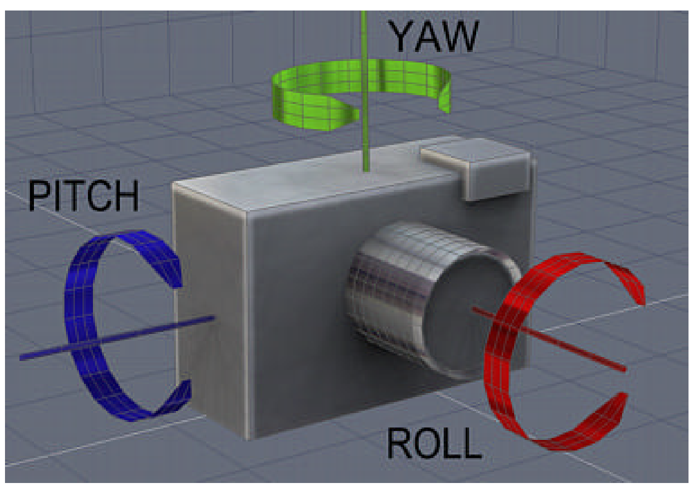

Figure 2. Pitch, roll and yaw of a camera, visualized [14]

6.3.1 Candidate 1 - Scissor Lift Cart Design

This design focuses on vertical linear motion for steady camera shots, with the option to move to different yaw angles, vertically up to about 1.5m, and pivot in pitch from the turret elbow joint, all supported by omni-wheels. The cart is powered by an integrated rechargeable battery, heat managed by front-facing vents.

This design has high horizontal freedom due to its omni wheels, but houses many scissor lift components, including hydraulics, which can cause significant maintenance concerns. The heavy-duty cart provides stability and a low centre of gravity (CoG), but can be troublesome to move vertically, as well as sometimes blocking the camera's line of sight. See Figure 2 below.

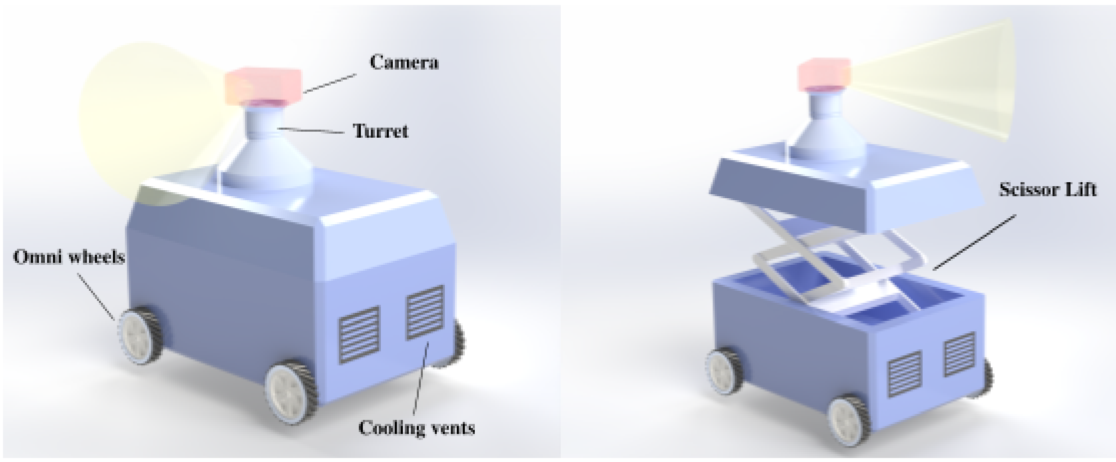

Figure 2. Scissor Lift Cart Design [4]

Key features of this design include omni wheels, cooling vents, a scissor lift, and an elbow-jointed turret on the camera mount. Table 9 below briefly summarizes how each major engineering specification is satisfied by this design. Table 10 outlines the construction of the joint configuration for this design.

Table 9. Functions of Design Satisfying Major Specifications

Major Specification	Specification-Enabling Features
Design shall be able to easily reach within the range of its work envelope	5 DoF - Scissor lift, omni-wheels, turret, and elbow joint allows the camera to capture the majority of its 3D surroundings
Design shall move in both linear and rotational ways (pan, tilt)	Linear ● Horizontal: Omni-wheels ● Vertical: Scissor Lift Rotational ● Yaw: Turret ● Pitch: Elbow Joint
Design shall be able to do a horizontal and vertical 180 degrees in X s in any configuration	Yaw/Horizontal

	● Turret is not working against any force and is free to move smoothly Pitch/Vertical ● Elbow joint is close to payload (minimal moment arm)
Design shall support a payload of no less than 5 kg	Load bearing mechanisms are mostly inline, thus being very stable and high load bearing.
Design shall have a minimum IP rating	Silicone Rubber Seals - Turret and elbow joints Hydraulics Systems - Generally watertight
Design shall be stable	Base mounted on omni wheels with weight distributed across all the wheels, with low CoG. The scissor lift distributes the weight into all the bushings and pins, maintaining good balance.

Table 10. Design Joint Configuration

DoF #	Features
1	Pneumatic Scissor Lift (Linear)
2	Turret (Yaw)
3	Elbow Join (Pitch)
4	Omni Wheels (Planar, Horizontal)
5	

6.3.2 Candidate 2 - Tracked Cart Design

With portability and modularity being the largest considerations in this design, the cart allows easy transportation for the system, with a battery box that allows for external charging.

Furthermore, the removable track allows for the arm to be used both grounded and elevated. Although the arm is capable of short linear shots, its rotational capabilities allow it to also do sweeping, tracking, rotational and complex shots, though limited by vertical reach. See Figure 3 below.

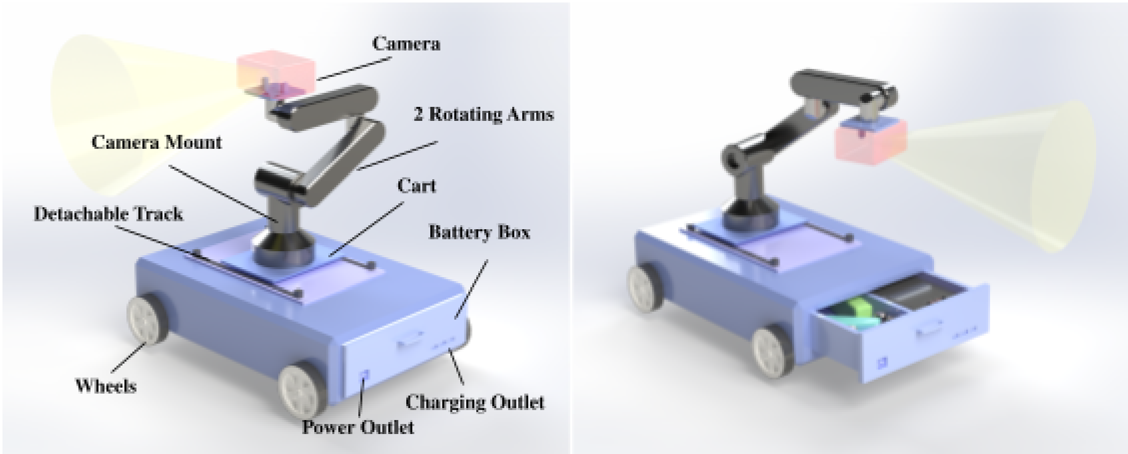

Figure 3. Tracked Cart Design [4]

Key features in this design are a battery box with power and charging outlets, a detachable track, and a high DoF robotic arm. Table 11 below briefly summarizes how each major engineering specification is satisfied by this design. Table 12 outlines the construction of the joint configuration for this design.

Table 11. Functions of Design Satisfying Major Specifications

Specification	Specification-Enabling Features
Design shall be able to easily reach within the range of its work envelope	7 DoF - The track and wheels allow for linear horizontal motion, while the rotating base enables yaw, and the 3 DoF arm, with its wrist and roll gimbal allow for rotational coverage.
Design shall move in both linear and circular rotational ways (pan, tilt)	Linear ● Horizontal: Track and Wheels ● Vertical: Articulated arm Rotational ● Yaw: Rotating base ● Pitch: Wrist ● Roll: Gimbal
Design shall be able to do a horizontal and vertical 180 degrees in X s in any configuration	Yaw/Horizontal ● Rotating base is free to rotate 360º Pitch/Vertical ● Elbow/shoulder/wrist joints all support pitch motion
Design shall support a payload of no less than 5 kg	Gimble mounts payload, with rotating arms to support, base securely attached to carriage on top of track. Moments arms also decrease with more

	outlying digits.
Design shall have a minimum IP rating	IP67 Slip rings - Arm joints and rotating base Sliding bellows - Tracks
Design shall be stable	Primary electronics will be at the base of the arm to lower the CoG. Gas springs serve to stabilize arm as well.

Table 12. Design Joint Configuration

DoF #	Features
1	Track and wheels (Linear)
2	Rotating Base (Yaw)
3	Rotating Arm # 1 (Pitch)
4	Rotating Arm # 2 (Pitch)
5	Rotating Arm # 3 (Pitch)
6	Wrist (Pitch)
7	Gimbal (Roll)

6.3.3 Candidate 3 - Linear Track Design

In this design, horizontal linear motion is prioritized by assembling on a large, straight track that can pivot to preset angles to also vertical motion by a cart. Rotational views are controlled by a pitch and yaw adjusting cart gimbals, all powered by and outlet plug.

Its vertical movement is limited, though is mostly covered by predetermined pop-pin insert locations on a semi-circular track. The track is also detachable for lower height shots and continuous angling with four flip-out legs on the end housings. See Figure 4 below.

Figure 4. Tracked Cart Design [4]

Key features of this design include modularity for a tripod, a track angler, an aluminum extrusion track, a v-slot wheeled cart, and a turreted gimbal. Table 13 below briefly summarizes how each major engineering specification is satisfied by this design. Table 14 outlines the construction of the joint configuration for this design.

Table 13. Functions of Design Satisfying Major Specifications

Specification	**Specification-Enabling Features**
Design shall be able to easily reach within the range of its work envelope	3 DoF - The track allows for horizontal (and vertical if configured) motion, while the rotational envelope is covered by the pitch and yaw turreted gimbal supporting the payload
Design shall move in both linear and circular rotational ways (pan, tilt)	Linear ● Horizontal: Aluminium extrusion track ● Vertical: Adjusted track Rotational ● Yaw: Turret on cart ● Pitch: Gimbal on turret
Design shall be able to do a horizontal and vertical 180 degrees in X s in any configuration	Yaw/Horizontal ● Turret on cat Pitch/Vertical ● Gimbal on turret
Design shall support a payload of no less than 5 kg	No rotational joints/arms to support. Track is supported either by 6-point connection to tripod or to 4 legs on its ends. The cart also has four points contact with the track.

Design shall have a minimum IP rating	Rubber gaiters - Cover track and belt Enclosure/housing - Side motor mechanisms, track bottom/underside belt
Design shall be stable	Mounts on standard camera tripods (1/4-20 UNC). Off-tripod configuration has 4 legs on its ends to provide stability. V-slot wheels can be installed to be properly firm (similar to 3D printers). Layout of pitch BLDC ensures the assembly relatively centered.

Table 14. Design Joint Configuration

DoF #	Features
1	Track (Linear)
2	Turret on cart (Yaw)
3	Pitch Gimbal (Pitch)

8.0 Final Design - Linear Track Design

8.1 Track Assembly

Figure 5. The track subassembly render (Solidworks Visualize) [4]

The track assembly is essentially the chassis of our final design that provides the frame for all other components, being both the track for the camera cart and support component for the side motor housings.

All components in the assembly are directly coupled and pivot together.

The important components of this subassembly are displayed and shown below in Table 15.

Table 15. Major components of the track assembly

Component	Function/Interfaces	Design Choices
Aluminium Framing	Major structural framing of the assembly Mounts to all other components in the assembly Provides a track for the Camera Cart Assembly through the V-slot tracks	Standardized Part (McMaster-Carr) Mill tracks to be V-slot instead of T-slot for better axial and radial load handling with the Camera Cart Assembly 2 in. by 5 in. cross-section, with the same count of individual extrusions to provide sufficient structural support and mourning space
Track End Brace	Provides a flexible mounting area for the otherwise minimal functions of Aluminium extrusion ends Mounts to the Aluminium Framing through bolts and framing fasteners Provides a mounting plate for the Motor Housing Assemblies	Easily Machinable Custom Part (Sheet Metal, Aluminium ⅛ in.) Large openings to allow for extrusions to be inserted by the Motor Housing Assembly for vertical direction support Wraps around Aluminium Framing to optimize support and rigidly couple with it Countersunk bolt holes to avoid interference with cart when it slides along the track
Pop-pin Track	Allows pop-pins to insert into fixed locations and support the pivoting of the Track Assembly and anything coupled to it. Rigidly couples to Track Side/Bottom	Easily Machinable Custom Part (Sheet Metal, Steel ⅜ in.) Different hole spacings on two sides to allow for more varied specific angle pivots

	Connectors through bolts and nylon locknuts Allows ⌀ 0.5 in. pop-pin insertions from the Pop-pin Assembly	Mounting holes to connectors are not inline, so that any crack propagation is not collinear through all mounting holes
Track Side Connector	Mounts the pop-pin tracks (on both sides) onto the Aluminium Framing to sufficiently support the pivoting of the Track Assembly Fastens to the Aluminium Framing through bolts and framing fasteners Rigidly couples to Pop-pin Tracks through bolts and nylon locknuts	CNC Machined Custom Part (Aluminium, block stock) Supports longitudinal motion through semicircular brace on the inside of this connector piece Counterbored on both sides to save space towards the inside of the Track Assembly Offset of mounting holes to better support latitudinal force against the Pop-pin Track
Track Bottom Connector	Support the Pop-pin Track mounting onto the Aluminium framing and support the central pivot shaft Fastens to the Aluminium Framing through bolts and framing fasteners Rigidly couples to Pop-pin Tracks through bolts and nylon locknuts	CNC Machined Custom Part (Aluminium, block stock) Thicker area closer to the central shaft to improve rigidity and ensure proper support of pivot axis Single sided mounting to the Pop-pin Track to open up space for other mounting components
Pivot Shaft	Acts as the pivoting axis of the track and Track Assembly Constrained by the Inline Bearings from the Pop-pin assembly for translation, while allowing Z-axis rotation	Easily Machinable Custom Part (Stainless Steel, ⅜ in. cylinder stock) Generous bevels on the ends to allow for easy assembly

8.2 Pop-Pin Assembly

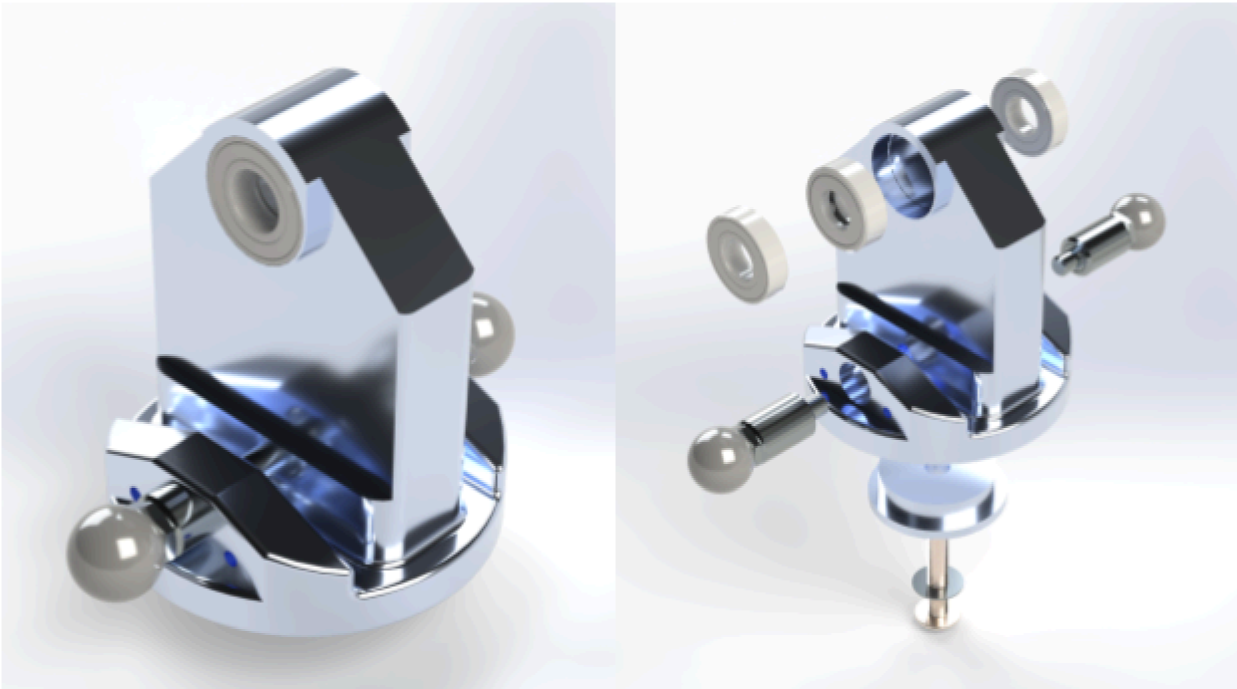

Figure 6. The pop-pin subassembly render (Solidworks Visualize) [4]

The Pop-pin assembly is the base that supports the track and connects the design to a tripod, while also providing a housing for the pop-pins and gas spring housings. Additionally, it supports the major pivoting shaft that the track rotates about.

All components in the assembly are coupled and do not pivot about the track - this assembly is meant to be a fixed base.

The important components of this subassembly are displayed and shown below in Table 16.

Table 16. Major components of the pop-pin assembly

Component	Function/Interfaces	Design Choices
Pop-pin Housing	Provides a fixed base for other components to couple their parts, while allowing the fixing of the entire design to a tripod Rigidly coupled to gas springs through a ball-jointed stud Rigidly coupled to Pop-pin through	CNC Machined Custom Part (Aluminium T6, block stock) Tapped holes to allow gas spring studs to screw into Recessed face to provide high clearance around the Pop-pin Track movement area to avoid snagging and friction (> ⅛ in. on both sides)

	press fit Rigidly coupled to tripod through a standard Mitchell mount Constrains the Pivot Shaft and its bearings in the X and Y directions Significant clearance fit of the Pop-pin Track from the Track Assembly to allow free movement as the Track Assembly pivots	Large base face to support assembly on tripod and on ground Single side bearing shoulder to support bearings in axial direction
Pop-pin Housing Bottom Clamp	Attaches the Pop-pin Housing to tripod/Mitchell mount connections Rigidly coupled, while detachable, to the Pop-pin Housing	Easily Machinable Part (Aluminium T6, 3 in. cylinder) Connected simply with a 3 in. long bolt that bolts the clamp to the housing
Pop-pin	Locks the track in pivot by inserting into the Pop-pin Track Rigidly coupled to the Main Housing through press fit Inserts into Pop-pin Track holes to fix the track at discrete pivot angles	Standardized Part (McMaster-Carr) Engagement/disengagement of piston allows for quick and convenient track pivoting, while still supporting radial loads well Ball-grip to avoid snagging and accidental disengagement
Inline Bearings	Supports the Pivot Shaft Constrains the Pivot Shaft completely in translation, but allow Z-axis rotation	Standardized Parts (McMaster-Carr) Usage of both ball bearings and thrust bearings to sufficiently support Z-axis and radial loads

8.3 Motor Housing Assembly

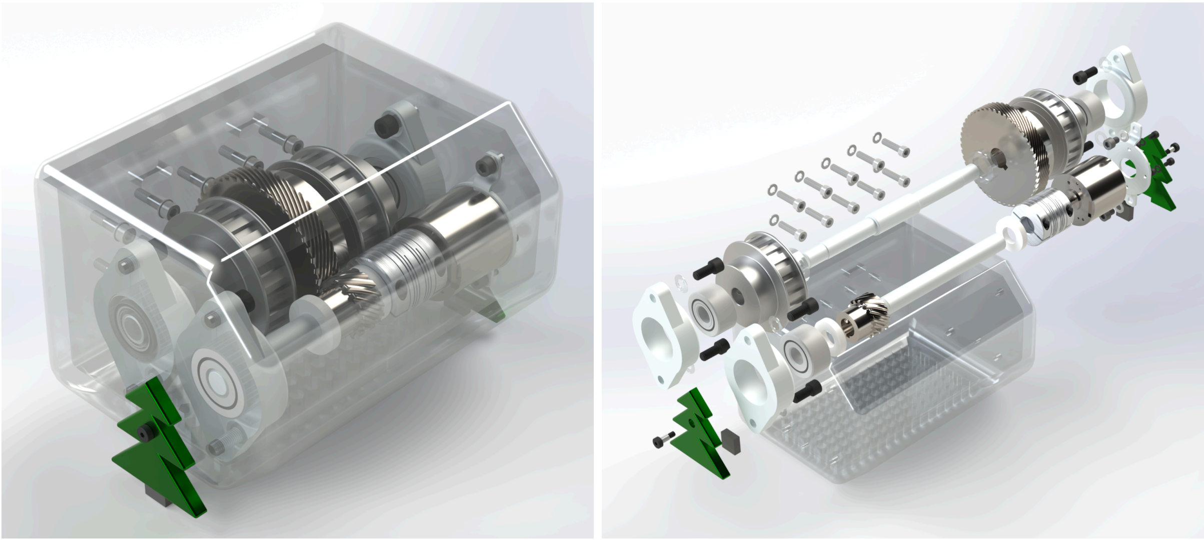

Figure 7. The motor housing subassembly render (Solidworks Visualize)

The Motor Housing Assembly contains the gearbox and associated motor that drives the belt that moves the Camera Cart Assembly along the Track Assembly. It also features two flip-out legs that allow for free angling of track. Two of these assemblies exist in the design - one on each side of Track Assembly.

All components in the assembly are coupled and do not pivot about the track - this assembly is meant to be fixed on the ends of the Track Assembly.

The important components of this subassembly are displayed and shown below in Table 17.

Table 17. Major components of the Motor Housing Assembly

Component	Function/Interfaces	Design Choices
Gearbox Housing	Motion support and housing for components in assembly Rigidly coupled (assembled by user) onto the Track Assembly by the Track End Brace using bolts Rigidly coupled with the bearing housings and motor bracket	Easily Machinable Custom Part (Sheet Metal, 6061 Alloy ⅜ in.) Sheet metal chosen to minimize machining parts - also designed without extra extrusions Sheet metal net can be easily water jet, avoiding waste from subtractive CNC
Timing Belt Pulleys	Supports and actuates the Track Belt to move the Camera Cart Assembly along the Track Assembly.	Standardized Parts (McMaster-Carr) Thick

Bearing Housing	Holds the double row angular contact bearings Supports the pulley shaft at both ends and the motor shaft at one end Fastened to the housing using socket head screws	Easily Machinable Custom Part (Aluminum, block stock)
Pulley Shaft	Holds the pulleys, 48-tooth helical gear, spacers, and double row angular contact bearings Supported by the bearing housing	Easily Machinable Custom Part (Aluminum, ⅝" cylinder stock)
48-Tooth Helical Gear	Paired with the 16-tooth gear to perform a reduction ratio of 3:1 Positioned and held in place by spacers Press-fitted onto the pulley shaft	Standardized Part (McMaster-Carr)
Spacers	Positions the 48-tooth and 16-tooth helical gear on the shaft Prevents the 48-tooth and 16-tooth helical gear from sliding Press-fitted onto the shafts	Standardized Part (McMaster-Carr)
Double Row Angular Contact Bearings	Supports axial, radial and moment loads of both shafts Press-fitted onto the shafts	Standardized Part (McMaster-Carr)
Motor Shaft	Holds the 16-tooth helical gear, spacers, shaft coupling and double row angular contact bearings	Easily Machinable Custom Part (Aluminum, **½"** cylinder stock)
16-Tooth Helical Gear	Paired with the 48-tooth gear to perform a reduction ratio of 3:1	Standardized Part (McMaster-Carr)

	Positioned and held in place by spacers Press-fitted onto the motor shaft	
Shaft Coupling	Clamps onto the motor output shaft and the motor shaft to rotate together, transitioning from a ¼” diameter motor shaft to a ½” diameter gear shaft	Standardized Part (McMaster-Carr)
Brushless DC Motor	Produces a rotational motion Fastened to the Motor Bracket	Standardized Part (McMaster-Carr)
Motor Bracket	Holds the motor in place using socket head screws into the mounting holes of the motor Fastened into the housing using socket head screws	Custom Sheet Metal Part
Christmas Tree Legs	Rigidly coupled to the gearbox housing with shoulder bolts The bottom of each leg has a rubber end glued to it for a soft interface Christmas spirit must be preserved: Made out of titanium	Easily Machinable Custom Part (Titanium, block stock)

8.4 Camera Cart Assembly

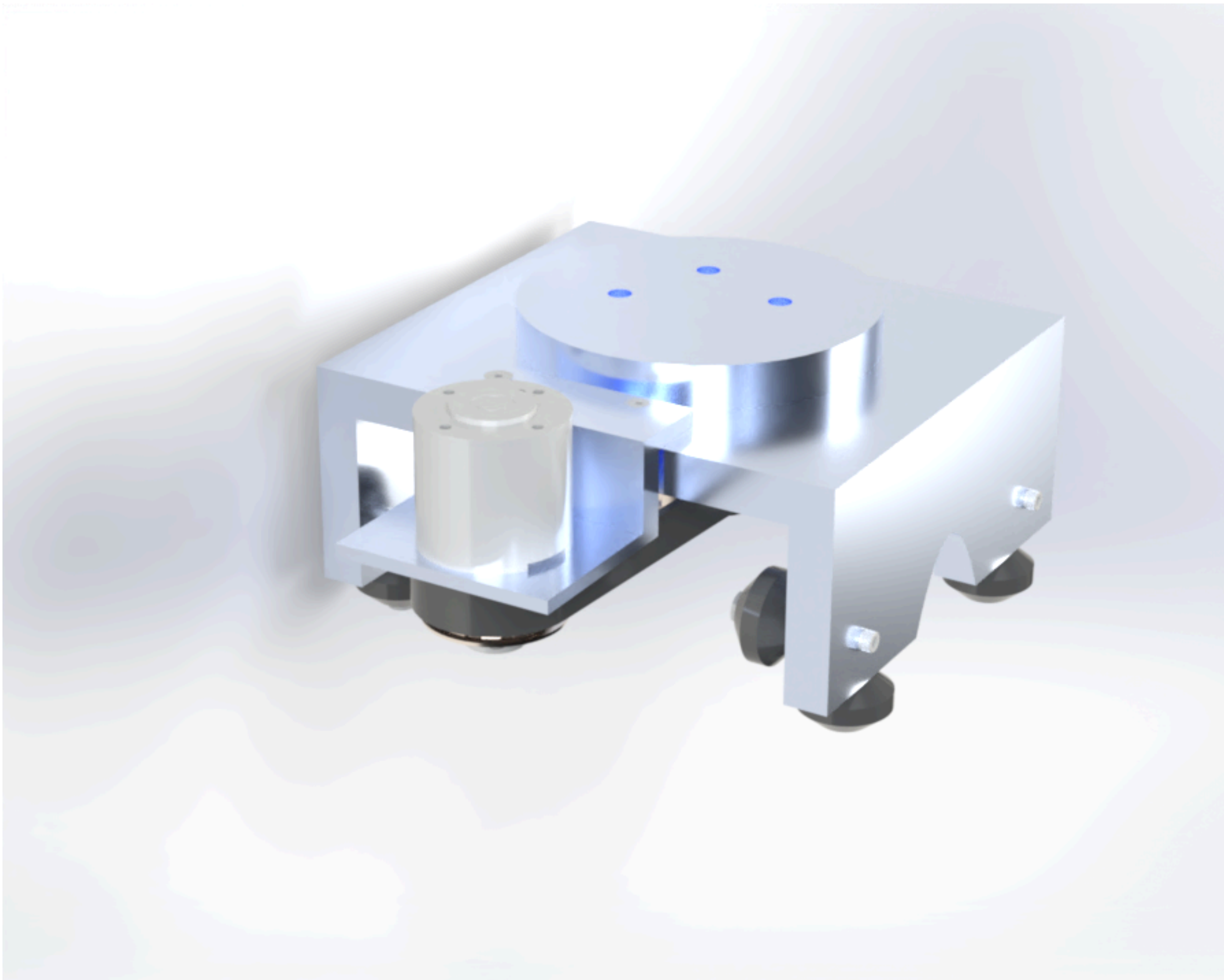

Figure 8. The cart subassembly render (Solidworks Visualize)

All components in the assembly move along the track, actuated by the Track Belt using the Track Belt Motor in the Motor Housing Assemblies at the ends of the Track Assembly.

The important components of this subassembly are displayed and shown below in Table 18.

Table 18. Major components of the Camera Cart Assembly

Component	Function/Interfaces	Design Choices
Cart Plate	Placed on the track, contains all components the camera needs to achieve all different camera shots	Large enough to handle payload of camera and motorized gimbal, fit on the track comfortably

V-slot Wheels	Fit into the Track Assembly	Standardized Part
Turret Plate	The Motorized Gimbal sits on the Turret so that the camera has 360 degree angle shots	Large enough for the Motorized Gimbal to sit on, Thick enough to handle the payload of all the motorized Gimbal components
Thrust Bearing	Able to spin the turret, acts as a lazy susan, connected between turret and bottom plate	Thick as the cart thickness to achieve an I shape section view, so that the thrust bearing sits between the turret and bottom plate
Brushless DC Motor	Produces a rotational motion Fastened to the Motor Bracket	Standardized Part (McMaster-Carr)
Bottom Plate	Holds thrust bearing in place	Custom Part
Timing Belt Pulley	Supports and actuates the Turret to move the Motorized Gimbal.	Standardized Parts (McMaster-Carr) Thick - must fit
Motor Brace	Holds the motor in place using socket head screws into the mounting holes of the motor Fastened into the housing using socket head screws	Custom Sheet Metal Part

8.5 Motorized Gimbal Assembly

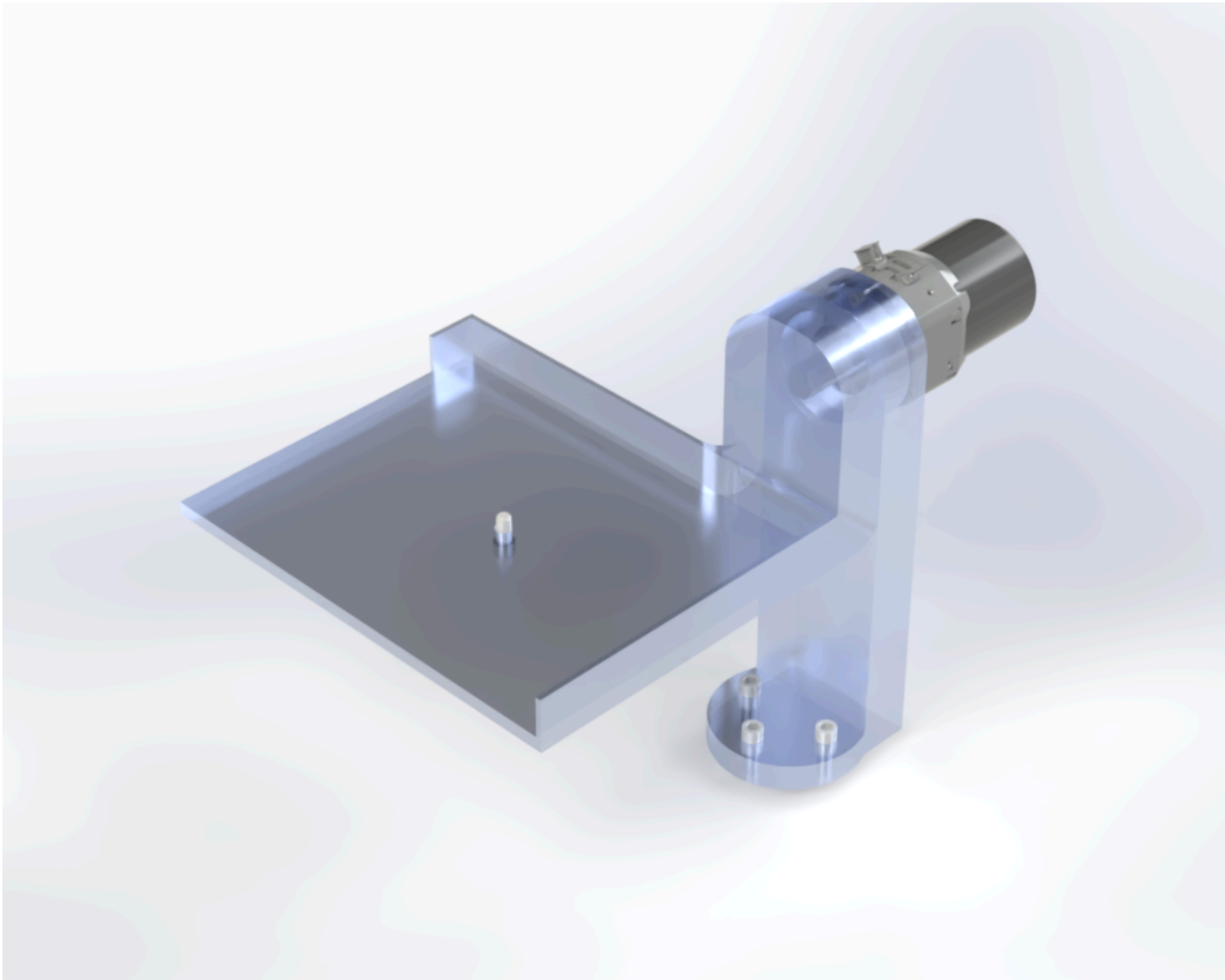

Figure 9. The cart subassembly render (Solidworks Visualize)

The Motorized Gimbal Assembly consists of a rotating gimbal tray attached to a stand, and can support a camera with a max payload of 5 kg.

The components of this assembly are mounted onto the turret plate of the camera cart assembly.

The important components of this subassembly are displayed and shown below in Table 19.

Table 19. Major components of the Camera Cart Assembly

Component	Function/Interfaces	Design Choices
Gimbal Stand	Motion support for components in assembly. Rigidly coupled (assembled by user) onto the Camera Cart Assembly by the bottom base of the stand using bolts.	Easily Machinable Part (Aluminum Stock)

Gimbal Tray	Supports the payload (5 kg) Fastened to rotating hex shaft with shaft collar	Easily Machinable Part (Aluminum Stock)
Motor Shaft	Runs through the hollow motor, hex shaft bearing, hex shaft collar, and attaches to and rotates the gimbal tray.	Standardized Part (McMaster-Carr) Machined to a length of ~4.63 in.
Hex Bearing	Provides support to the pivot shaft, but allows rotational motion	Standardized Part (Rev Robotics)
Shaft Collar	Holds gimbal tray in place with the shaft	Standardized Part (McMaster-Carr)
Hollow Brushless DC Motor	Produces a rotational motion Fastened to the gimbal stand	Standardized Part (Rev Robotics)

9.0 Bill of Materials

This section outlines the materials used to construct our final design. The bill of materials (BOMs) are broken up into sub-assemblies.

9.1 Track Assembly BOM

This section highlights the materials used to construct the track assembly. Table 19 below briefly describes

Table 19. Track Assembly Bill of Materials

Pt #	Part Name	Source	Product Number (IF NOT CUSTOM)	Qty	Price (USD)
TR-01	Aluminium Extrusion (2 in. by 2 in. by 4 ft.)	McMaster - Carr [15]	47065T678	2	$156.26 (2x $78.13)

TR-02	Aluminium Framing (1 in. by 2 in. by 4ft)	McMaster - Carr [16]	47065T493	1	$57.41
TR-03	Track End Brace	Custom	-	2	$13.36 (2 x $6.68*)
TR-04	Pop-pin Track	Custom	-	2	$33.50 (2 x $16.75*)
TR-05	Track Side Connector (L)	Custom	-	2	$47.68 (2 x $23.84*)
TR-06	Track Side Connector (R)	Custom	-	2	$47.68 (2 x $23.84*)
TR-07	Track Bottom Connector	Custom	-	1	$62.08 (2 x $31.04)
TR-08	Centre Shaft (⅞ in.)	McMaster - Carr [17]	89055K399	1	$90.10
TR-09	Two-Piece Shaft Collar	McMaster - Carr [18]	6436K17	2	$22.74 (2 x $11.37)
HW-01	Socket Head Steel Bolt (10-32, ¾ in.)	McMaster - Carr [19]	91251A345	36	$16.28 (1x pack of 100)
HW-02	Thin Nylon Locknut (10-32)	McMaster - Carr [20]	91581A345	12	$27.03 (3x packs of 5)
HW-03	Aluminium Frame Fastener (10-32)	McMaster - Carr [21]	5508N12	24	$34.62 (6x packs of 4)
HW-06	Flat Head Steel Screw (10-32, ⅜ in.)	McMaster - Carr [22]	91253A001	20	$11.21 (1x pack of 50)

* Cost estimated using Solidworks Costing tool [4].

9.2 Pop-Pin Assembly BOM

Table 20. Pop-pin Assembly Bill of Materials

Pt #	Part Name	Source	Product Number (IF NOT CUSTOM)	Qty	Price
PP-01	Pop-pin Housing	Custom	-	1	$208.40*
PP-02	Pop-pin Housing Bottom Clamp	Custom	-	1	$10.05*
PP-03	Pop-pin	McMaster-Carr [23]	90222A643	2	$50.94 (2 x $25.47)
PP-04	Ball Bearing	McMaster-Carr [24]	4668K18	2	$139.24 (2 x $69.62)
PP-05	Thrust Bearing	McMaster-Carr [25]	60715K14	1	$23.79
HW-04	Flanged Button Head Bolt (½-13, 3 in.)	McMaster-Carr [26]	97654A361	1	$13.34
HW-05	Stainless Steel Washer (for ½ in. ID)	McMaster-Carr [27]	90107A033	1	$9.31 (1x pack of 5)

* Cost estimated using Solidworks Costing tool [4].

9.3 Motor Housing Assembly BOM

Table 21. Motor Housing Assembly Bill of Materials

Pt #	Part Name	Source	Product Number (IF NOT CUSTOM)	Qty	Price
MH-01	Timing Belt Pulley	McMaster-Carr [28]	1304N12	4	$121.00 (4x $30.25)
MH-02	Pulley Shaft	Custom	-	2	$8.76 (2x $4.38*)

MH-03	48-Tooth Helical Gear	McMaster-Carr [29]	2585N17	2	$349.60 (2x $174.80)
MH-04	Aluminum Spacer (for ⅝ in. ID)	McMaster-Carr [30]	92510A497	4	$38.12 (4x $9.53)
MH-05	Clamping Shaft Coupling	McMaster-Carr [31]	6208K565	2	$200.94 (2x $100.47)
MH-06	Brushless DC Motor	McMaster-Carr [32]	4853N13	2	$990.46 (2x $495.23)
MH-07	16-Tooth Helical Gear	McMaster-Carr [33]	2585N12	2	$160.54 (2x $80.27)
MH-08	Motor Shaft	Custom	-	2	$6.78 (2x $3.39*)
MH-09	Gearbox Housing	Custom	-	2	$21.40 (2x $10.70*)
MH-10	Motor Bracket	Custom	-	2	$9.94 (2x $4.97*)
MH-11	Nylon Spacer (for ½ in. ID)	McMaster-Carr [34]	94639A263	4	$6.76 (1x packs of 25)
MH-12	Bearing Housing	Custom	-	6	$67.38 (6x $11.23*)
MH-13	Angular-Contact Double Row Ball Bearing	McMaster-Carr [35]	8828T312	6	$749.52 (6x $124.92)

MH-14	Socket Head Steel Bolt (¼”-28, ¾ in.)	McMaster-Carr [36]	91864A047	12	$15.30 (2x $7.65 - packs of 10)
MH-15	Aluminum Washer (for ¼” screw size)	McMaster-Carr [37]	94589A631	12	$11.60 (1x packs of 50)
MH-16	Socket Head Steel Bolt (10-32, ¾ in.)	McMaster-Carr [38]	91251A345	20	$16.28 (1x packs of 100)
MH-17	Stainless Steel Washer (for #10 screw size)	McMaster-Carr [39]	90945A740	24	$18.06 (1x packs of 250)
MH-18	Socket Head Steel Bolt (M3 x 0.5mm)	McMaster-Carr [40]	91290A110	8	$11.91 (1x packs of 100)
MH-19	Stainless Steel Washer (for M3 screw size)	McMaster-Carr [41]	98269A121	8	$5.71 (1x packs of 100)
MH-20	Socket Head Steel Bolt (10-32, ¼ in.)	McMaster-Carr [42]	91251A338	4	$12.15 (1x packs of 25)
MH-21	Christmas Tree Legs	Custom	-	4	$56.00 (4x $14*)
MH-22	Leg Rubber	Custom	-	4	$214.12 (4x $53.53*)
MH-23	Alloy Steel Shoulder Screw (6-32, 5/32” Shoulder Diameter, ¼” Shoulder Length)	McMaster-Carr [43]	91259A161	4	$12.36 (4x $3.09)

* Cost estimated using Solidworks Costing tool [4].

9.4 Camera Cart Assembly BOM

Table 22. Camera Cart Assembly Bill of Materials

Pt #	Part Name	Source	Product Number (IF NOT CUSTOM)	Qty	Price
CC-01	Cart Plate	Custom	-	1	$16.37
CC-02	V-slot wheels	3DPrintingCanada [44]	625ZZ	8	$4.95
CC-03	Turret Plate	Custom	-	1	$59.12
CC-04	Ball Bearing	McMaster-Carr [45]	60355K708	1	$13.73
CC-05	Brushless DC Motor	McMaster-Carr [46]	4853N13	1	$495.23
CC-06	Bottom Plate	Custom	-	1	$9.69
CC-07	Timing Belt Pulley	McMaster-Carr [47]	1375K13	1	$10.47
CC-08	Timing Belt Pulley	McMaster-Carr [48]	1375K17	1	$11.12
CC-09	Timing Belt	Custom	-	1	$29.68
CC-10	Motor Brace	Custom	-	1	$15.34
CC-11	Shaft Collar	McMaster-Carr [49]	6436K18	1	$11.59
CC-12	Hex Drive Flat Head Screw	McMaster-Carr [50]	91253A113	2	$13.07
CC-13	Hex Nuts (6-40)	McMaster-Carr [51]	90480A175	6	$2.45

CC-14	Flat Head Screw (6-20)	McMaster-Carr [52]	91253A151	6	$14.34
CC-15	Head Screw Steel Socket	McMaster-Carr [53]	90044A257	4	6.87
CC-16	Cart Walls	Custom	-	2	$60.78
CC-17	High Strength Shaft	McMaster-Carr [54]	7786T412	1	$8.8
CC-18	Push on External Retaining Ring	McMaster-Carr [55]	98430A156	1	$6.87
CC-19	Low Carbon Steel Disc	McMaster-Carr [56]	7786T412	1	$11.20

* Cost estimated using Solidworks Costing tool [4].

9.5 Motorized Gimbal Assembly BOM

https://3dprintingcanada.com/products/solid-pom-v-slot-wheel-with-625zz-bearing-5x11x24mm

Pt #	Part Name	Source	Product Number (IF NOT CUSTOM)	Qty	Price
MG-01	Gimbal Stand	Custom	-	1	$58.93
MG-02	½” Hex Bearing	Rev Robotics [57]	REV-21-1915	1	$13.00 (1x packs of 4)
MG-03	Gimbal Tray	Custom	-	1	$227.57
MG-04	1 ft Low-Carbon Steel Hex Bar	McMaster-Carr [58]	6512K182	1	$4.24
MG-05	½” Hex Shaft Collar	McMaster-Carr [59]	7552K15	1	$25.80

MG-06	Neo Vortex Motor and Spark Flex Motor Controller with 8mm Shaft	Rev Robotics [60]	REV-21-1652	1	$90.00
HW-06	Socket Head Steel Bolt (6-32, ½ in.)	McMaster-Carr [61]	91251A148	6	$11.95 (1x packs of 100)
HW-07	Socket Head Steel Bolt (¼"-20, ½ in.)	McMaster-Carr [62]	91251A537	1	$16.44 (1x packs of 100)
HW-08	Socket Head Steel Bolt (¼"-20, ¾ in.)	McMaster-Carr [63]	91251A540	3	$11.38 (1x packs of 50)

* Cost estimated using Solidworks Costing tool [4].

9.6 Accessory BOM

Any components/assemblies fixed to more than one subassembly are listed below in Table 23.

Table 24. Accessory Bill of Materials

Pt #	Part Name	Source	Product Number (IF NOT CUSTOM)	Qty	Price
AC-1	Gas Springs (5/16-18 Stubs)	McMaster-Carr (64)	4155T101	4	$309.56 (4 x $77.39)
AC-2	Timing Belt	McMaster-Carr (65)	1840K3	2	$1250.4 (2x $625.2) (120 x $5.21/ft)
3	Timing Belt End Plate	McMaster-Carr (66)	7644N13	2	$41.42 (2x $20.71)

9.7 Total Cost

Assembly	**Cost**
Track Assembly	$619.90

Motor Housings (2)	$2885.92
Camera Cart	$804.20
Gimbal Assembly	$456.02
Accessories	$1600.42
Total: $6 364	

10.0 Technical Assembly Drawings

11.0 High Level Calculations

To briefly gain a sense of whether the design is operable up to our engineering specifications standards, 3 basic calculations are done: time for the cart to travel the track length, time for the cart to rotate 180° in yaw, and time for the cart to rotate 180° in pitch.

11.1 Cart Travel Time

From our engineering specifications, we want the cart to travel the 48 in. (1.2192 m) track in about 3 seconds. From this, a target belt speed of v = 0.4064 m/s is taken. From the McMaster-Carr website, the pitch radius = 1.3125 in. = 0.03334 m [28]. Using $v = \omega r$, we get that the required angular velocity of the pulley to be $\omega_p = 12.189 rad/s$, and with motor $\omega_m = 12.189 rad/s * 1/3 = 4.063 rad/s$

Converting this value to rpm, we get that

$$\omega_m = 4.063 rad/s * 1\, rev/2\pi\, rad * 60s/1min = 38.8 rpm$$

Again from McMaster-Carr, the motor rpm-torque graph can be taken. Shown below in Figure 10.

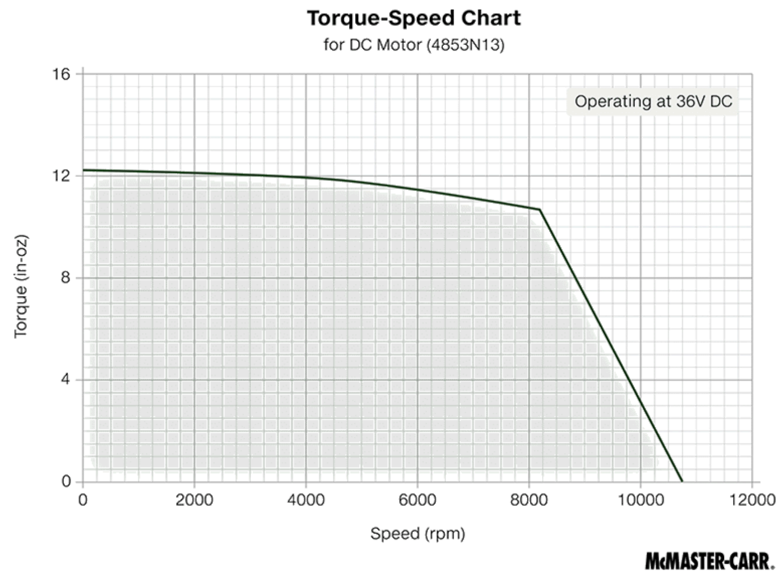

Figure 10. Torque-Speed Chart for the chosen belt drive motor

Using this graph, we get that the torque at 38.8rpm is about 12 in. oz. Converting to Nm, we get that the available motor torque at this speed is $\tau_m = 0.0847Nm$. Finding linear force using pitch radius of 0.03334 m, and $\tau = Fr$, we get that the output force at this target rpm is $F_{out} = 7.612N$.

With a total loaded cart mass of about $m_T = 8kg$, this force can drive the cart at an acceleration of $a = 7.612N/8kg = 0.58626m/s^2$. Using the simple kinematic equation of $d = v_0 t + \frac{1}{2}at^2$ and initial velocity $v_0 = 0$ and $d = 1.2192m$, we get $t = 2.034s$. Therefore, assuming no friction (appropriate due to ball bearings) and negligible torque change at these speeds (appropriate as seen in chart), the cart can actually move across the track at 2s, faster than our minimum viable of 3s from engineering specifications.

In similar methods, we get that the yaw rotation time of 180º and pitch rotation time of 180º are both within our engineering specifications, making a 180º yaw rotation in 0.555s and 180º in pitch in 3.74e-3s. Rough work can be seen in Appendix C.3.

12.0 Conclusion

The final proposed design is the Linear Track Design, optimized for simplified and smooth linear travel, while still permitting rotational shots. Featuring a large pivoting aluminium track braced by gas springs, supporting a camera cart that enables the rotational mechanisms for the cameras to move for rotational shots. The frequent usage of sheet metal, aluminum composition, and minimal DoFs allow for a relatively low cost and weight, permitting portability as well.

However, further design iterations should aim to improve its vertical mobility, as well as more consistent fastener key types, as the current model requires a variety of hex keys to assemble. Additionally, basic prototyping of key mechanisms, such as the core pivoting track, the camera cart's mounting system, and the motor housing gearbox should be performed to ensure practicality.

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Appendix A

Current Cinematic Robot Arms

- MRMC Bolt (shown in Tut2) - https://www.mrmoco.com/motion-control/bolt/
    - 6 axis of rotation (4 on arm, 2 on camera) + short rail
    - 20kg camera payload
    - 12m/s shooting speed
    - 2m arm reach
    - Z-axis max 3.5m
    - Longer reach and smaller models also avail
    - ~70K USD

- Motorized precision EVO - https://www.motorizedprecision.com/evo
    - 6 joints + mitchell mount (standard camera to tripod mounting style)
    - 5kg camera payload
    - 2m/s shooting speed
    - 20kg robot unload weight
    - .85m arm reach
    - Z-axis max 1.2m
    - Seems to be almost the exact market we're looking for
    - ~25K USD

- NOXON Arm (Quite barebones construction) - https://noxon.tech/noxon-arm/
    - Mitchell mount
    - 6kg camera payload
    - 30kg robot unloaded weight
    - 1.3m arm reach
    - ~8.1K USD
    - Max Height: 127 cm
    - Lowest Position: -105cm
    - Repeatability Precision: 0.01 mm
    - Weight: 30kg
    - Payload: 6kg

- G-Ka Motion Control - https://www.gkamoco-global.com/
    - Luna model - small, compact
    - Many arms, flexible, medium size arms
    - $44,187
    - 3.50 m/s camera speed
    - 7kg dynamic payload
    - 100 mm arm reach
    - 0.02 mm motion repeatability

- 38 kg for the arm, 40 kg for base

→ Estimate in cinematic robot arm (~30 000USD)

Decent Robot Arms (not camera/videography specific)
UR3e - 40 000 USD - https://vention.io/parts/universal-robots-ur3e-collaborative-robot-arm-2446
uFactory 850 Arm - 9 000 USD - https://www.ufactory.cc/
Fairino FR5 Arm- 3500 USD - https://www.frtech.fr/FRSeriesProducts
Dobot CR5 - 22 000USD - https://www.dobot-robots.com/products/cr-series/cr5.html
Jaka Zu 3 - 18 000USD - https://www.jaka.com/en/productDetails/JAKA_Zu3
AE AIR3-A - 13 000USD -
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→ Estimate a quality Robot arm (non-cinematic to be ~ 13000 USD)

Cheap Robot Arms & Kits (not camera/videography specific)

- Lynxmotion SES-Pro 900mm - 8 000 USD - https://www.lynxmotion.com/ses-pro-robot-arms/
- Lynxmotion SES Pro 550 - 7 000 USD
- RealMan RML - 6 500 USD - https://www.realman-robotics.com/rml63-b.html
- UFactory xArm - 6 000 USD - https://www.ufactory.cc/
- Elephant Robotics - myCobot Pro 630 - 10 000 USD - https://shop.elephantrobotics.com/en-ca/collections/mycobot-pro-630/products/mycobot-pro-630-robotic-arm-commercial-collaborative-robot
- Borunte 4Axis SCARA - 6000 USD https://www.borunte.net/i-m-m-robot/4-axis-servo-manipulator/technical-industrial-scara-robot.html

→ Estimate a cheap robot arm (non-cinematic) to be ~8000 USD

Appendix B

Appendix B.1

- Common types of photo/cinematic shots needed? Make sure the associated motion is smooth and doable
    - Framings
        - Extreme wide shot ~ environments, establishing
        - Full shot ~ entirety of subject + some context
        - Medium Shot ~ usually torso up, usually for dialogue
        - Medium/Normal/Extreme Close-up ~ emotional or prop detail
    - Angles

            - Over the shoulder/POV shots - would likely require more rotation than linear movement
            - High/low angle shots - prob could be done by hand, but does NOT require the camera to be significantly lower or higher than subject - maybe design this way though?
            - Bird's eye - not relevant here imo
    - Camera movements
        - Pan (left/right)
        - Tilt (up/down)
        - Tracking/Dolly Shots (moving object - rail?)
        - Zoom and Dolly Zoom/Vertigo (more to do with lens, but having good reach can help alleviate that a bit

Appendix B.2

Table B.2.1. Common beginner camera and lenses and their mass.

Camera	mass (kg)	Camera	mass (kg)	Lens	mass (kg)
Sony A7 IV	.721	Panasonic LUMIX GH5 II	.725	Tamron RXD	.550
Sony FX3	.715	Panasonic S1R II	.795	Sigma 24-70 f/2.8 DN Art II	.745
Sony ZV-E10	.343	Fujifilm X-H2S	.660	Canon RF 24-105mm IS USM	.700
Blackmagic Pocket Cinema Camera 4K	.722	Fujifilm X-T50	.438		
Blackmagic Pocket Cinema Camera 6K pro	1.240	Nikon Z8	.920		
Canon C70	1.340	Nikon Z fc	.455		
Canon EOS R6 II	.670	Panasonic LUMIX GH7	.805		

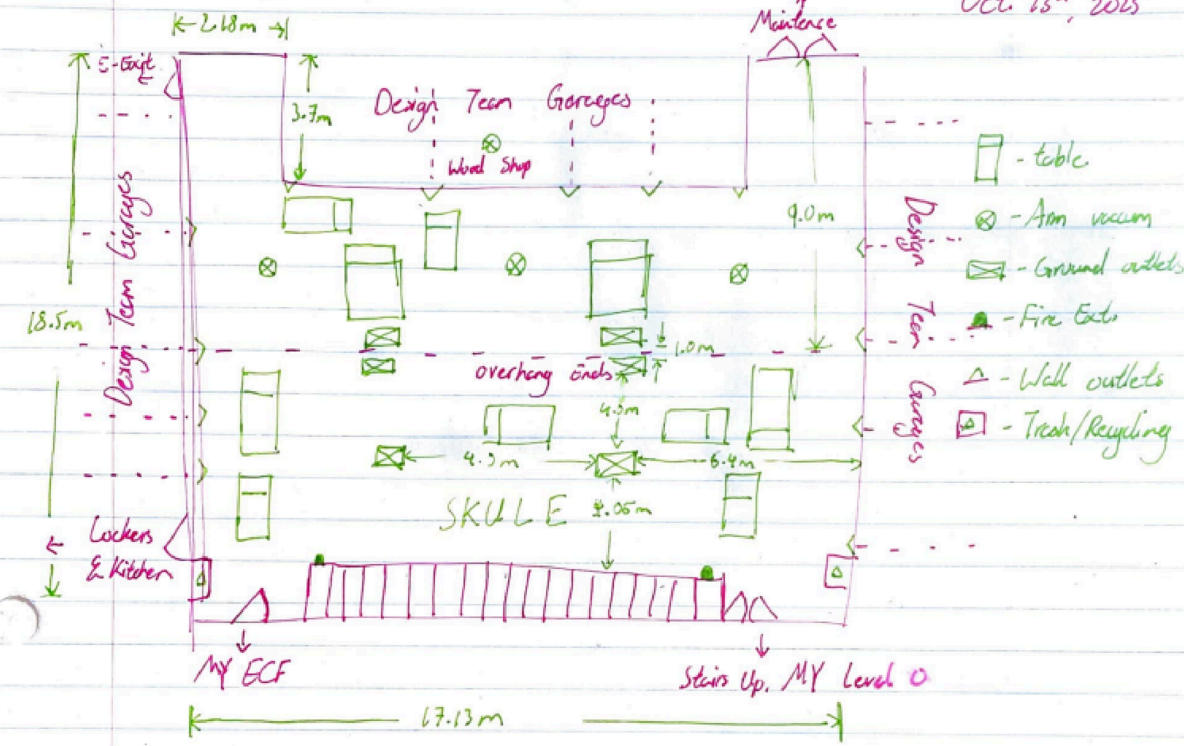
Taking the 95th percentile of the camera masss, with an additional .8 kg allocated for a possibly more massive lens, with an approximately 2.5x safety factor, as is common in moderate industrial usage (source), results in a payload design mass of 5 kg.

Appendix B.3

Engineering observations done to evaluate specific environmental conditions. Also accessible here.

Engineering Observations: Myhal EngSoc Arena

Jaden Zheng
Oct. 13th, 2025



Power/Signal
- Full bars WIFI (UofT)
- 2-3 bars cell service
- 13 Wall outlets x2 Plugs each
- 6 Ground outlet boxes x 8 plugs

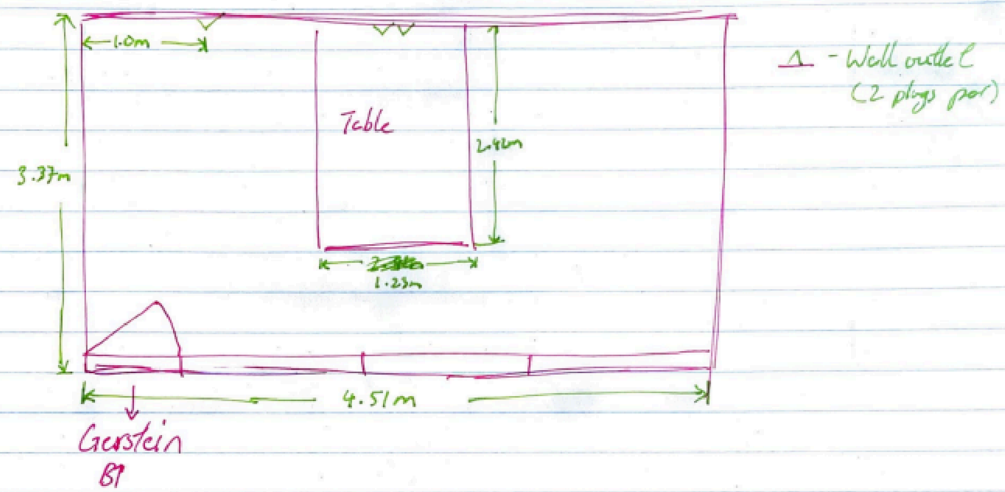
Elemental Exposure
- AC regulated temperature (~25°C)
- No wind (except vaccums & fans (artificial))
- Dust from clubs working
- Fluids rarely from clubs

Other Considerations:
- Shop vaccums (~4m radius range 3 dof arm from overhang) available
- 27 chairs & 10 tables available - all easily moveable / have wheels
- High traffic during non-holidays due to club garages
- No noise norms - a group making noise is expected/acceptable

- 10pt Arial font very easily readable, 6pt can be read

Engineering Observations: Gerstein GSR B105A

Jaden Zhang
Oct 14th, 2025



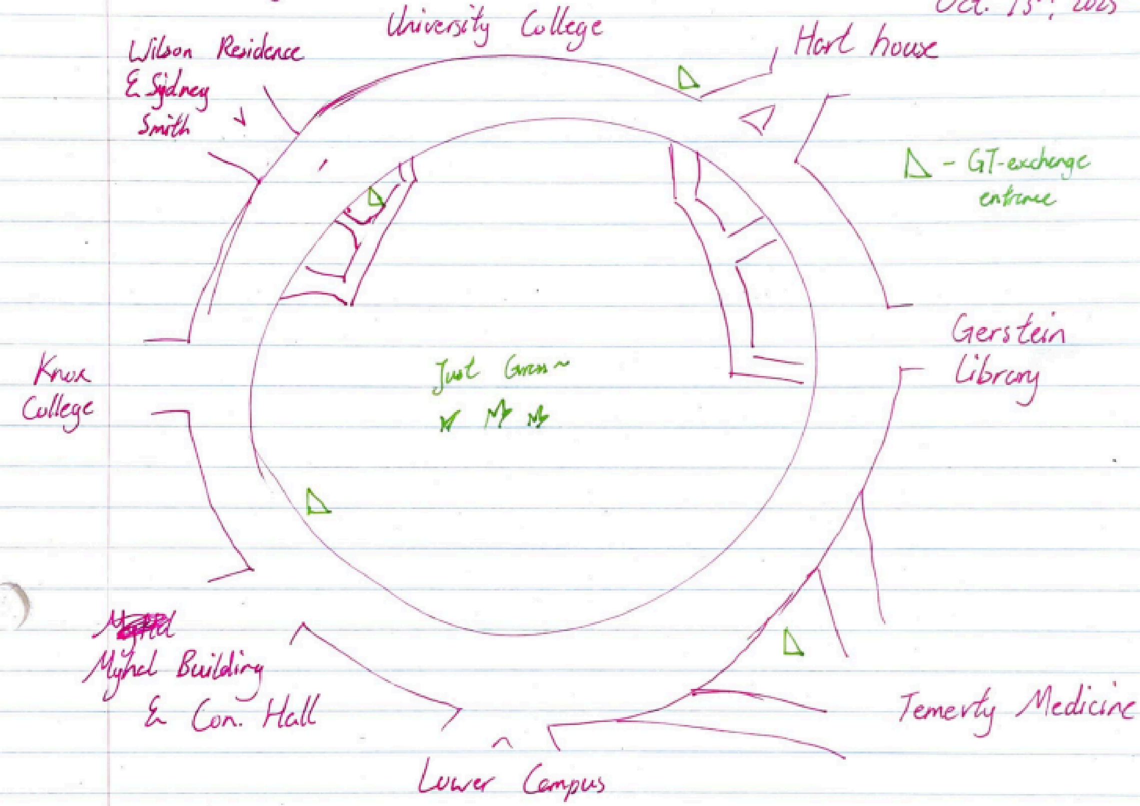
Power/Signal
- Full bars WIFI (UofT)
- Full bars cell service
- 3 wall outlets (2 plugs, 2 USB)
  - ↳ Attached to table
- Possible ceiling outlets

Elemental Exposure
- AC regulated (~25C)
- No wind
- Fully enclosed space
- Glass wall to B1

Other Considerations:
- Table is NOT wheeled but is moveable, 7 chairs are wheeled
- Typically little/moderate noise is normal for groups inside
- Usually fully booked for 1 day in advance, rush hours booked ~3 days ~~ahead~~ ahead
- ~~Pre~~ Existing TV setup - could be detached for more outlets?
- 10 pt Arial font very easily visible - very well lit, likely limited by vision

Engineering Observations: Front Campus

Jaclen Zhang
Oct. 13th, 2025



Power/Signal
- Weak/2bar Wifi (UofT)
- Full bar Cell service
- No easily accessible outlets
- Closest power is ↓ flight of stairs and past a door @ GT exchange entrances

Elemental Exposure (cloudy, 2pm)
- Exposed, minor shade around paths → minimal overhead cover
- Minimal wind cover towards centre of grass

Other Considerations
- Benches surrounding circular path
- Often photography in front of UC + studying students
- EV charging station adjacent to GT exchange station
- 12pt Arial very visible, 5pt still visible in day
  - ↳ difficult @ night

Appendix B.4

Full Requirements Traceability Matrix linked.

Requirements Traceability Matrix.pdf

A snapshot of all requirements, their testing method and acceptance criteria, for reference.

Requirement	Testing Method	Acceptance Criteria
Design shall have sufficient degrees of freedom	Validation in component choices and layout	3 DOF
Design shall be able to easily reach within the range of its work envelope	Find maximum reach of the robot, then qualitatively record how difficult it is for the camera to reach each possible position	Should be able to reach all points within its range in a continuous manner (not stepped)
Design shall move in both linear and circular rotational ways (pan, tilt)	Can be simply observed, or validation in component choice and layout	Be able to move in both coordinate systems
Design shall be able to move the payload at a max speed no less than X m/s	Full speed straight line movement test (full payload)	12m/s
Design shall be able to move relative to surroundings at speeds of no more than X m/s	Full speed straight line movement test (full payload)	5m/s
Design shall be able to do a horizontal and vertical 180 degrees in X s in any configuration	Horizontal and vertical arcs at full speed (full payload)	3s
Design shall have repeatability up to X meters?	ISO 9283 Repeatability Test	0.04E-3 m to 0.003 m
Design shall be wired with minimum 7+ m cord length to a standard NA 120V outlet if wired	Measure (using measuring tape) the cord distance	3m (from EO)
Design shall support a payload of no less than 5 kg	Attach a 5kg weight on the camera mount, and operate the robotic arm at maximum speeds & rotations.	Movement and rotation are not disrupted, and robotic arm remains stable throughout entire test In the event of catastrophic failure, the payload should not be significantly damaged.

Design shall have a minimum clearance of 0.01 m from the ground (if wheeled)	Measure (using measuring tape) the close ground clearance distance	0.01m
Must be 3D printable or Low-cost CNC	Validation in component choices and layout	plus minus 0.03
Design shall not overheat	Place robot in different temperatures	-10°C =< x<= 55°C
Design shall have a sufficient IP rating	Spray water on robot and ensure no dust is collected after a long period of time	Body must be no less than IP%4 and the arm & wrist shall be a minimum of IP67
Design shall not have sharp edges/parts poking out	Measure angle	no angle less than 90°
Design shall be stable	Attach a 5kg weight on the camera mount, and operate the robotic arm at maximum speeds & rotations.	Movement and rotation are not disrupted, and robotic arm remains stable throughout entire test
Design shall offer modularity with a standard camera	Test to standards of ISO 1222:2010 by the ANSI	Mitchell mount with adapter for 1/4-20 UNC Thread Size
Design shall be operable by one operator	A singular person should be observed to properly operate the machine for all common cinematography shots	Pan (left/right) Tilt (up/down) Tracking/Dolly Shots Zoom and Dolly Zoom/Vertigo
Design shall be open-source	Online Accessible	Online Accessible
Design shall be affordable for intended users	BOM - labour costs might be offloaded to user	Budget around ~15 000 USD to be sold, ~13 000USD to produce (~15% profit margin)

Appendix C

Appendix C.1

The full morph chart for the ideation of 8 full conceptual designs

Morph Chart.pdf

Appendix C.2

The full Pugh Chart, using design L1 as the datum, is shown below

	A1	A2	J1	J2	M1	M2	L1	L2
Sufficient DOF	1	1	0	-1	1	1	0	0
Max Speed - Linear	1	-1	-1	1	1	0	0	0
Max Speed - Rotational	1	0	0	-1	0	-1	0	1
Repeatability	1	1	0	1	1	0	0	-
Manufacturability	-1	-1	0	1	-1	-1	0	1
Stable	1	1	-1	1	1	1	0	0
Safety	0	0	0	0	0	0	0	1
Portability	0	-1	0	1	-1	0	0	0
Maintenance	-1	-1	0	0	-1	-1	0	-1
Sum	3	-1	-2	3	1	-1	0	2

Also accessible through the following link.
Pugh Chart.pdf

Appendix C.3
The full weighted decision matrix, along with the associated grading criteria to rank the designs.

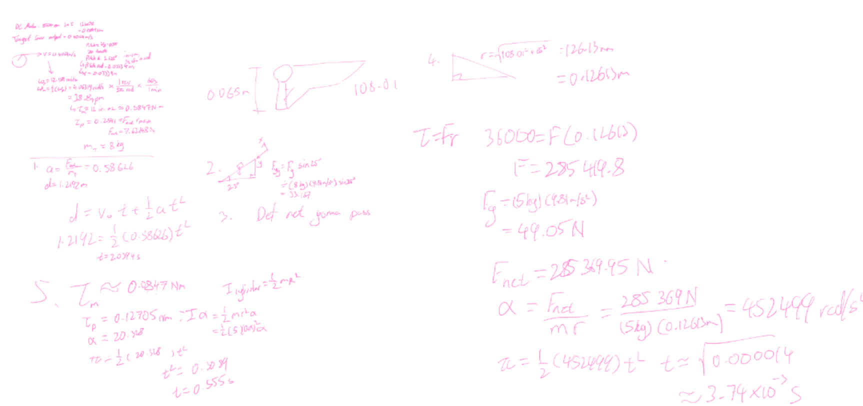
Criteria	Weight	Candidate 1	Weighted Score 1	Candidate 2	Weighted Score 2	Candidate 3	Weighted Score 3
Sufficient DOF	10	1	0.1	4	0.4	1	0.1
Max Speed - Linear	10	4	0.4	4	0.4	4	0.4
Max Speed - Rotational	15	5	0.75	5	0.75	5	0.75
Repeatability	10	4	0.4	5	0.5	4	0.4
Manufacturability	5	2	0.1	2	0.1	4	0.2
Safety	20	3	0.3	5	1	4	0.8
Portability	10	5	0.75	3	0.3	5	0.5
Maintenance	5	3	0.3	1	0.05	3	0.15
Cost	15	1	0.15	1	0.15	4	0.6
Sum			3.25		3.65		3.9

1/5	2/5	3/5	4/5	5/5	
3DOF	4DOF	5DOF	6DOF	7DOF	
Low linear reach in both horizontal and vertical capacities. No dedicated actuators	Low linear reach in one of hori. and vert. No dedicator actutors	Low linear reach in one of hori. and vert. Weak dedicated actuators	Low linear reach in one of hori. and vert. Strong dedicated actutor	High linear reach in both hori. and vert. Strong dedicated actutor	*Highest criteria met
Rotational reach in both horizontal and vertical capacities. No dedicated actuators	Low rotational reach in one of pitch and yaw. No dedicator actuators	Low rotational reach in one of pitch and yaw. Weak dedicated actutors	Low rotational reach in one of pitch and yaw. Strong dedicated actuator	High rotational reach in both pitch and yaw. Strong dedicated actuator	
>= 4 imprecise actuators, motion transmission, modification	3 imprecise actuators, motion transmission, modification	2 imprecise actuators, motion transmission, modification	1 imprecise actuators, motion transmission, modification	No imprecise actuators, motion transmission, modification	

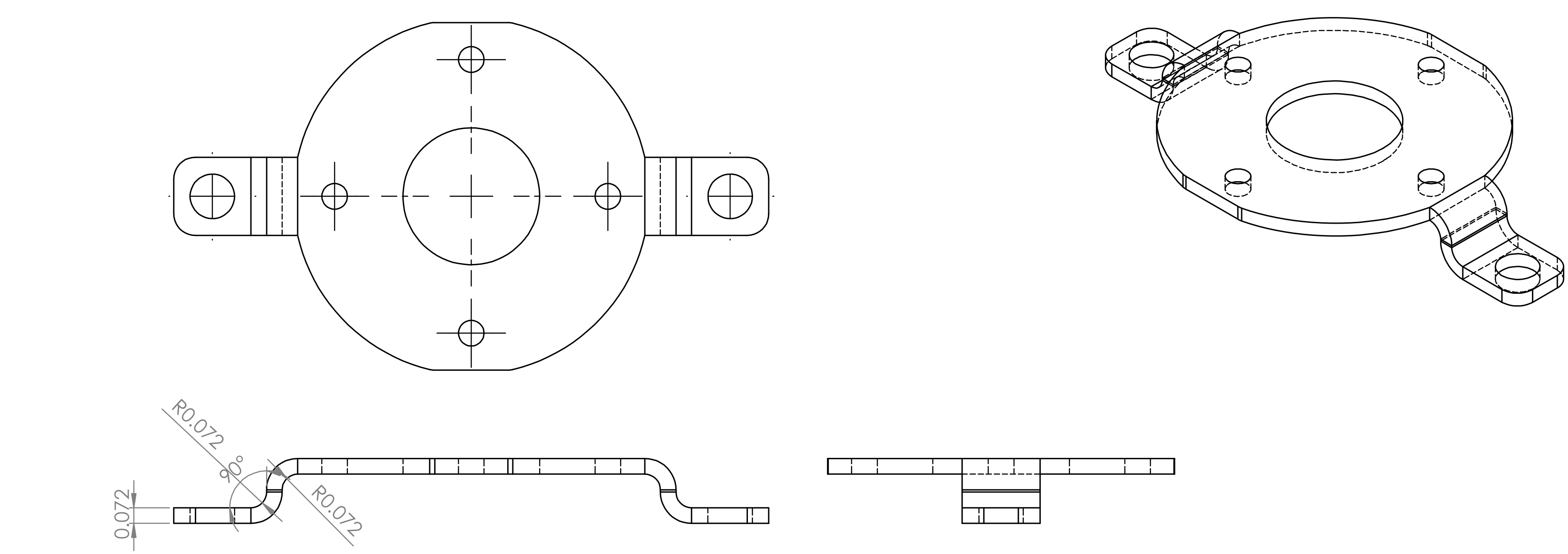
Requires machinery outside of MC78 and professional machinists. Possible additive metalurgy	Requires machinery present in MC78 and professional machinists	requires expertise whih can be created only in MC78 and professional machinists	Requires some expertise, but is able to be created within MC78 or MyFab	requires all parts to be manufactured in MyFab	
No redundant E-stop for failures. Possible major bodily harm if within work envelope	One redundant E-stop failures. Possible major bodily harm if within work envelope.	Two redundant E-stop failures. Possible bodily harm if within work envelope	Three redundant E-stop failures. Extremely unlikelihood of bodily harm if within work envelope.	Multiple redudant E-stop for failures. Extremly unlikelidhood of bodily harm if within work envelope.	
	Long setup time, doable by one person. Can be transported by one person. Large footprint		Slow setup time, doable by one person. Can be transported by one person. Low footprint	Quick setup time, doable by one person. Can be transported by one person. Low footprint	*One person is standard to FSAE Percy
Complex mechanical design. Only repairable by specialist.				Open and simple mechanical design. Repairable by non-specialist.	
Use of non-standardized parts,				All parts are standardized or 3D printable (ploymers)	

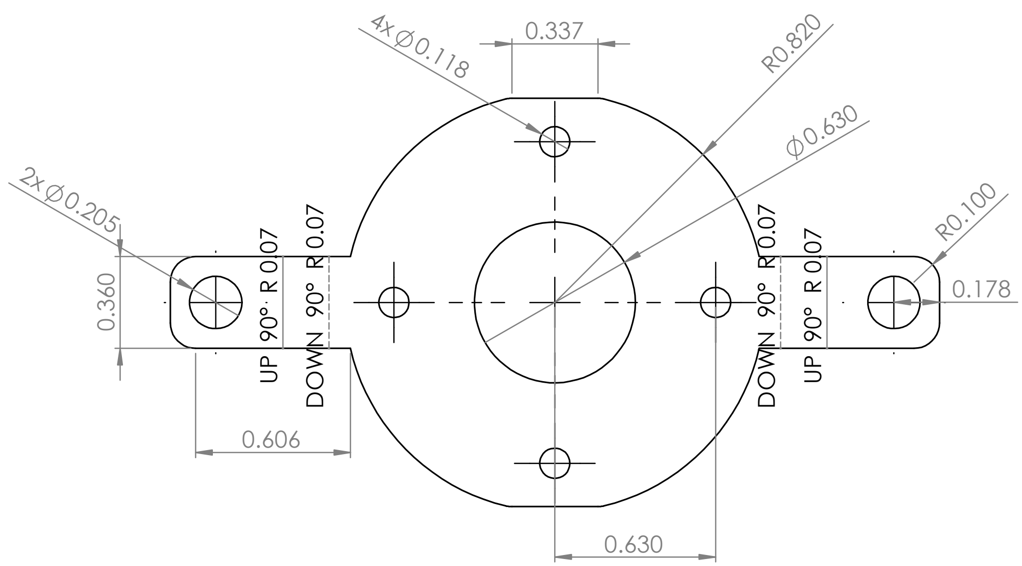
Appendix D

Very rough calculations for the linear travel speed, pitch rotational and yaw rotational speeds.

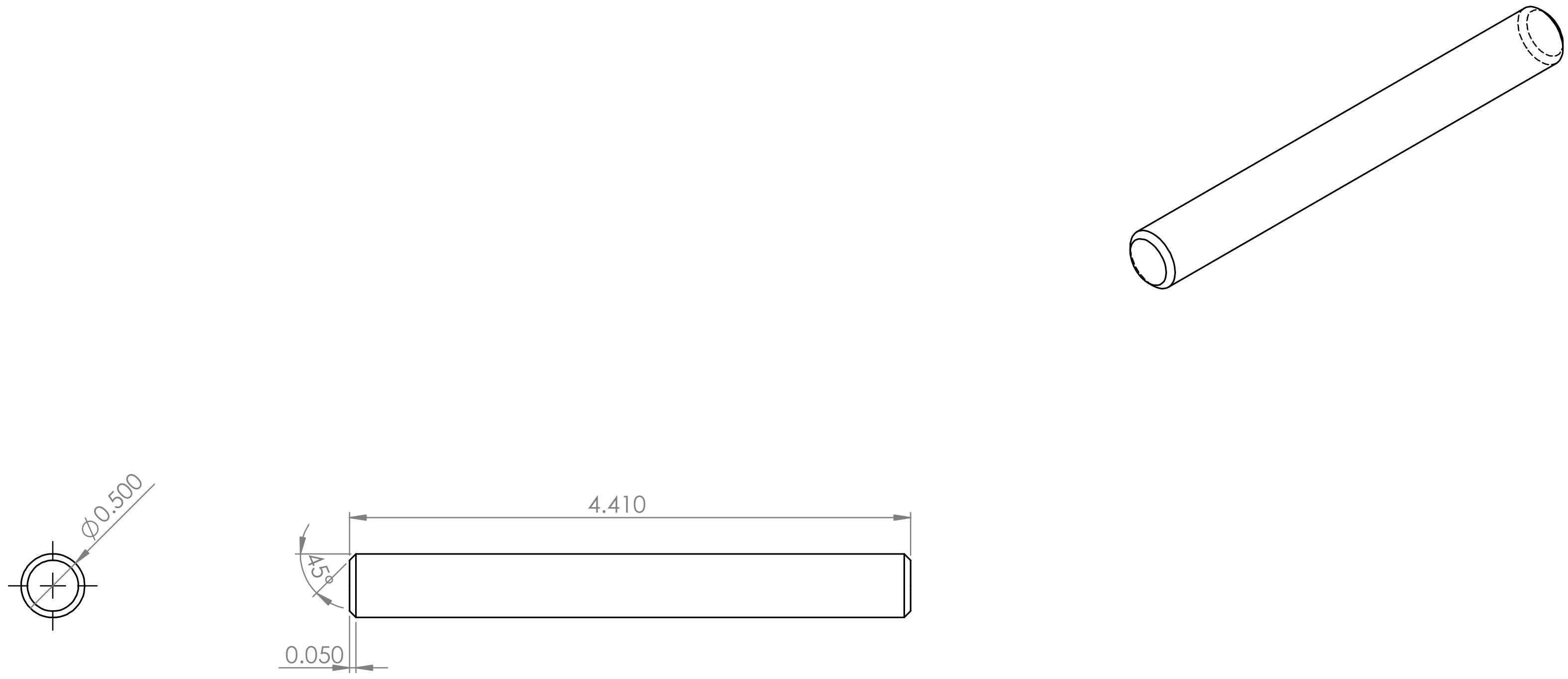


Appendix E: All Drawings

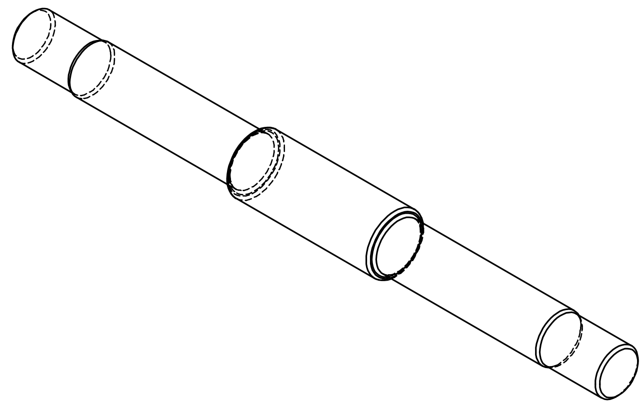


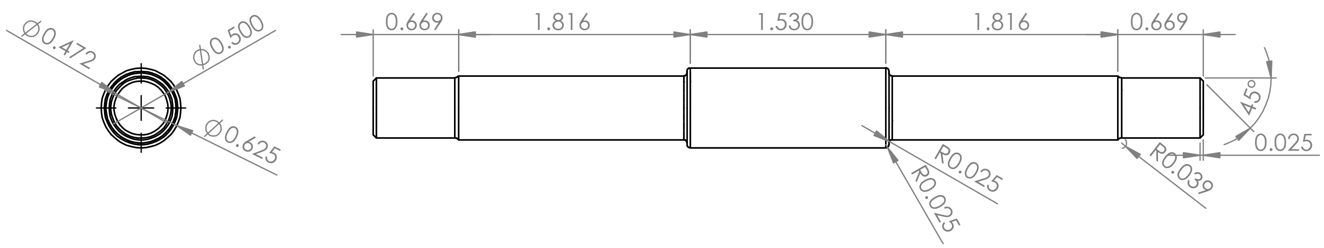


AUTHOR: Adalric Tai	CLASS: MIE 243	Group #: 3	PREPARED FOR: Motor Housing
STUDENT NO. 1010961924	TITLE: Motor Bracket		
DATE: 2025-12-02			
MATERIAL: 6061-Aluminum	PART NO. N/A		REV. 1
UNLESS OTHERWISE SPECIFIED, UNITS: IN, DEGREE	SCALE:1:1	SHEET 1 OF 1	

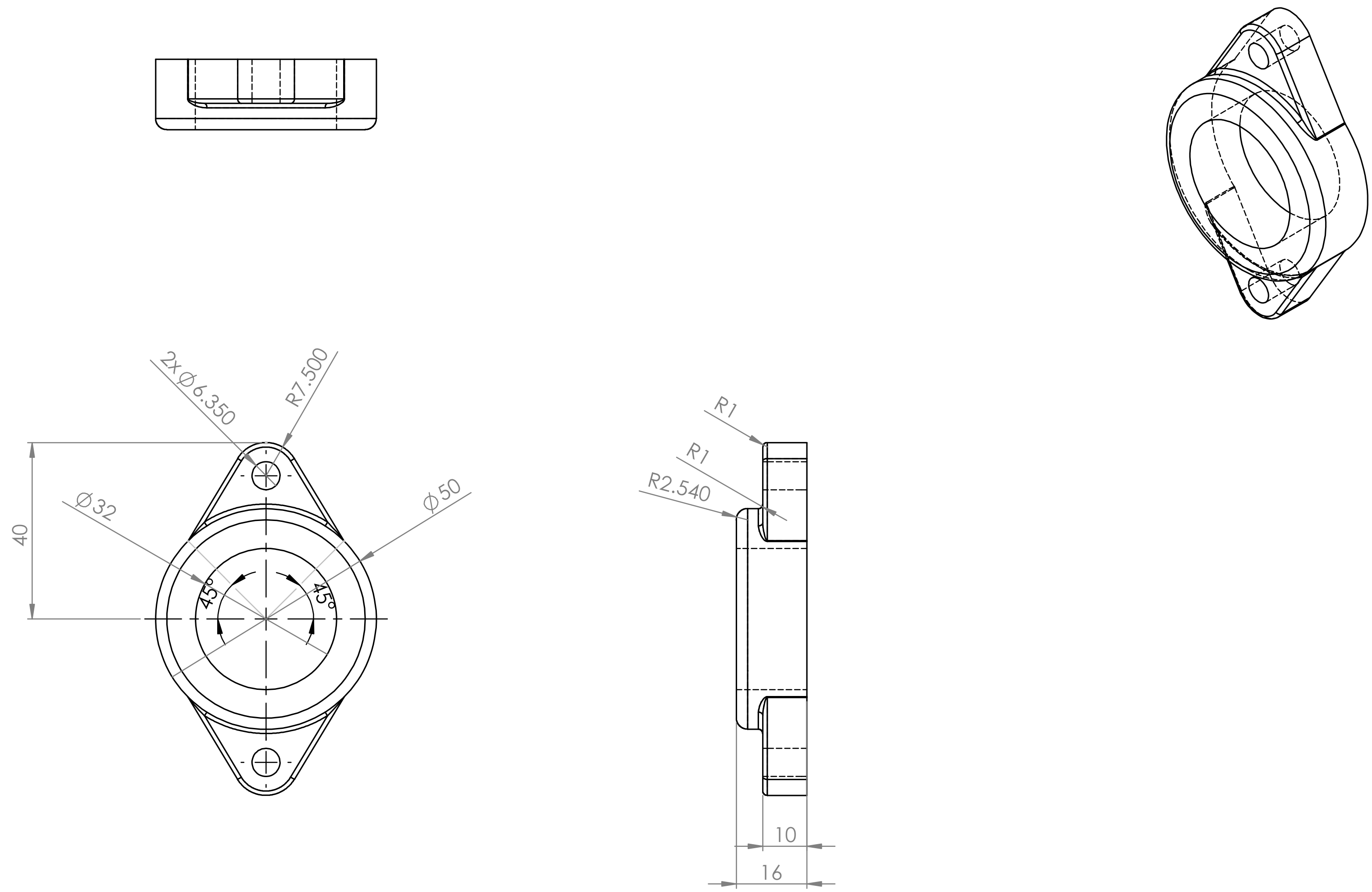


AUTHOR: Adalric Tai	CLASS: MIE 243	Group #: 3	PREPARED FOR: Motor Housing
STUDENT NO. 1010961924	TITLE: Motor Shaft		
DATE: 2025-12-02			
MATERIAL: 6061-Aluminum	PART NO. N/A		REV. 1
UNLESS OTHERWISE SPECIFIED, UNITS: IN, DEGREE	SCALE:1:1	SHEET 1 OF 1	

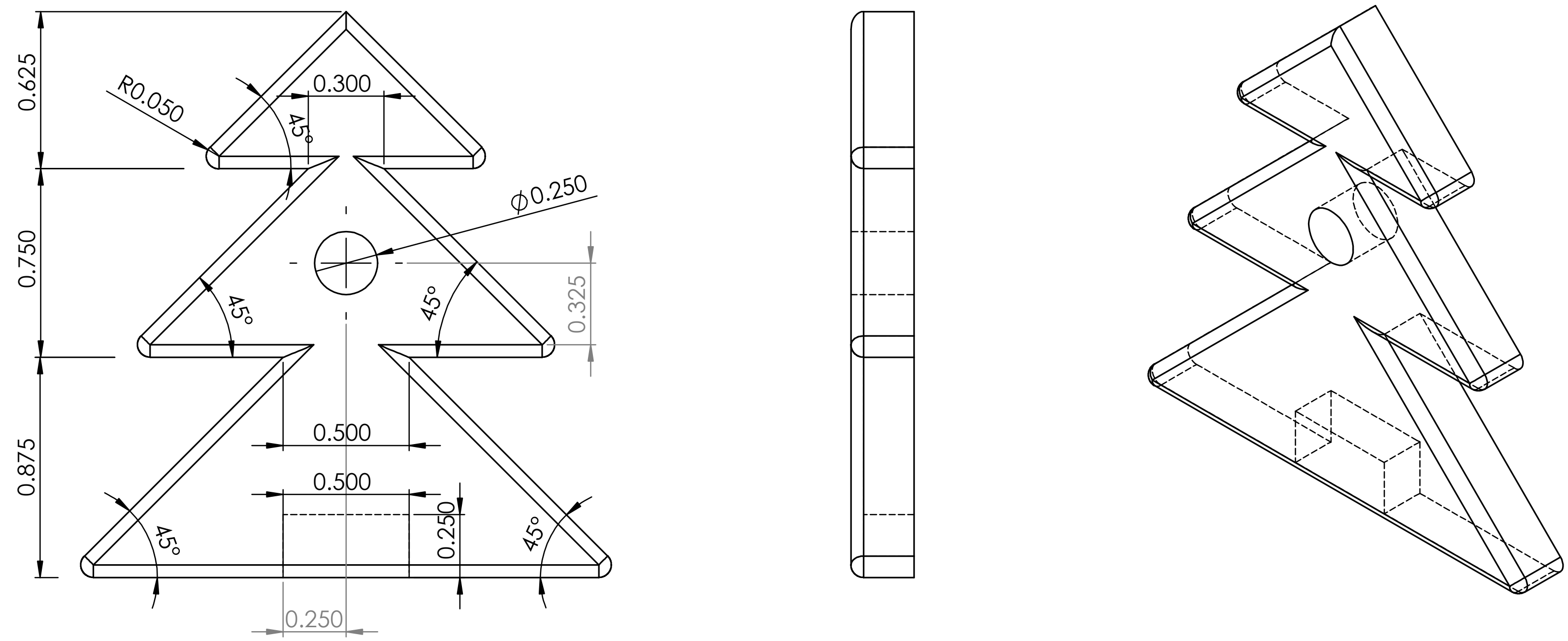


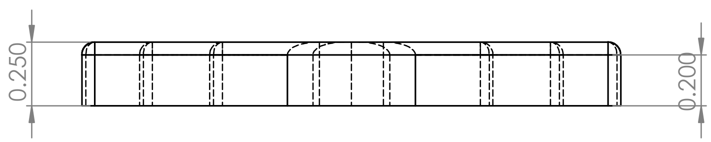


AUTHOR: Adalric Tai	CLASS: MIE 243	Group #: 3	PREPARED FOR: Motor Housing
STUDENT NO. 1010961924	TITLE: Pulley Shaft		
DATE: 2025-12-02			
MATERIAL: 6061-Aluminum	PART NO. N/A		REV. 1
UNLESS OTHERWISE SPECIFIED, UNITS: IN, DEGREE	SCALE:1:1		SHEET 1 OF 1



AUTHOR: Adalric Tai	CLASS: MIE 243	Group #: 3	PREPARED FOR: Motor Housing
STUDENT NO. 1010961924	TITLE: Bearing Housing		
DATE: 2025-12-02			
MATERIAL: 6061-Aluminum	PART NO. N/A		REV. 1
UNLESS OTHERWISE SPECIFIED, UNITS: MM, DEGREE	SCALE:1:1		SHEET 1 OF 1





AUTHOR: Adalric Tai	CLASS: MIE 243	Group #: 3	PREPARED FOR: Motor Housing
STUDENT NO. 1010961924	TITLE: Christmas Tree Leg		
DATE: 2025-12-02			
MATERIAL: Titatnium	PART NO. MH21	REV. 1	
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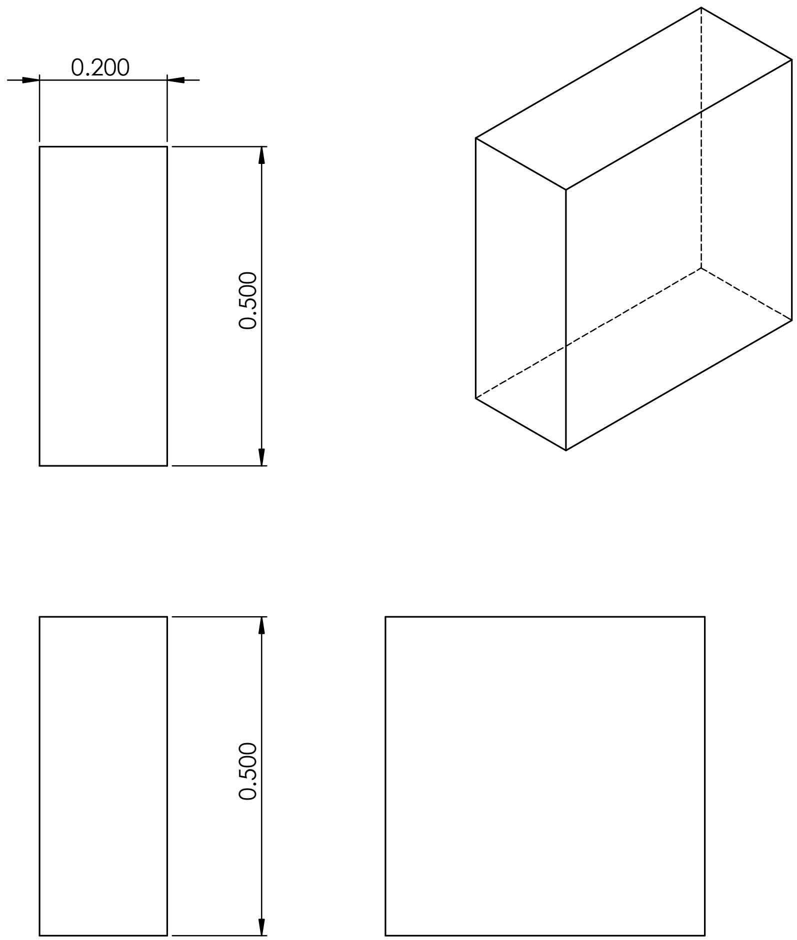
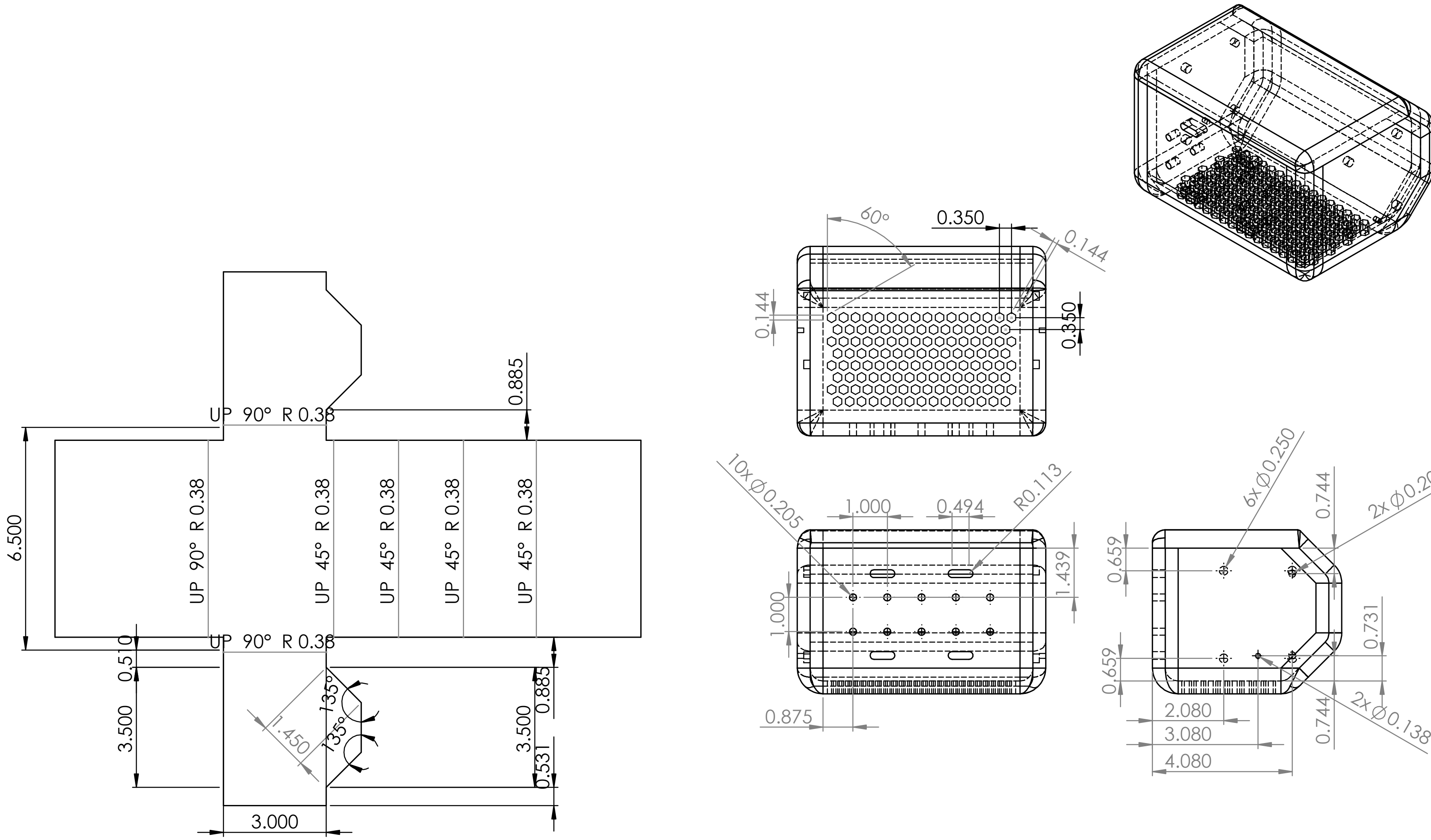
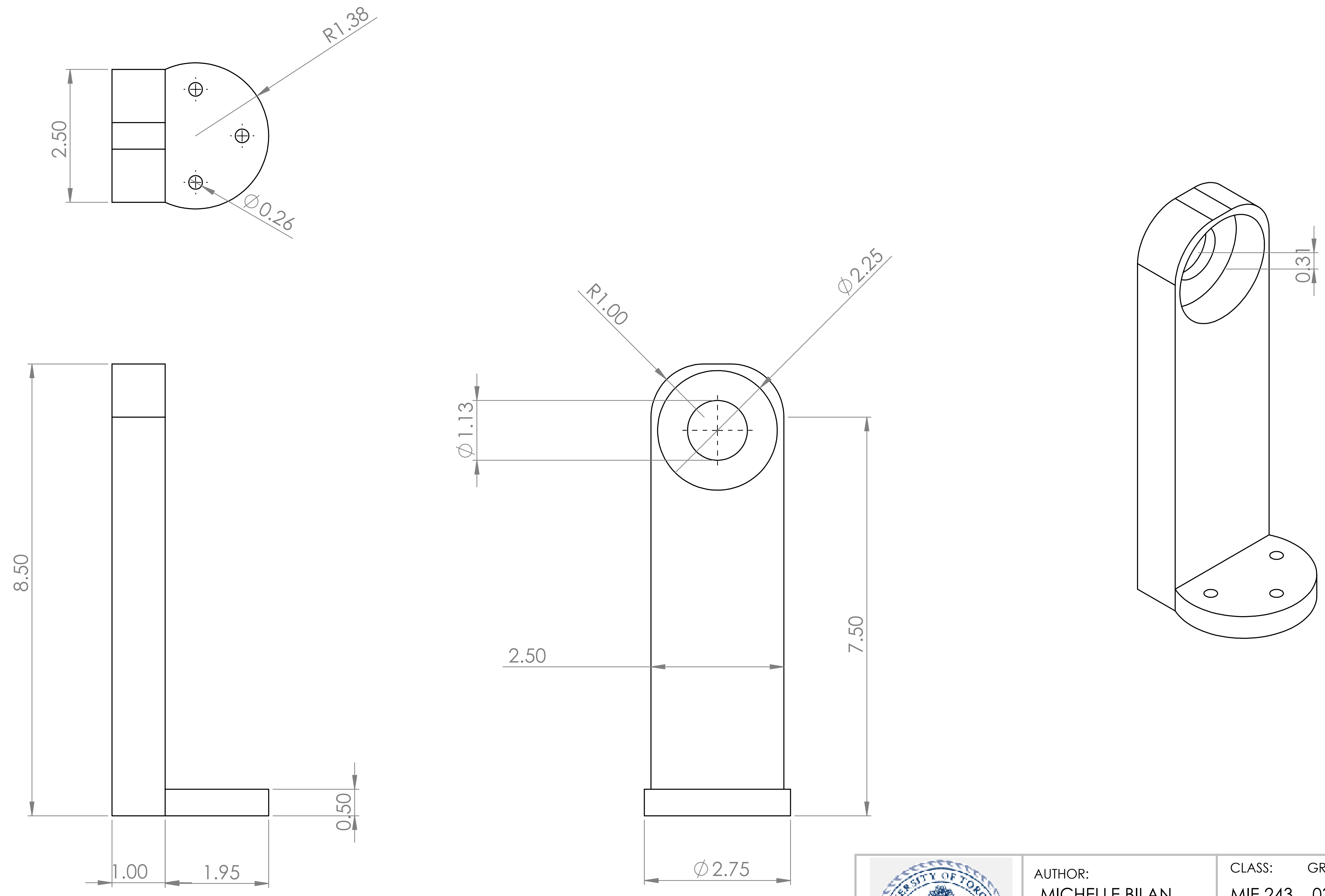


AUTHOR: Adalric Tai	CLASS: MIE 243	Group #: 3	PREPARED FOR: Motor Housing
STUDENT NO. 1010961924	TITLE: Leg Rubber		
DATE: 2025-12-02			
MATERIAL: Rubber	PART NO. MH22		REV. 1
UNLESS OTHERWISE SPECIFIED, UNITS: IN, DEGREE	SCALE:1:1	SHEET 1 OF 1	



AUTHOR: Adalric Tai	CLASS: MIE 243	Group #: 3	PREPARED FOR: Motor Housing	
STUDENT NO. 1010961924	TITLE: Gearbox Housing			
DATE: 2025-12-02				
MATERIAL: 6061-Aluminum	PART NO. M09		REV. 1	
UNLESS OTHERWISE SPECIFIED, UNITS: IN, DEGREE	SCALE:1:1		SHEET 1 OF 1	



AUTHOR: MICHELLE BILAN

CLASS: MIE 243

GROUP: 03

PREPARED FOR: DRAWING PURPOSE

STUDENT NO. 1010946185

DATE: 2025-12-02

TITLE:

Gimbal Stand

MATERIAL: 2014 T6 ALUMINUM

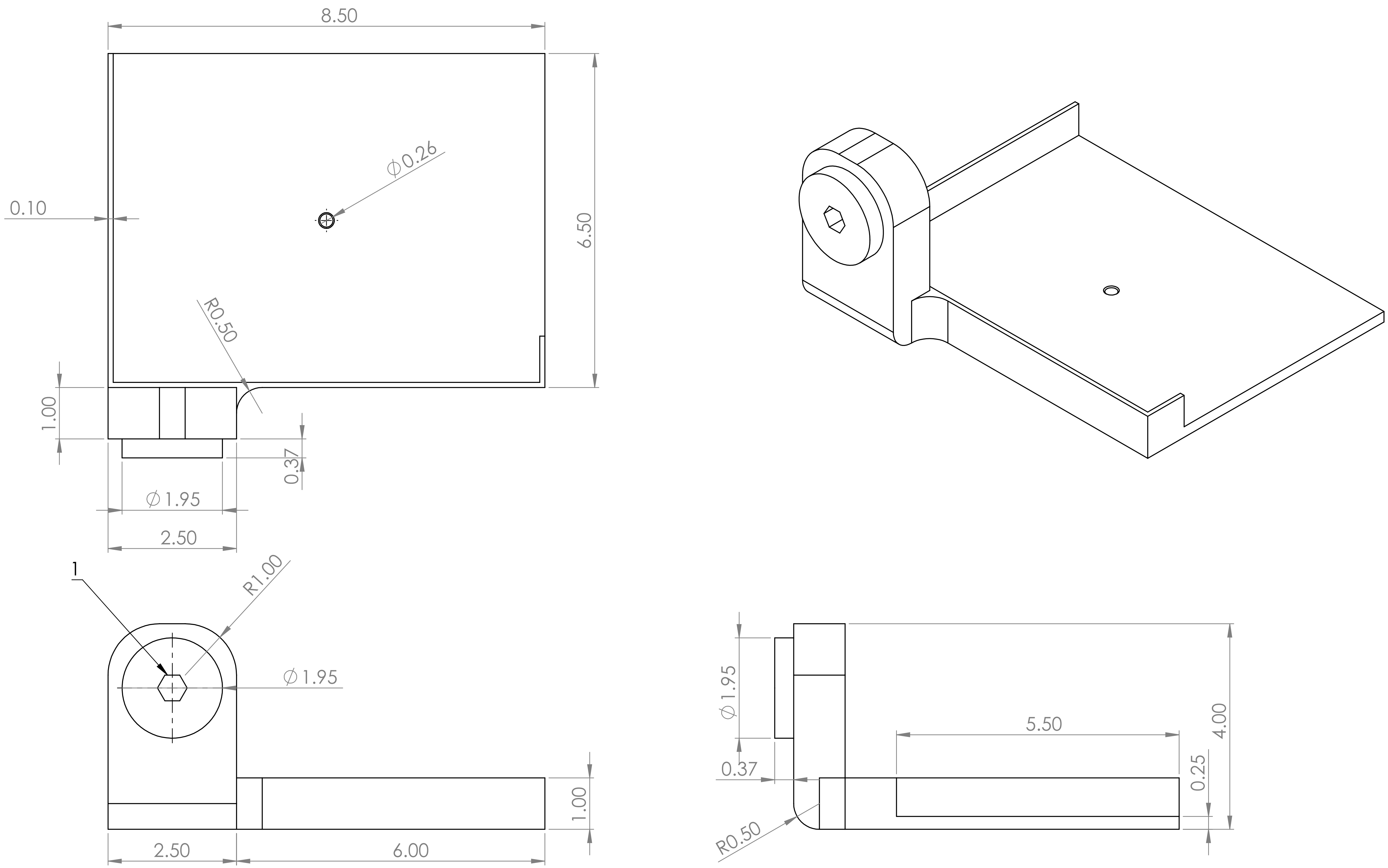
PART NO. N/A

REV. 1

UNLESS OTHERWISE SPECIFIED, UNITS: IN, DEGREE

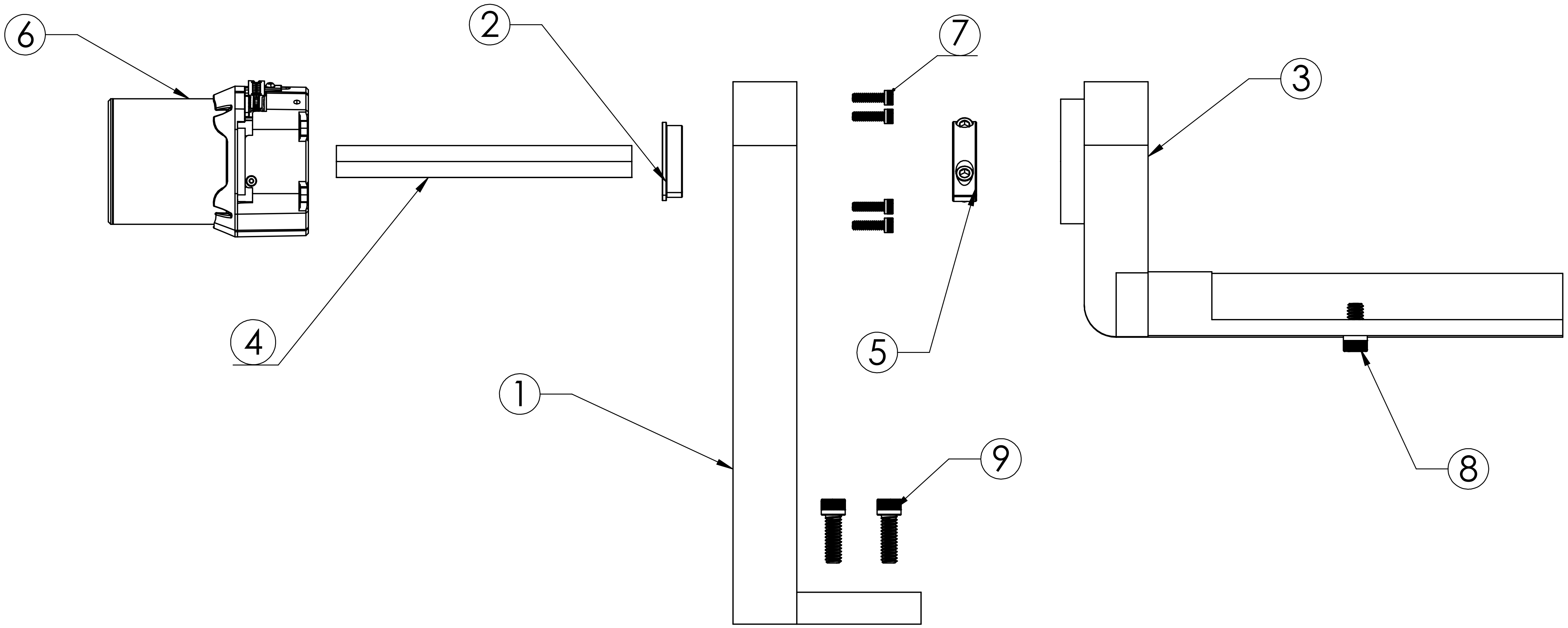
SCALE:1:2

SHEET 1 OF 1



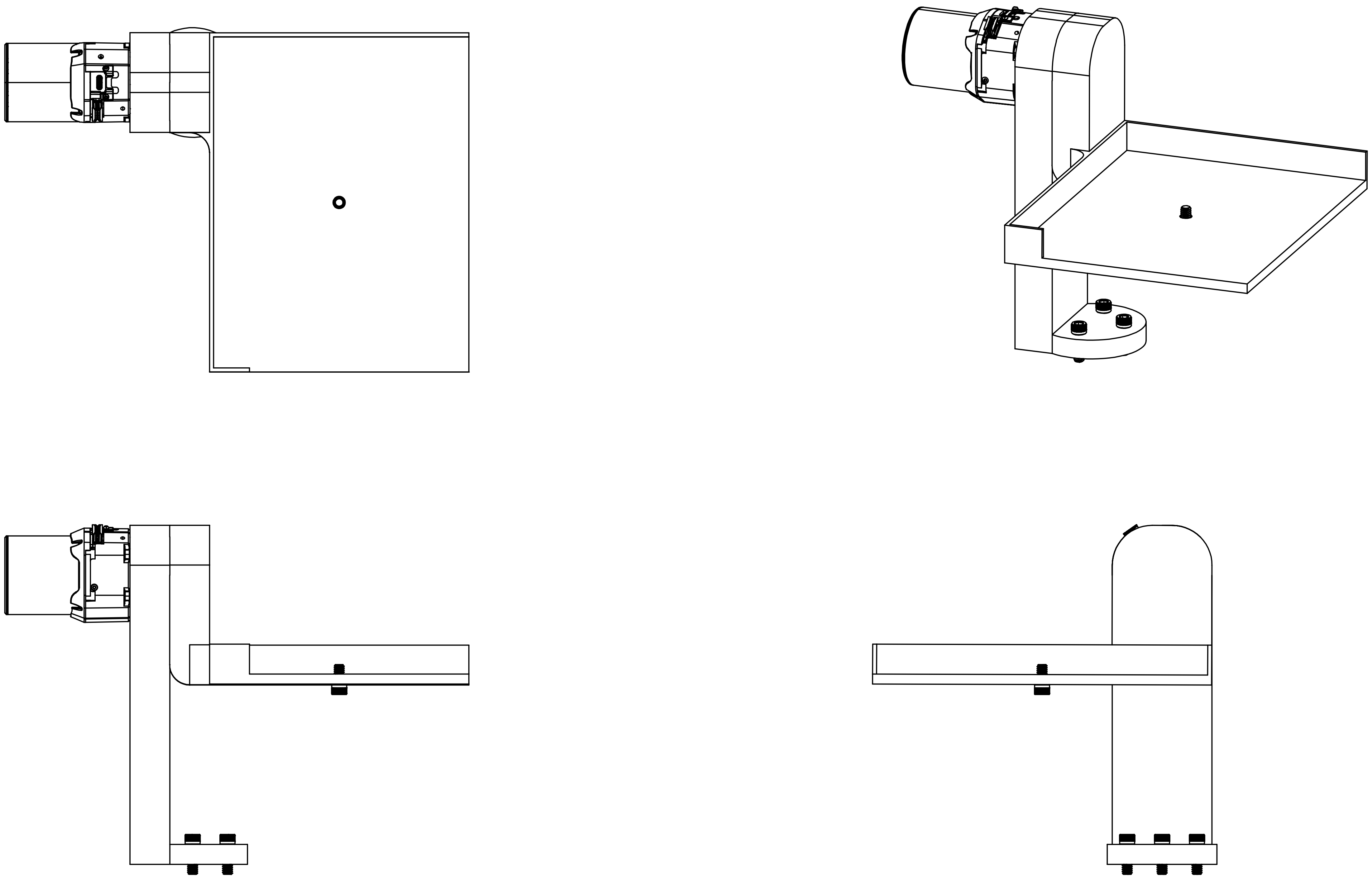
NOTES:
1. 1/2" Hex Bore

AUTHOR: MICHELLE BILAN	CLASS: MIE 243	GROUP 03	PREPARED FOR: DRAWING PURPOSE
STUDENT NO. 1010946185	TITLE: Gimbal Tray		
DATE: 2025-12-02			
MATERIAL: 2014 T6 ALUMINUM	PART NO. N/A	REV. 1	
UNLESS OTHERWISE SPECIFIED, UNITS: IN, DEGREE	SCALE:1:2	SHEET 1 OF 1	



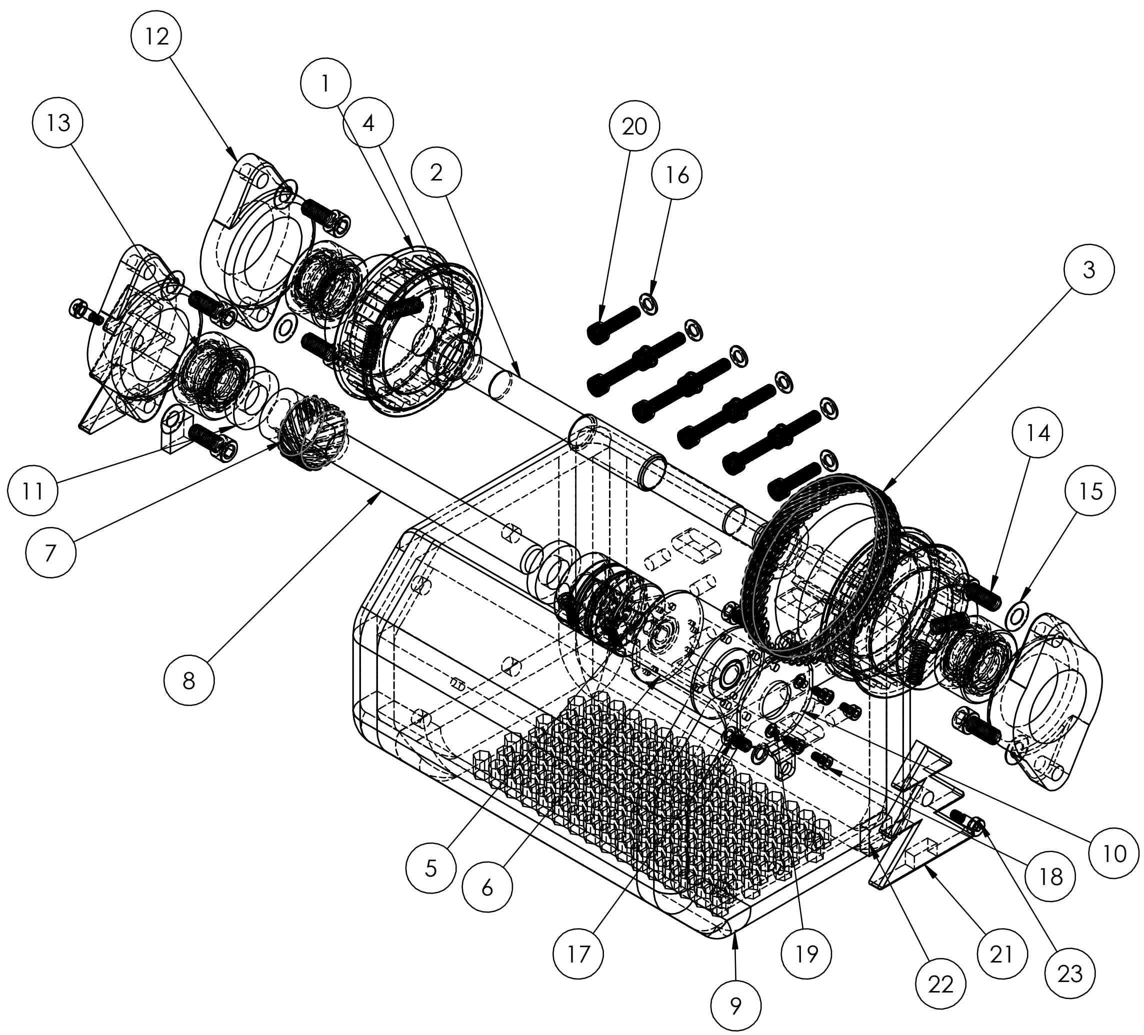
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	MG-01	Stand	1
2	MG-02	Hex Bearing	1
3	MG-03	Gimbal Tray	1
4	MG-04	Low-Carbon Steel Hex Bar	1
5	MG-05	Hex Shaft Collar	1
6	MG-06	NEO-Vortex-Moter-and-SPARK-Flex-Motor-Controller-with-8mm-Shaft	1
7	HW-06	1/2" 6-32 Black-Oxide Alloy Steel Socket Head Screw	6
8	HW-07	1/2" 1/4-20 Black-Oxide Alloy Steel Socket Head Screw	1
9	HW-08	3/4" 1/4-20 Black-Oxide Alloy Steel Socket Head Screw	3

UNIVERSITY OF TORONTO ENGINEERING	AUTHOR: MICHELLE BILAN	CLASS: MIE 243 GROUP: 03	PREPARED FOR: DRAWING PURPOSE
	STUDENT NO. 1010946185	TITLE: Motorized Gimbal Assembly	
	DATE: 2025-12-02		
	MATERIAL: MIXED	PART NO. N/A	REV. 1
UNLESS OTHERWISE SPECIFIED, UNITS: IN, DEGREE		SCALE:1:2	SHEET 1 OF 1



	AUTHOR: MICHELLE BILAN	CLASS: MIE 243 GROUP: 03	PREPARED FOR: DRAWING PURPOSE
	STUDENT NO. 1010946185	TITLE: Gimbal Assembly	
	DATE: 2025-12-02		
	MATERIAL: MIXED	PART NO. N/A	REV. 1
UNLESS OTHERWISE SPECIFIED, UNITS: IN, DEGREE		SCALE:1:3	SHEET 1 OF 1

PART #	PART NUMBER	DESCRIPTION	QTY.
1	MH01	L Series Corrosion-Resistant Timing Belt Pulley	2
2	MH02	Pulley Shaft	1
3	MH03	48-Tooth Helical Gear	1
4	MH04	Aluminum Unthreaded Spacer	2
5	MH05	Clamping Precision Flexible Shaft Coupling	1
6	MH06	Brushless DC Motor	1
7	MH07	16-Tooth Helical Gear	1
8	MH08	Motor Shaft	1
9	MH09	Gearbox Housing	1
10	MH10	Motor Bracket	1
11	MH11	Off-White Nylon Unthreaded Spacer	2
12	MH12	Bearing Housing	3
13	MH13	Angular-Contact Double Row Ball Bearing	3
14	MH-14	Black-Oxide Alloy Steel Socket Head Screw	6
15	MH-15	Aluminum Mil. Spec. Washer	6
16	MH-17	18-8 Stainless Steel Mil. Spec. Washer	12
17	MH-20	Black-Oxide Alloy Steel Socket Head Screw	2
18	MH-18	Alloy Steel Socket Head Screw	4
19	MH-19	Black-Oxide 18-8 Stainless Steel Washer	4
20	MH-16	Black-Oxide Alloy Steel Socket Head Screw	10
21	MH-21	Christmas Tree Leg	2
22	MH-22	Leg Rubber	2
23	MH-23	Alloy Steel Shoulder Screw	2



AUTHOR: Adalric Tai

CLASS: MIE 243 Group #: 3

PREPARED FOR: Motor Housing

STUDENT NO. 1010961924

TITLE: Motor Housing Sub-Assembly

DATE: 2025-12-02

MATERIAL: N/A

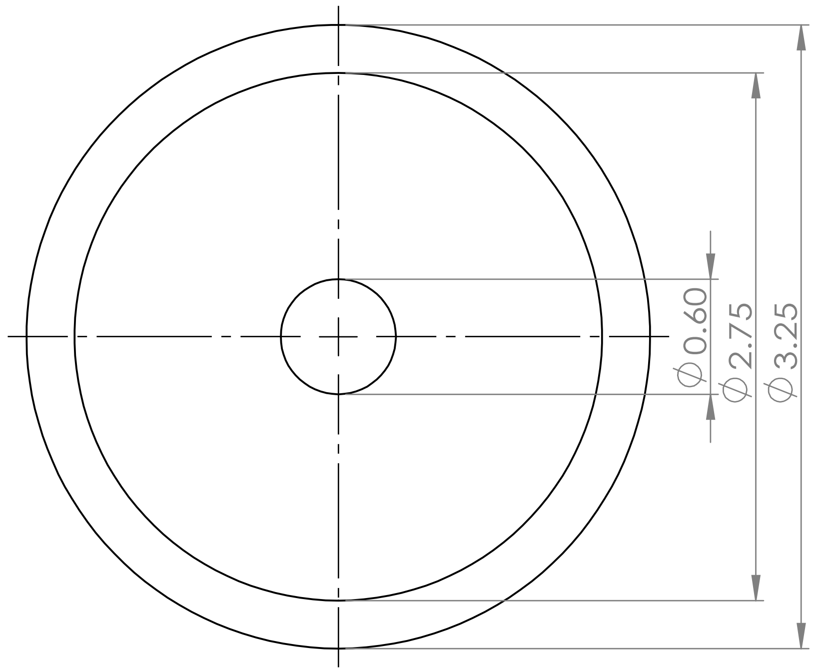
PART NO. N/A

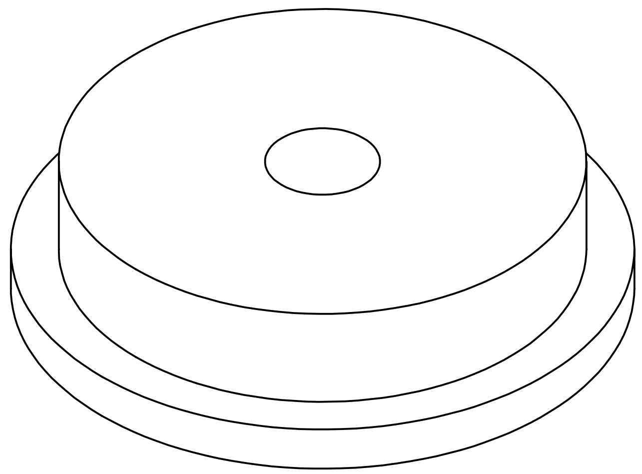
REV. 1

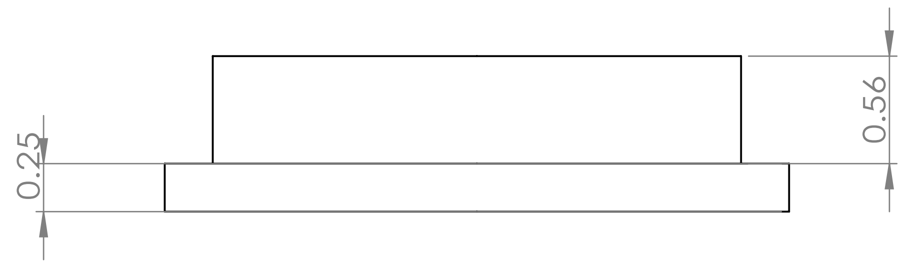
UNLESS OTHERWISE SPECIFIED, UNITS: MM, DEGREE

SCALE:1:1

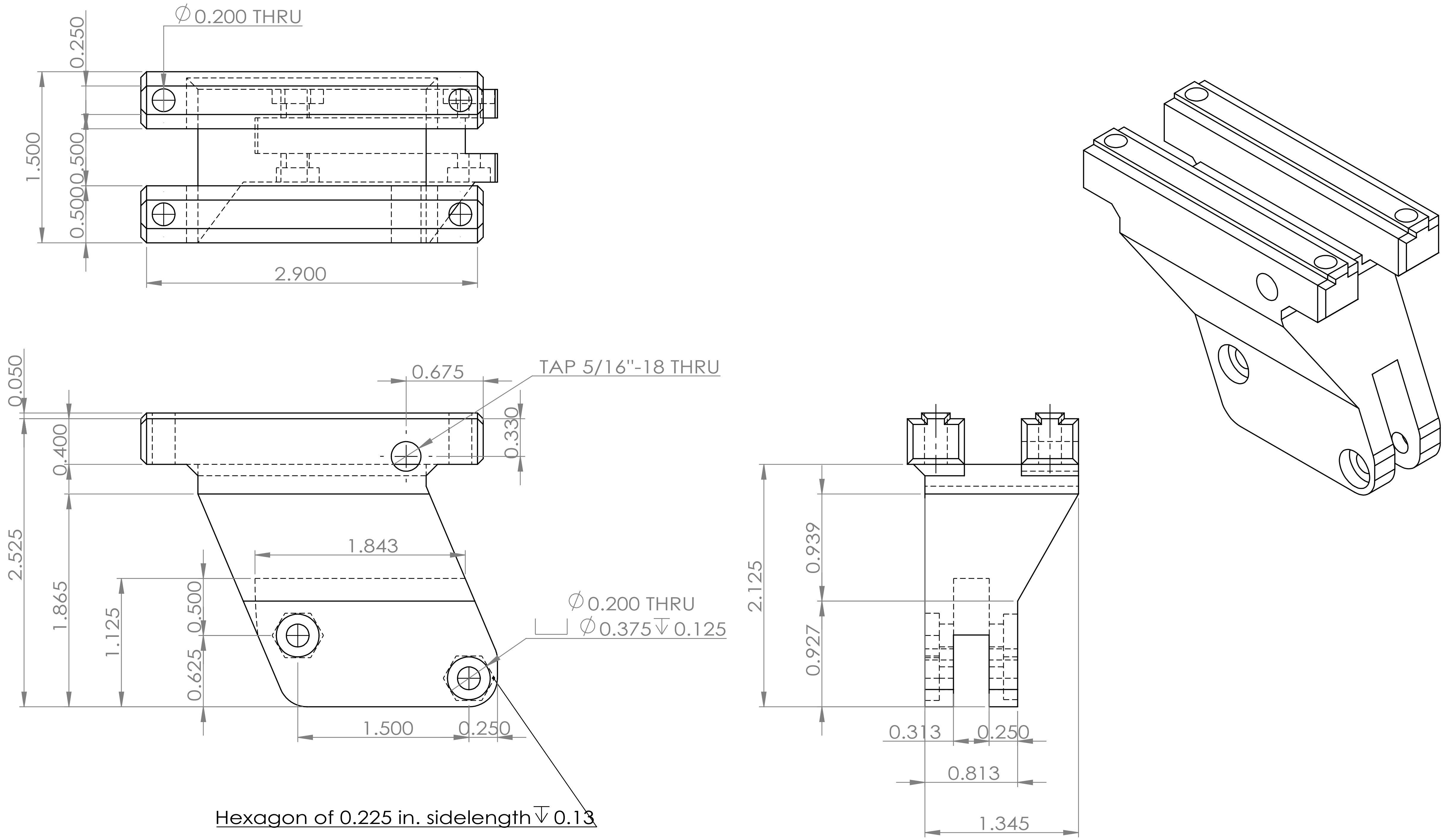
SHEET 1 OF 1



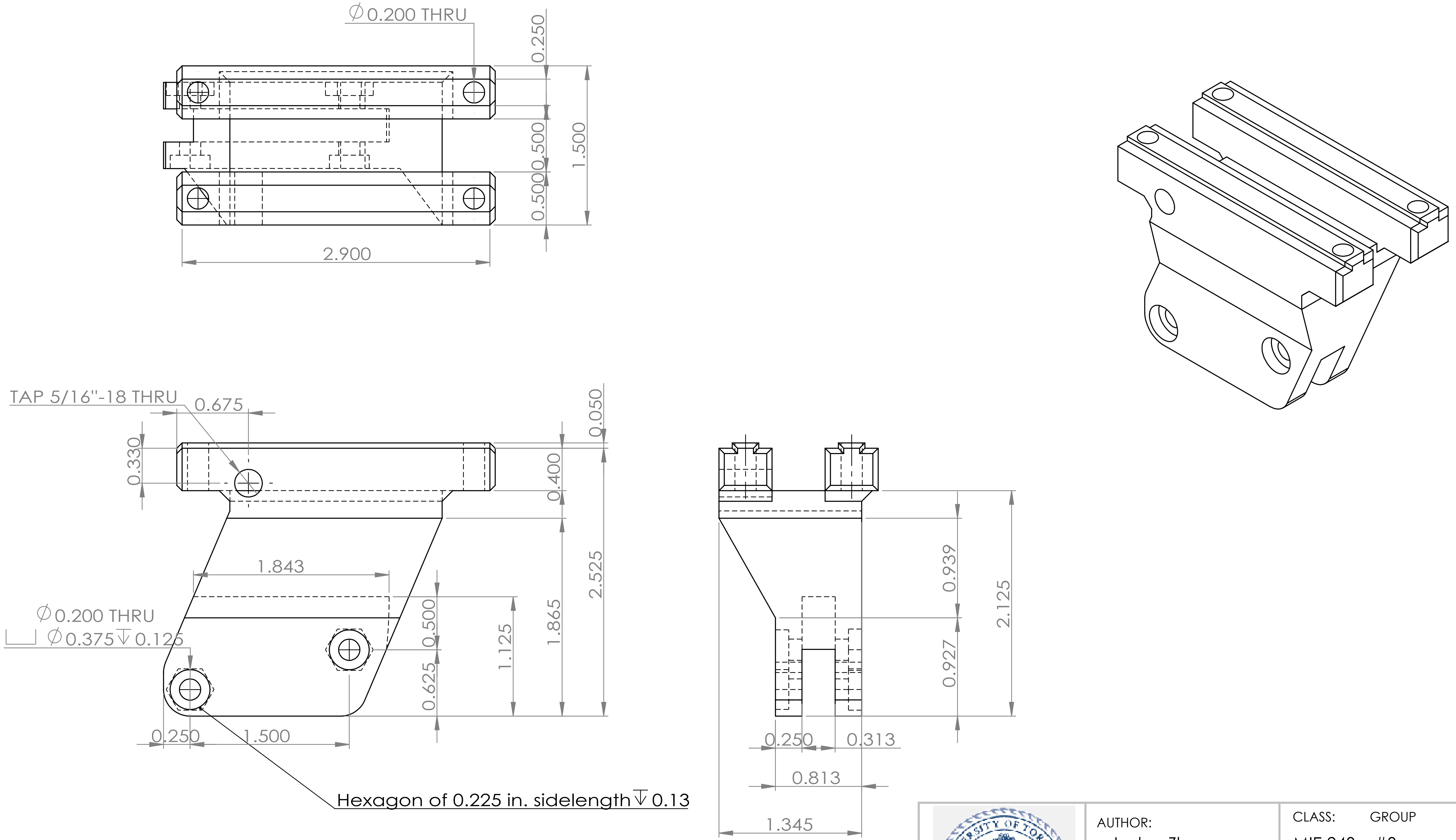




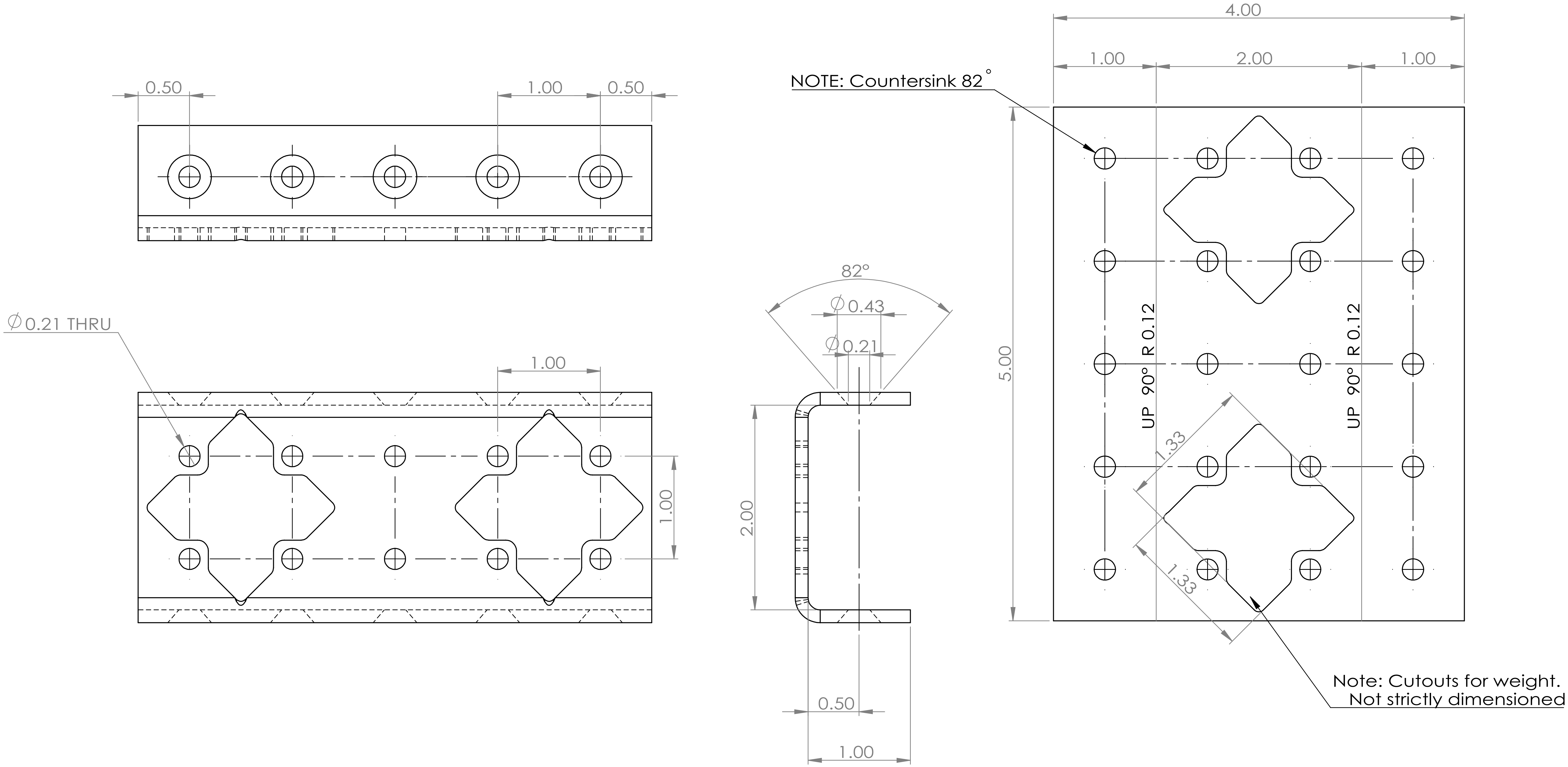
AUTHOR: Jaden Zhang	CLASS: MIE 243	GROUP #7	PREPARED FOR: DRAWING PURPOSE	
STUDENT NO. 1011011815	TITLE: Pop-pin Housing Bottom Clamp			
DATE: 12/2/2025				
MATERIAL: 6061-T6(SS)	PART NO. PP-2		REV. 1	
UNLESS OTHERWISE SPECIFIED, UNITS: INCHES, DEGREE	SCALE:1:1		SHEET 1 OF 1	



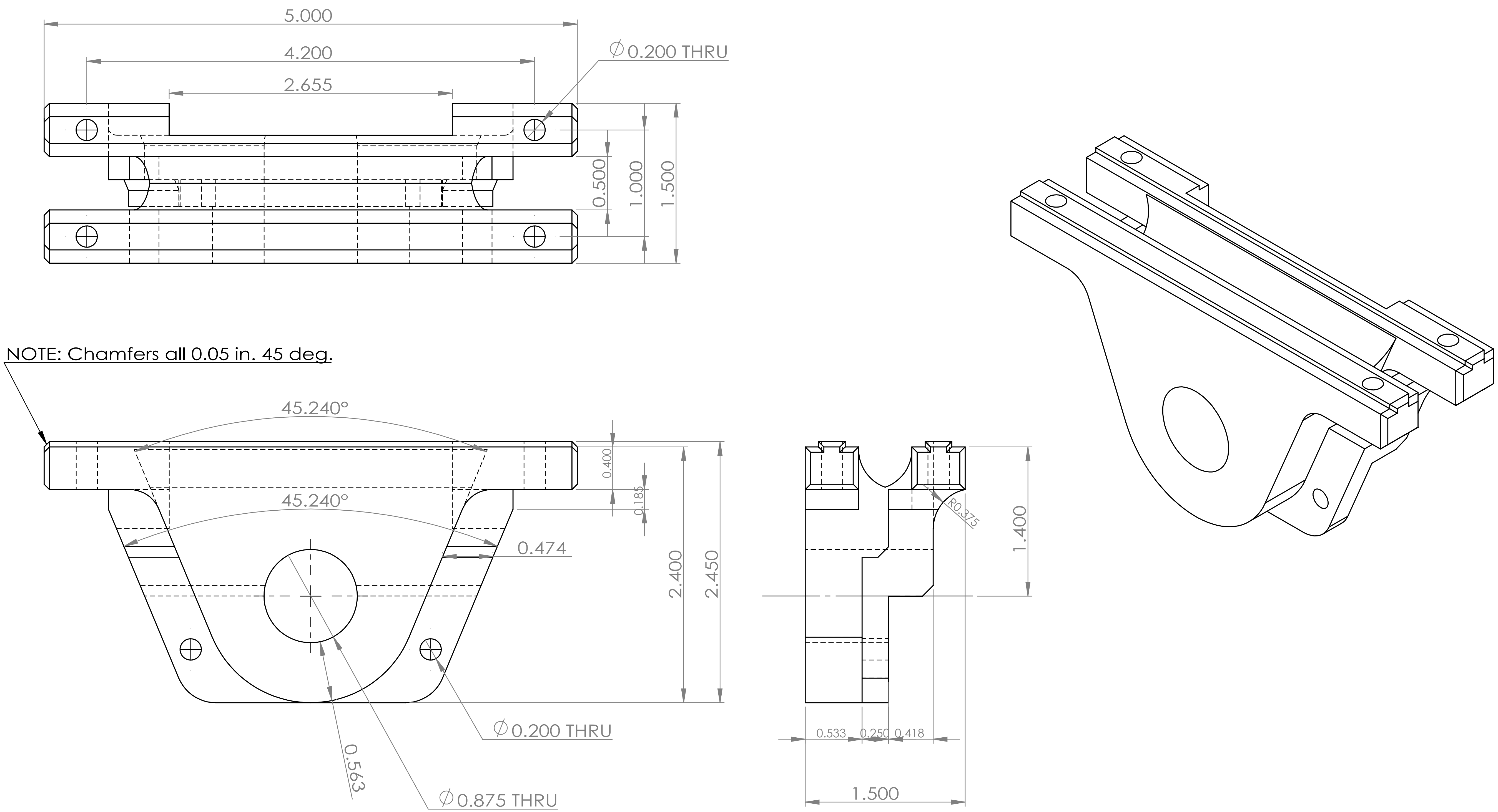
	AUTHOR: Jaden Zhang	CLASS: MIE 243 GROUP #3	PREPARED FOR: DRAWING PURPOSE
	STUDENT NO. 1011011815	TITLE: Track Side Connecter (R)	
	DATE: 12/2/2025		
	MATERIAL: 1060 Alloy	PART NO. TR-06	REV. 1
UNLESS OTHERWISE SPECIFIED, UNITS: INCHES, DEGREE		SCALE:1:1	SHEET 1 OF 1



AUTHOR: Jaden Zhang	CLASS: MIE 243	GROUP #3	PREPARED FOR: DRAWING PURPOSE
STUDENT NO. 1011011815	TITLE: Track Side Connecter (R)		
DATE: 12/2/2025			
MATERIAL: 1060 Alloy	PART NO. TR-06		REV. 1
UNLESS OTHERWISE SPECIFIED, UNITS: INCHES, DEGREE	SCALE:1:1		SHEET 1 OF 1



AUTHOR: Jaden Zhang	CLASS: MIE 243	GROUP #3	PREPARED FOR: DRAWING PURPOSE
STUDENT NO. 1011011815	TITLE: Track End Brace		
DATE: 12/2/2025			
MATERIAL: 6061 Alloy (Sheet)	PART NO. TR-03		REV. 1
UNLESS OTHERWISE SPECIFIED, UNITS: INCHES, DEGREE	SCALE:1:1		SHEET 1 OF 1



AUTHOR: Jaden Zhang

CLASS: MIE 243 GROUP #3

PREPARED FOR: DRAWING PURPOSE

STUDENT NO. 1011011815

DATE: 12/2/2025

TITLE: Track Bottom Connector

MATERIAL: 1060 Alloy

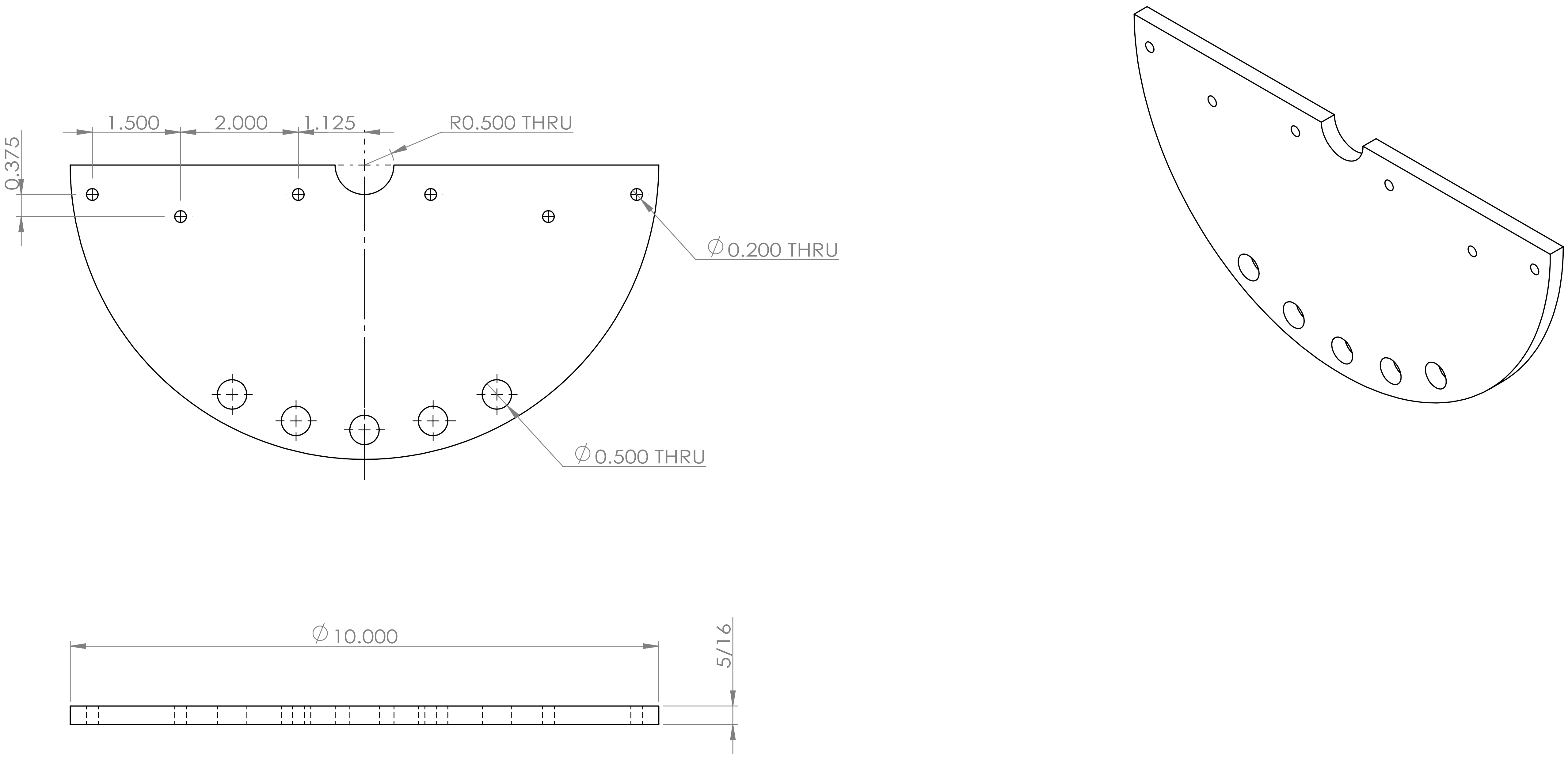
PART NO. TR-07

REV. 1

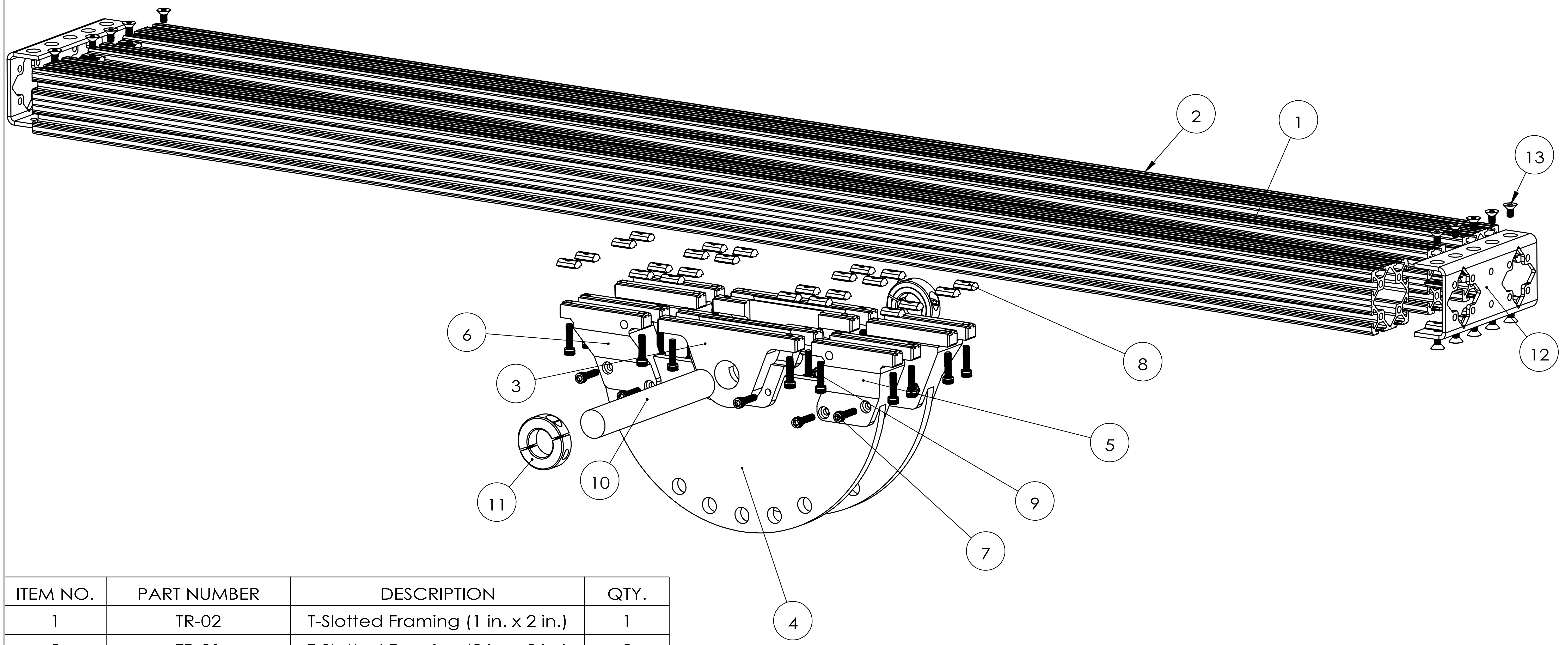
UNLESS OTHERWISE SPECIFIED, UNITS: INCHES, DEGREE

SCALE:1:1

SHEET 1 OF 1



AUTHOR: Jaden Zhang	CLASS: MIE 243	GROUP #3	PREPARED FOR: DRAWING PURPOSE
STUDENT NO. 1011011815	TITLE: Pop-pin Track		
DATE: 12/2/2025			
MATERIAL: 201 Annealed SS (Sheet)	PART NO. TR-04		REV. 1
UNLESS OTHERWISE SPECIFIED, UNITS: INCHES, DEGREE	SCALE:1:2	SHEET 1 OF 1	



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	TR-02	T-Slotted Framing (1 in. x 2 in.)	1
2	TR-01	T-Slotted Framing (2 in. x 2 in.)	2
3	TR-07	Track Bottom Connector	2
4	TR-04	Pop pin track	2
5	TR-06	Track Track Connector (R)	2
6	TR-05	Track Track Connector (L)	2
7	HW-01	Black-Oxide Alloy Steel Socket Head Screw	36
8	HW-03	T-Slotted Framing Fasteners	44
9	HW-02	Low-Strength Steel Thin Nylon-Insert Locknut	12
10	TR-08	High-Strength Grade 5 Titanium Rod	1
11	TR-09	Clamping Two-Piece Shaft Collar	2
12	TR-03	Track End Brace	2
13	HW-06	Black-Oxide Alloy Steel Hex Drive Flat Head Screw	20

AUTHOR: Jaden Zhang

STUDENT NO. 1011011815

DATE: 12/2/2025

CLASS: MIE 243 GROUP #3

PREPARED FOR: DRAWING PURPOSE

TITLE: Track Assembly

MATERIAL: Mixed

PART NO. N/A

REV. 1

UNLESS OTHERWISE SPECIFIED, UNITS: INCHES, DEGREE

SCALE:1:3

SHEET 1 OF 1