FAMU-FSU College of Engineering

TEAM 506: MATERIAL HANDLING ROBOT

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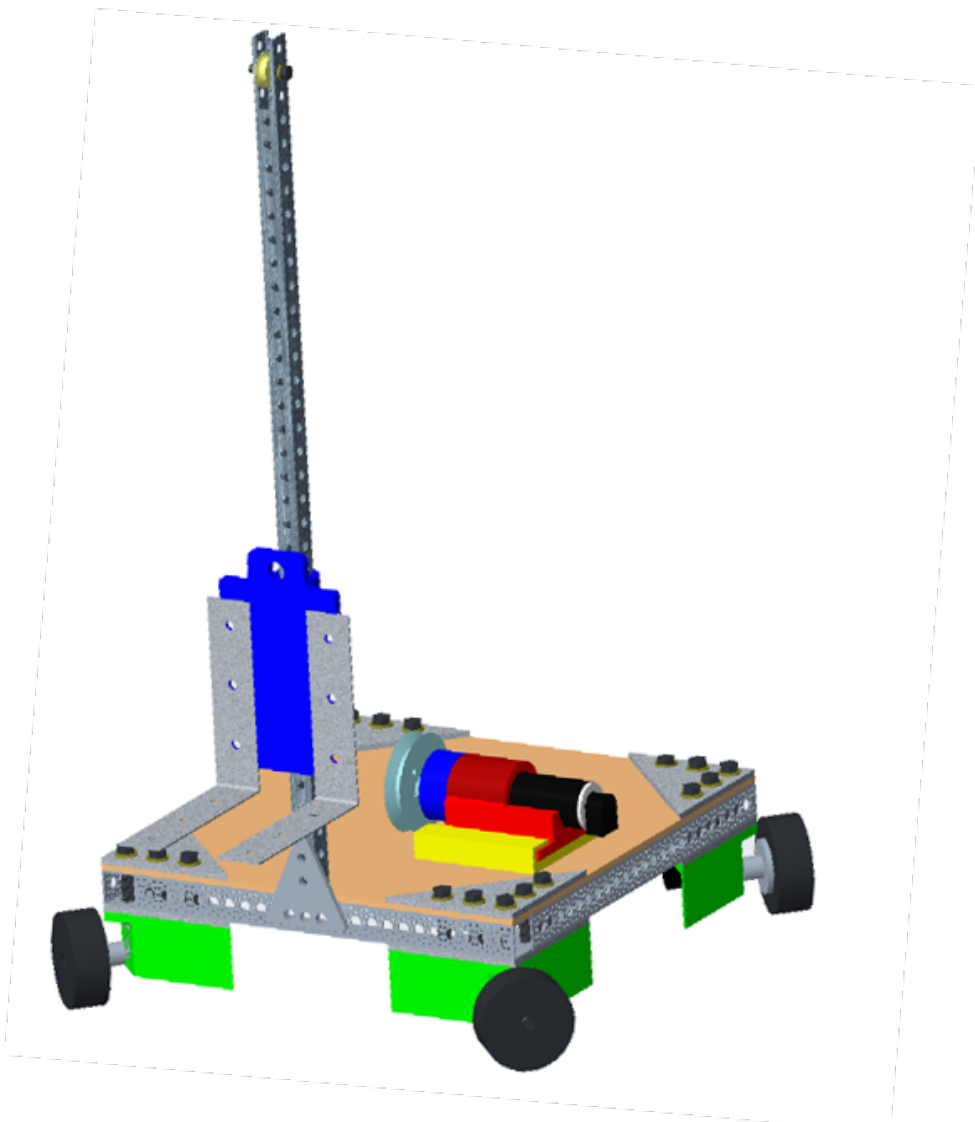
Project Overview

The objective of this project is to create a partially autonomous material handling robot that works in a dark warehouse with conditions unfavorable to human workers. The robot will be an automated, guided vehicle (AGV), meaning that it will move in a guided path around the warehouse. It will follow a black line that designates its path around the warehouse, as well as quick read (QR) codes to localize itself. To identify packages, a camera on the robot is used to scan QR codes attached to the packages. The robot will use omni-directional wheels for movement, making the robot more flexible in its movement and allowing it to line up more easily when trying to pick up packages on shelves. A forklift mechanism is attached to the front of the robot for lifting the packages on pallets. The forklift mechanism is powered by a large DC motor that can lift our desired load weight of 25lbs.

Components

The fully assembled CAD of the system is shown in the image below. The two physical functions the robot must perform are to be able to move and drive around freely and lift packages. Hence, the overall system can be divided into 2 subsystems: the drive train and the lifting mechanism.



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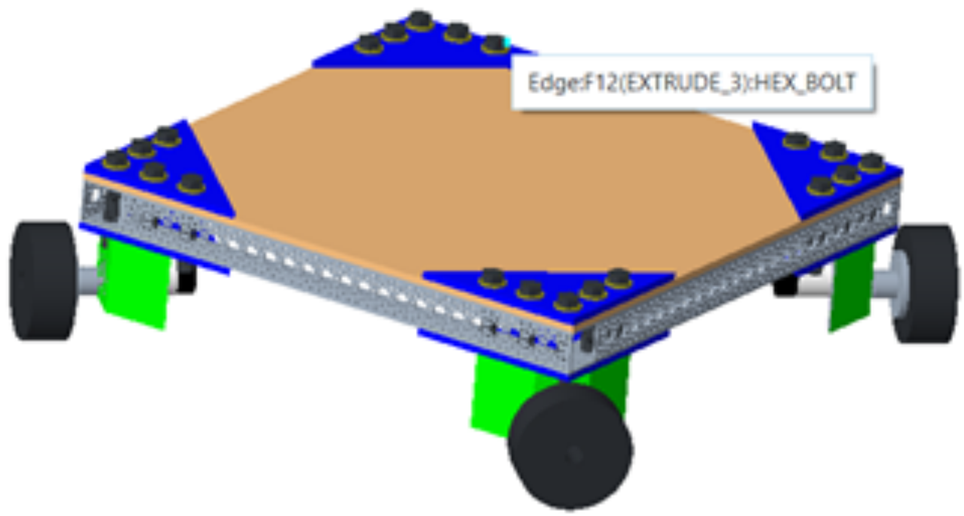
Drive Train:

The full assembly of the drivetrain, as well as the description of the different components is shown below.



Base frame

The frame of the robot is composed of four 18-inch U-shaped channels. The channels are placed in a square configuration and are fixed together using 8 aluminum brackets. A thin plank of plywood is placed on top of the U-channels and under the top bracket to hold any additional components, such as the battery, Arduino, or Raspberry Pi.

Motor configuration/mounts

Motor mounts are connected to the bottom corners of the chassis frame to rigidly connect the motors to the chassis. The mounts are designed so a wheel configuration of 45 degrees relative to the U-channels is achieved, which is important for using the omni-directional wheels.

Wheel configuration

The robot uses universal omni-directional wheels for movement. The universal wheels are made up of two separate wheels, which are screwed together, each with rollers on them. The rollers on one part of the wheel are out of phase with the rollers on the other part of the wheel, allowing for translational motion perpendicular to the direction the wheels turn towards, no matter the orientation of the wheels. Planar motion and rotation about its center are achieved, granting 3 degrees of freedom to the AGV. The wheels are angled at 45 degrees with the respect to its path and motion (directions perpendicular to the side of the chassis). Aluminum wheel hubs are connected to each wheel so it can be rigidly connected to and rotate with a motor shaft, allowing for control over the wheel's motion.

Motor controls

Controlling the motors for the robot's wheels is accomplished using an Arduino Due. Since each motor needs to connect to 2 pins with interrupt capabilities to accurately use the encoders, a microcontroller with a lot of pins with interrupt capabilities was desired. The Due was chosen because it has 12 pins with PWM signaling capabilities and all digital pins having interrupt capabilities. Each motor is connected to a motor driver; one motor driver can control two motors each, so 2 motor drivers total are needed to control all the wheels. The motors need six wires each to connect the power outputs to the drivers, a ground wire to connect to the common ground, a power input wire which is connected to a 5V pin, and two wires to perform two-phase encoder functions. The schematics below show how two drivers are connected to the due along with a schematic showing how one motor is connected to the driver and Due. It is important to note that in total 8 interrupt pins and 4 PWM pins are necessary to execute the desired four-wheel independent drive. Each wheel needs two interrupt pins for the motor encoders, an added two interrupt pins for the driver's inputs, and one PWM pin to enable the motor drivers.

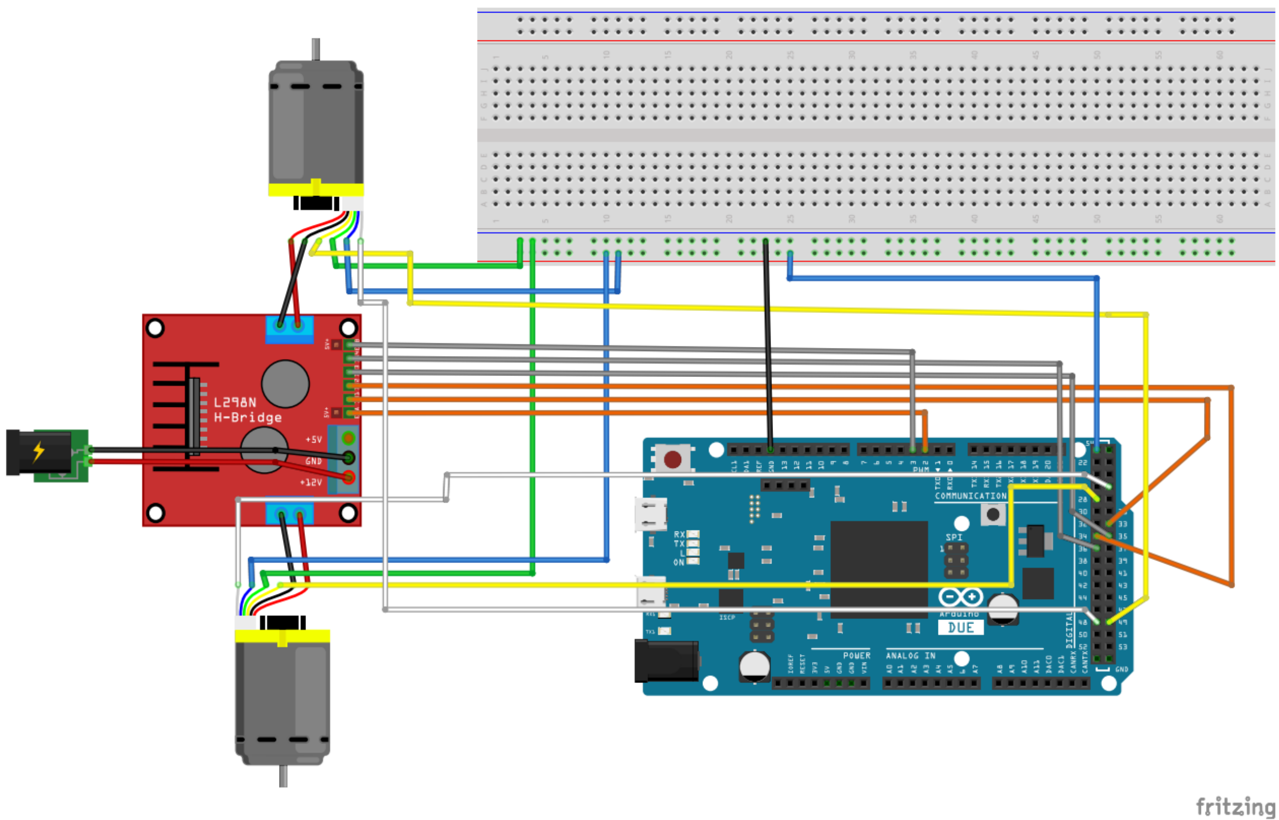


Figure 1 a

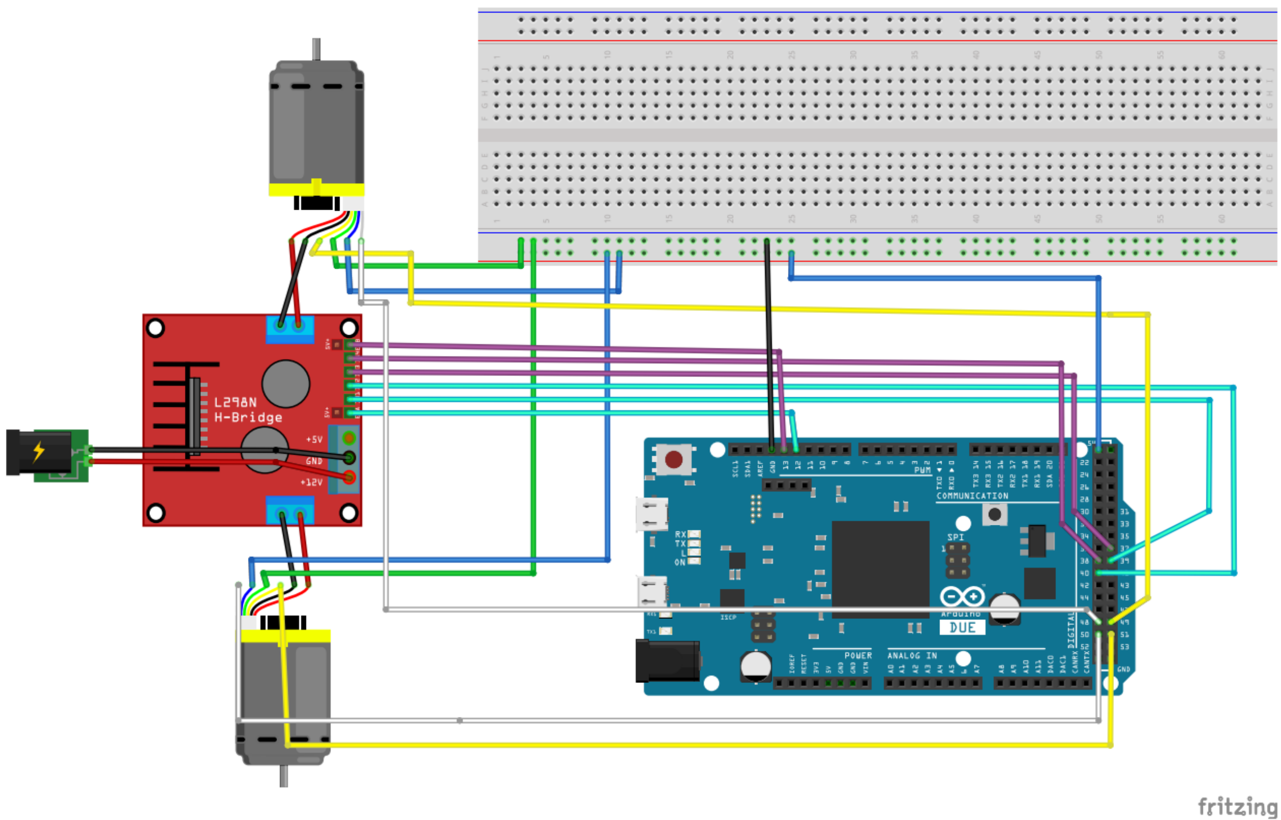


Figure 1 b

Figure 1 a and b: (a) Motor driver to Arduino Due schematic. (b) Motor to motor driver and Arduino Due schematic.

In Figure 1a, the blue wires represent the enable functions that need to be pinned in PWM ports to control speed; green and grey wires represent the input functions that need to be wired to interrupt pins to control direction. In Figure 1b, the motor's red and black wires are used for positive and negative outputs, green wire is pinned to a ground port, blue to a 5V port, and grey and yellow are the encoder wires pinned to interrupt ports; the driver shows which pins would be used specifically for the motor connected to output one and two.

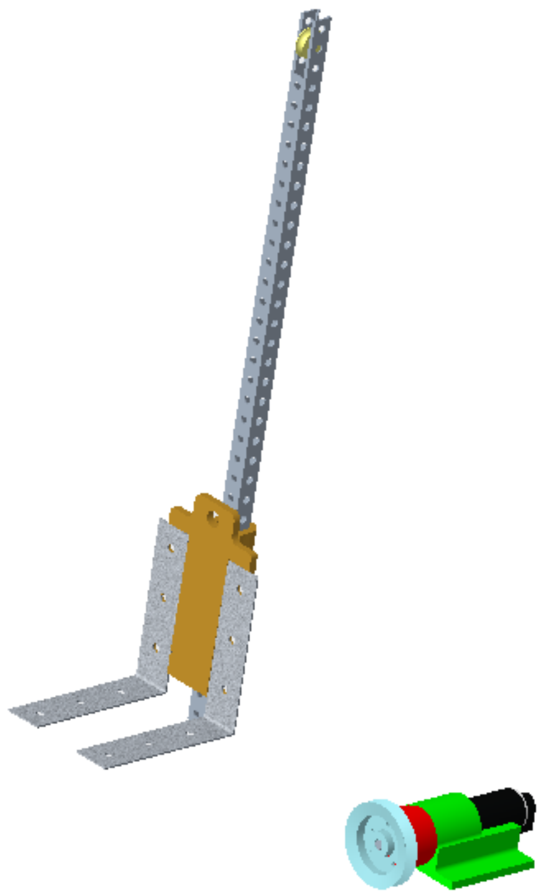
Bill of Materials: Drive Train

Drive Train Components

Purpose	Description	Part #	Unit Cost	Quantity	Vendor
Chassis Frame	18" Aluminum Channel	585462	$13.99	4	https://www.amazon.com/Actobotics-18-Aluminum-Channel/dp/B00KRJ7T3U/ref=sr_1_13?dchild=1&keywords=u-channel+servocity+18%22&qid=1616077096&s=industrial&sr=1-13
Universal Omni-Directional Wheels	Nexus Robot 100mm Omnidirectional Wheel (Brass Bearing for Rollers)	14049	$20.16	4	https://www.amazon.com/Nexus-Robot-Omnidirectional-Bearing-Rollers/dp/B01CTUT6WG/ref=cm_cr_arp_d_product_top?ie=UTF8
Wheel Hub (comes with bolts to attach to wheels)	6mm Set Screw Hub	RB-Nex-17	$8.46	4	https://www.robotshop.com/en/set-screw-hub-6mm.html
Aluminum Bracket	1ft x 5in x 0.25 in Hardened 6061 Aluminum (machined to fit design)	8975K432	$11.64	1	https://www.mcmaster.com/plates/aluminum/multipurpose-6061-aluminum-sheets-and-bars-7/thickness~1-4/width~5/
Chassis Bolts (16 needed); (comes in packs of 10)	High-Strength Class 10.9 Steel Hex Head Screw, M12 x 1.75 mm Thread, 80 mm Long, Fully Threaded	91310A144	$14.75	2	https://www.mcmaster.com/catalog/127/3388
Chassis Nuts (16 needed);	High-Strength Steel Hex Nut	90685A110	$9.52	1	https://www.mcmaster.com/catalog/127/3442

(comes in packs of 25)	Class 10, M12 x 1.75 mm Thread				
Motor Mounts	3D printed PLA motor mounts	N/A	$7.46	4	3D printing service (FSU Innovation Hub used for this project)(Note: free for students)
Bolts for Motor Mounts (comes in pack of 50)	Zinc-Aluminum-Coated Alloy Steel Socket Head Screw M3 x 0.5 mm Thread, 10 mm Long	91274A105	$5.56	1	https://www.mcmaster.com/catalog/127/3358
Base	1/4 in. x 12 in. x 12 in. Birch Plywood	438046	$9.91	1	https://www.homedepot.com/p/Dimensions-1-4-in-x-12-in-x-12-in-Birch-Plywood-438046/315171651

Lifting Mechanism – Pulley System



Pulley

The pully is made of brass with an inner diameter of one inch, an outer diameter of 1.5 inch, and a thickness of ½".

Mast

The mast is made of a 1"x1"x3' galvanized steel hollow square tube. On the tube 13/32" holes are on all sides placed every inch.

Carriage

This was made custom, and 3D printed with PLA. Two separate square holes slide over the mast, while the circular hole at the top is where the rope is fastened. Three 5/8” holes are on each side to allow the forks to be connected.

Forks

The forks are galvanized steel 90-degree brackets with each side being 8” long by 2” wide. The 5/8” holes on each side line up with Carriage so that bolts can be used to secure them.

Polypropylene chord

A chord connects to the carriage holding the forks, over the pulley on the mast, and then to the pulley on the motor so that it can be used to lift the package. The chord is made of polypropylene and can withstand loads up to 60 lbs.

Motor with motor mount and pulley

To actuate the lifting mechanism a Maxon motor is incorporated into the lift design and connected to the polypropylene chord through a second pulley. The Maxon motor is rigidly attached to the base frame through a 3D printed motor mount and slip. The slip is screwed onto the base frame and the motor mount is placed into the slip. The motor mount then has a cap which screws into the gear head of the motor; this is how the motor is rigidly attached to the mount. A second pulley wheel, which was found in the senior design lab, is attached to the motor shaft so when in rotation the chord can wrap/unwrap around the pulley wheel, hence, causing the lift carriage to move along the mast. The motor includes its own encoders for motor control that way the system’s processing unit can regulate the speed of the motor depending on the load it must lift.

Power supply

The entire system is powered by an ECO-WORTHY 12 V/10 Ah Lithium Iron Phosphate rechargeable battery. Both the electrical-computer and mechanical team agreed that 12 V was the ideal voltage for the system since it is adequate to power our processor and its components. For this reason, a battery with high current capacity since many components would require power. The ECO-WORTHY battery not only met are specifications regarding voltage and current capacity but came with added features that were deemed favorable for the project. Not only was the battery rechargeable but it comes with preventative features for over-charging and discharging as well as protection against short circuits and overcurrent being delivered to system. The battery itself was built to withstand external, outdoor environments along with having longer service life; this is ideal for our application because although the battery will be placed in an indoor environment, the larger number of cycles would be ideal for the autonomous nature of the robot. The battery will be incorporated into the system using applicable DC adapters to connect the robot's electrical components to the mechanical features. A common ground was created by attaching a bread board to the back of the Arduino since many components needed to be connected through the ground.

Material selection

Additive manufacturing

For the additive manufacturing, or 3D printing, used in the project, polylactic acid informally known as PLA, was used for all 3D printed features. Components that were 3D printed and included in the final design are: the smaller motor mounts for the wheels, carriage for lifting mechanism, and large motor mount for the motor used in the lifting mechanism. Each 3D printed component was printed with a 0.3 mm layer thickness, 0.8 mm shell thickness, and a minimum of 25% infill. The printers used for the prints were Dremel 3D45 Idea Builder's. The temperature's used, in Celsius, for the extruder and table were 210 degrees and 55 degrees respectively.

Bill of Materials: Lifting Mechanism

Lifting Mechanism Components					
Purpose	**Description**	**Part #**	**Unit Cost**	**Quantity**	**Vendor**
Fork	8" on both sides 5/16 holes 6 places	1005468437	$8.98	2	https://www.homedepot.com/p/MiTek-8-in-G90-Corner-Brace-UB88/313507573
Pulley	1-1/2 in. Zinc-Plated Swivel Single Pulley	205882606	$5.98	1	https://www.homedepot.com/p/Everbilt-1-1-2-in-Zinc-Plated-Swivel-Single-Pulley-44154/205882606
Mast	1 in. x 36 in. Zinc-Plated Punched Square Tube	206939549	$15.52	1	https://www.homedepot.com/p/Everbilt-1-in-x-36-in-Zinc-Plated-Punched-Square-Tube-803037/206939549
Pulley Bolt	Zinc Yellow-Chromate Plated Hex Head Screw Grade 8 Steel, 5/16"-18 Thread Size, 1-1/2" Long, Fully Threaded	92620A587	$5.44	1	https://www.mcmaster.com/bolts/hex-head-screws/high-strength-grade-8-steel-hex-head-screws/thread-size~5-16-18/length~1-1-4/length~1-3-8/length~1-1-8/length~1-1-2/length~1-5-8/
Pulley Nut	Medium-Strength Steel Hex Nuts - Grade 5, Black Ultra-Corrosion-Resistant Coated, 5/16"-18 Thread Size	98797A030	$7.89	1	https://www.mcmaster.com/nuts/hex-nuts/medium-strength-steel-hex-nuts-grade-5/thread-size~5-16-18/

Carriage (for connecting forks to mast)	3D PLA carriage for connecting forks to mast	N/A	N/A	1	3D printing service (FSU Innovation Hub used for this project)(Note: free for students)
Aluminum Mounting Bracket (mounts lifting mechanism to chassis)	Bracket for attaching mast to chassis (machined to specified dimensions)	8975K426	$8.89	1	https://www.mcmaster.com/plates/aluminum/multipurpose-6061-aluminum-sheets-and-bars-7/thickness~1-4/thickness~3-8/width~3-1-2/width~4/
Bolts for Mounting Bracket (comes in pack of 50)	Zinc-Aluminum-Coated Alloy Steel Socket Head Screw M3 x 0.5 mm Thread, 6 mm Long	91274A102	$5.38	1	https://www.mcmaster.com/catalog/127/3358
Nuts for Mounting Bracket (comes in pack of 10)	Extreme-Strength Steel Hex Nut Grade 9, Cadmium Yellow-Chromate Plated, 1/2"-13 Thread Size	95036A024	$9.90	1	https://www.mcmaster.com/catalog/127/3439
Pulley Rope	3/16 in. x 50 ft. Assorted Colors Polypropylene Diamond Braid Rope	205804718	$2.98	1	https://www.homedepot.com/p/Everbilt-3-16-in-x-50-ft-Assorted-Colors-Polypropylene-Diamond-Braid-Rope-70652/205804718
Motor	Maxon motor 402626	402626	$1400 (roughly translated from Euros)	1	https://www.maxongroup.com/maxon/view/service_search?query=402626
Motor Pulley	Stainless steel pully 3inch inner diameter	N/A	Found in SD lab	1	N/A
Motor Mount	3D printed PLA motor mounts	N/A	$9.49	1	3D printing service (FSU Innovation Hub

					used for this project)(Note: free for students)

Integration

Chassis/Base frame

The aluminum U-channels are placed in a square configuration and are fixed together using 8 aluminum brackets. The channels are arranged so they are in a square configuration with the inside of the "U" facing inward. There are 2 brackets at each corner. One is on the top and the other on the bottom. There are 5 holes in each bracket. The hole in the corner is unused, but the two sets of holes on the sides of the brackets are used. M12 x 1.75 by 80 mm bolts are stuck through the side holes in the bracket through the U-channel and then through the corresponding holes on the bracket on the other side. A thin plank of plywood is placed on top of the U-channels and under the top bracket to hold any additional components, such as the battery, Arduino, or Raspberry Pi. The bolts are held firmly in place by nuts.

Drivetrain to Base frame

Motor mount to chassis

The motor mount is placed on the bottom of the chassis at each corner with holes lining up with the holes and bolts going through the brackets. They are held down by nuts that are threaded on the large bolts.

Motor to motor mount

The motors each have 6 equidistant holes that go along the edge of the perimeter for rigidly mounting to a motor mount. The motor mounts have corresponding holes. Bolts

(M3x0.5 with 10mm length) are inserted through the holes and threaded through the tapped holes on the motors. It is important to note that the tapped holes in the motors are only about 3.65 mm deep, with only about 2.3 mm clearance above the motor gears.

Wheels

The wheels in pieces with both main parts of the wheel unattached and a pack of bolts. The two main wheel components are placed together so the rollers on one wheel alternate with the rollers on the other. The holes encircling the center of the wheels will line up when the wheels are placed together properly. Then, the bolts are then threaded through the lined-up holes in groups of 2 (and then skipping 2 holes) around the wheel. This will leave 6 holes, in groups of 2, with bolts in them, and 6 holes without bolts in them.

Wheels to wheel hub to motor

The wheels and the shaft of the motors must be rigidly attached so the wheels can be properly and accurately controlled by the motors. To accomplish this, the aluminum wheel hubs are used to secure the connection between the wheels and the motor. The larger side of the hub is lined up and centered on the wheel so holes in the hub are lined up with the empty threaded holes of the wheel. Bolts that come with the wheel hub are threaded through the hub and the wheels to secure the hub to the wheel. The shaft of the motor is then inserted into the bore of the hub, and an M5-0.8 x 9 mm set screw locks the motor shaft in placed. Note that there is a flat section on the shaft of the motor, and the set screw should be in contact with the flat section, which ensures there will be no slip between the set screw and the shaft.

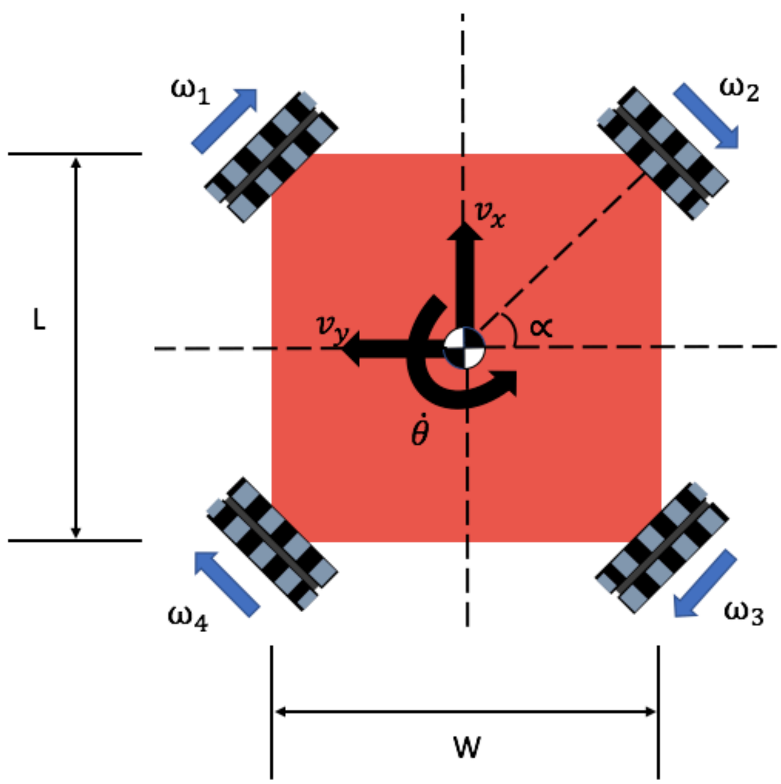
Lifting Mechanism Integration

The mast that holds the forks, lifting frame, and pulley system is attached to the base frame using a customized bracket meant to limit the degrees of freedom of the mast along with providing added support to prevent unwanted manipulation to the base frame. The motor is secured to the base by a custom 3D printed mount. The mount has holes to allow for it to be bolted into the plywood base using ½"-13 thread by 1-inch-long bolts. The mount allows the motor to be secured to the base and raises the motor to create enough room for the motor pully to be fully operational without interference from the base. The motor is powered by a battery and controlled by an Arduino, this will allow the robot to appropriately lift or lower the forks when needed. The motor pully is looped in Polypropylene chord, and then is placed around the mast pully. The mast pully is mounted in galvanized steel hollow tube, which has been machined with a notch to allow the pully to be securely attached to the mast. This will prevent the mast pully from translational movement but allowing for angular rotation. Finally, the cord is fastened on the fork carriage. The carriage has been 3D printed to allow the forks to be mounted on the front using 5/16-18 bolts and the cord to be attached while the back of the carriage is secured around the square tubing of the mast.

Navigation

There are 4 reflectance sensors that are used to sense the line the robot must follow. The sensors can sense an error in the position and orientation relative to the line. The error in this scenario is the difference between the robot's actual and desired position and orientation relative to the line. This is important in controlling the robot to follow the line. For example, if the robot is facing several degrees away from the line, and it continues to move straight, then it will eventually move away from the line. This error in the robot's location is important in controlling the robot's movements. From the error, the desired forward, lateral, and angular velocity are constantly updated and determined for the robot to stay on and follow the line. A PID controller uses the error to determine these values. Since the robot's movements are controlled by the motors attached to its wheels, the desired angular velocities of these wheels must be determined. "Inverse kinematics" equations, shown below, are used to determine the desired wheel angular velocities using the desired forward, lateral, and angular velocities of the robot. Encoders on the motors are used to measure the actual angular velocity of the wheels, and a PID controller is used to correct any error to get the actual wheel angular velocity to be the desired values.

The inverse kinematics used for determining the proper robot wheel velocities are shown below, along with a schematic to better visualize the variables in the equations.



Inverse kinematics:

$$\omega_1 = \left(\frac{1}{R}\right)\left(v_x \sin(\propto) - v_y \cos(\propto) + L_1\dot{\theta}\right)$$

$$\omega_2 = \left(\frac{1}{R}\right)\left(-v_x \sin(\propto) - v_y \cos(\propto) + L_1\dot{\theta}\right)$$

$$\omega_3 = \left(\frac{1}{R}\right)\left(-v_x \sin(\propto) + v_y \cos(\propto) + L_1\dot{\theta}\right)$$

$$\omega_4 = \left(\frac{1}{R}\right)\left(v_x \sin(\propto) + v_y \cos(\propto) + L_1\dot{\theta}\right)$$

In the equations above,

- ω_i stands for the angular velocity of each wheel (i = 1, 2, 3, 4)
- R stands for the radius of the wheels (in our robot this is 0.1 meters)
- v_x represents the forward robot velocity
- v_y represents the lateral (or sideways) robot velocity
- $\dot{\theta}$ is the robot's angular velocity
- α is the angle the wheels are placed at with respect to the robot. (Our robot uses 45°)
- $L_1 = -\left(\frac{W}{2}\sin(\propto) + \frac{L}{2}\cos(\propto)\right)$
- W is the width of the robot (19.5 inches or 0.4953 meters)
- L is the length of the robot (19.5 inches or 0.4953 meters)

Operation

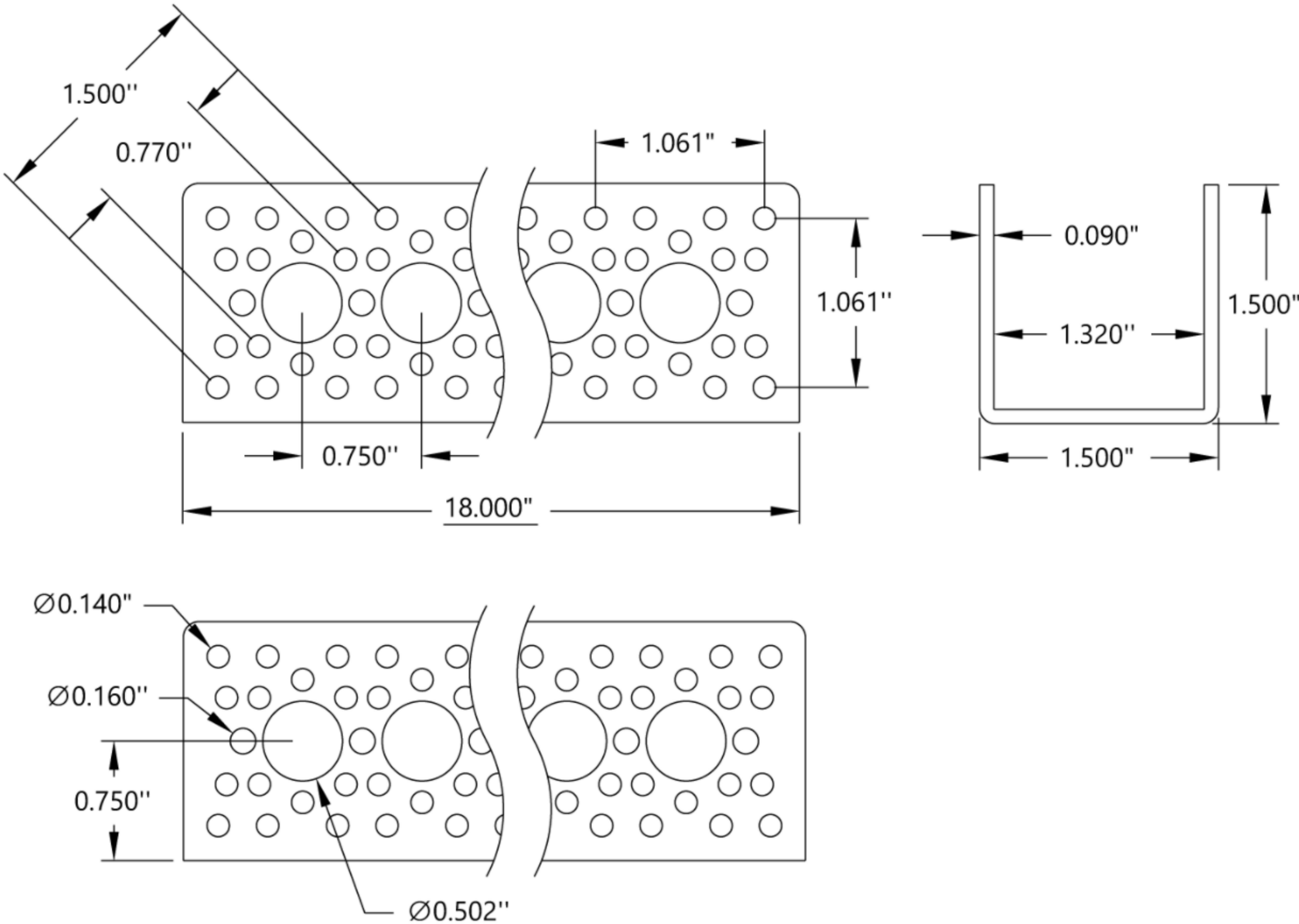
Since the robot has autonomy, there is not much direct human interaction with the robot involved in its operation. There are steps that need to be taken, however, to help the robot perform the proper functions. Tape needs to be placed around the warehouse to map out the path the robot can follow to move through the aisles. Quick read (QR) codes are placed at intersections of the black tape path for robot localization, as well as on the packages to identify their contents. Once the warehouse is ready for the robot to navigate, the AGV is placed in the starting position and begins traversing the warehouse, following the black line path and saving a map of where it moves around to. Additionally, the incoming packages to be stored in the warehouse will be placed on pallets in the loading dock so the robot can lift them.

Troubleshooting

- Wheels are not spinning properly - To ensure the wheels are spinning properly, ensure that the set screw on the wheel mount are securely attached to the motor shaft. If the issue persists, check to ensure all connections from the DC motor are connected to the Arduino and motor driver.
- Forklift is not properly lifting packages – If the motor is unresponsive, check to ensure the motor is connected to the Arduino and the motor controller. If the motor is responsive, check to see if the pully attached to the motor shaft is not slipping, if there is slip, tighten the set screw on the pully hand tight. If the cable has come unattached from the forklift frame, cease operation and reattach the cable to the frame.
- Robot lost location in warehouse – Ensure the robot is still on and receiving power. If the warehouse is dark, ensure that the LED light is still fully functioning to allow the robot to read the QR node points in the warehouse. Check to see if the robot is still on the line paths within the warehouse and has not been completely knocked off course. If so, reposition the robot on the line paths, and resume normal operation.

Appendix

Appendix A: Drawings



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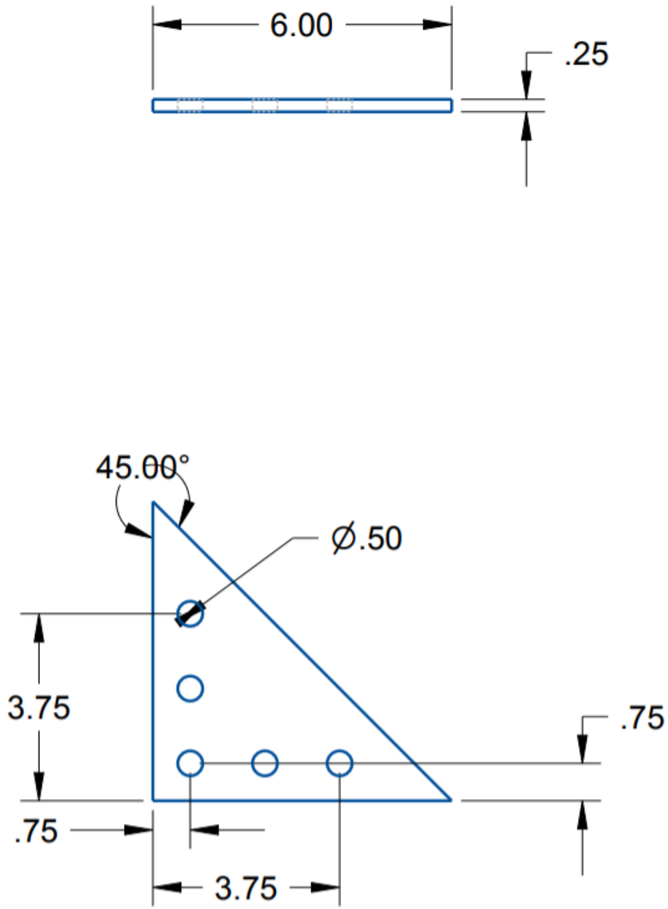
	SCALE: 1.000 / REV: 0	SHEET NUMBER: 1 OF 1	PART NUMBER: SP21-SD-P-01



UNITS: INCHES

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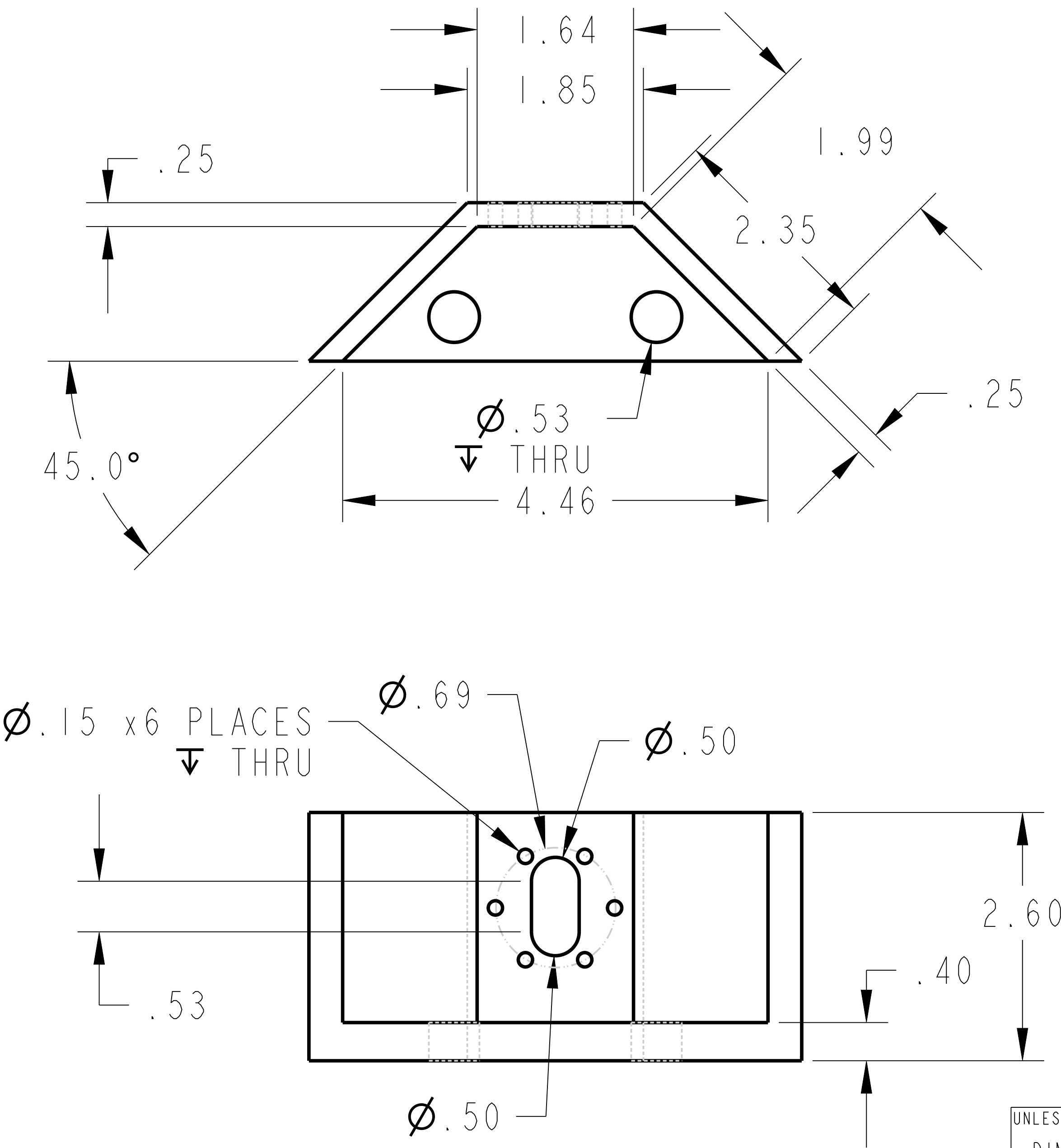

UNLESS OTHERWISE SPECIFIED	SIZE:	PART NAME:		PROJECT NAME:
DIMENSIONS IN INCHES TOLERANCES: X.X± .0.1 X.XX± .0.01 X.XXX± .0.003 ANGLES± 0.5°	A	MOTOR MOUNT 45°		SENIOR DESIGN
	DRAWN BY: ALEXANDER WOZNY		DATE: 3/19/2021	MATERIAL: PLA
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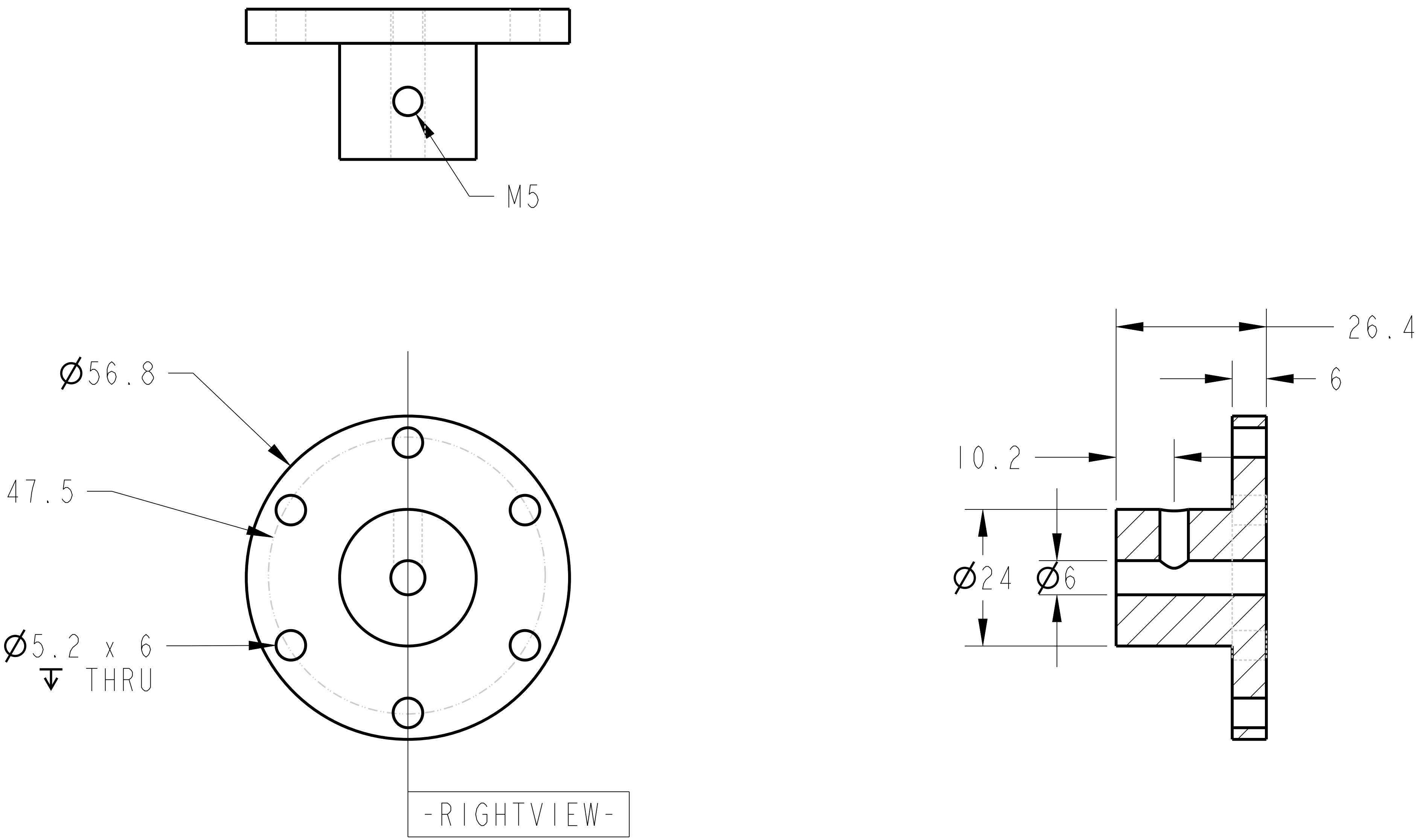

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	ALEXANDER WOZNY		3/19/2021		ALUMINUM	
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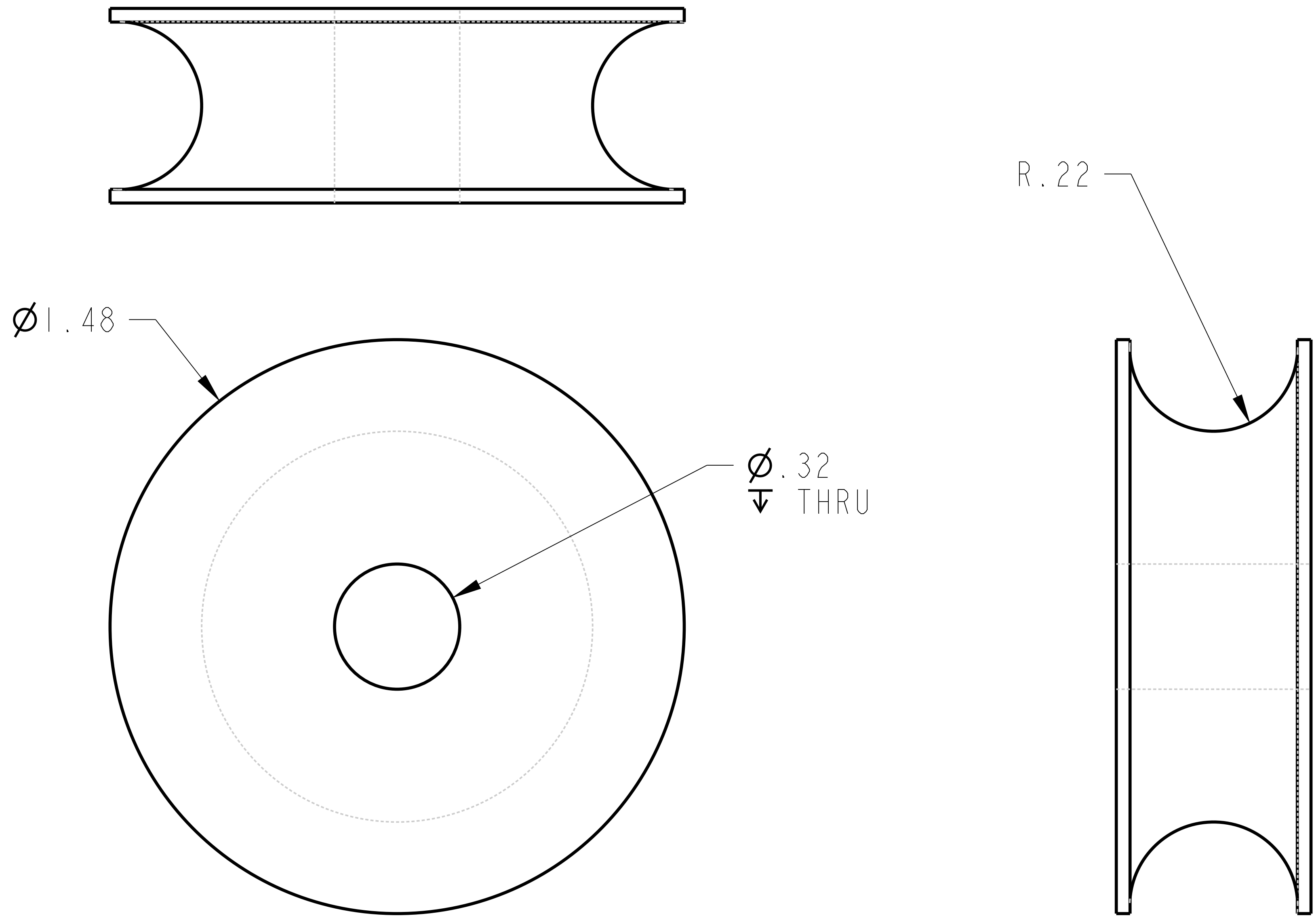

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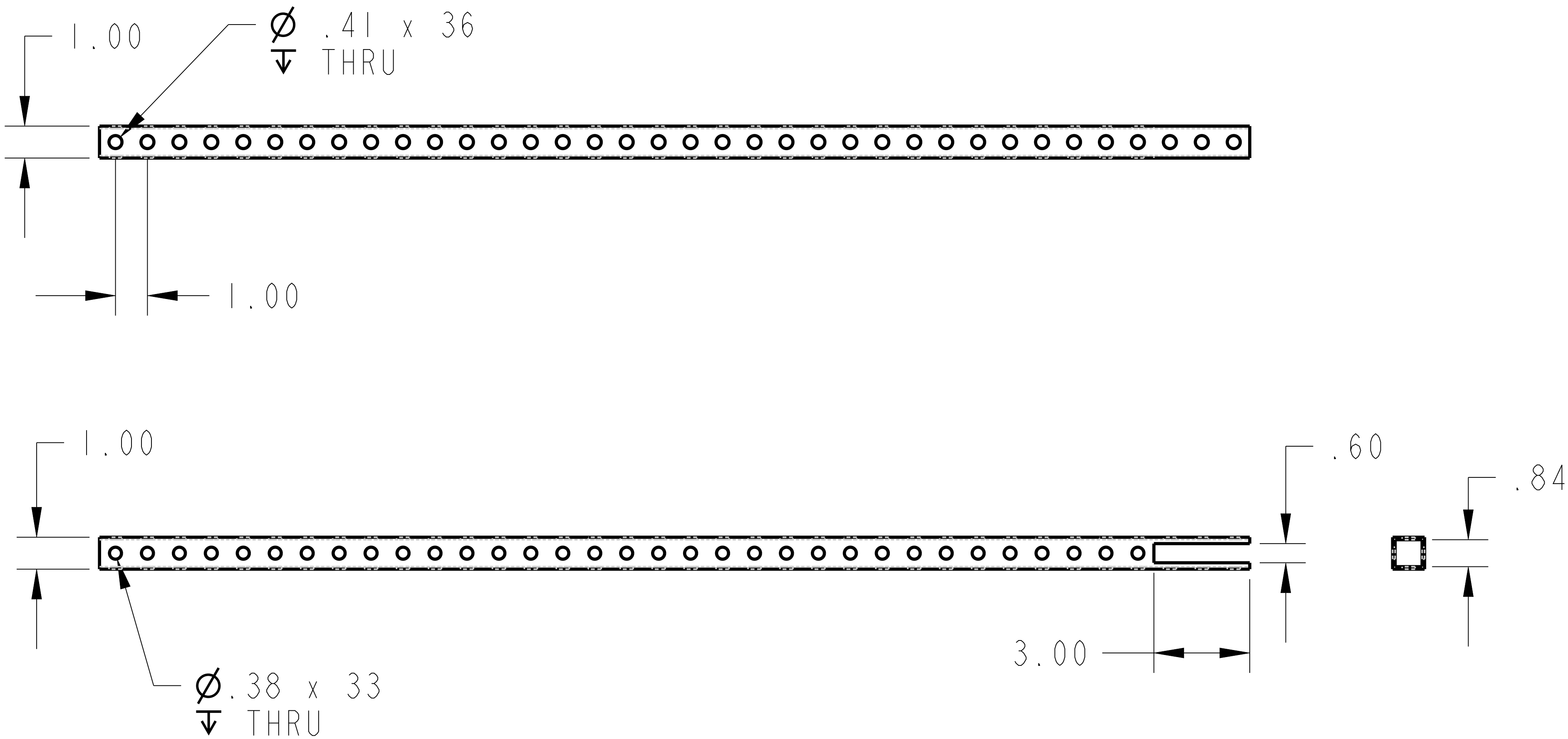

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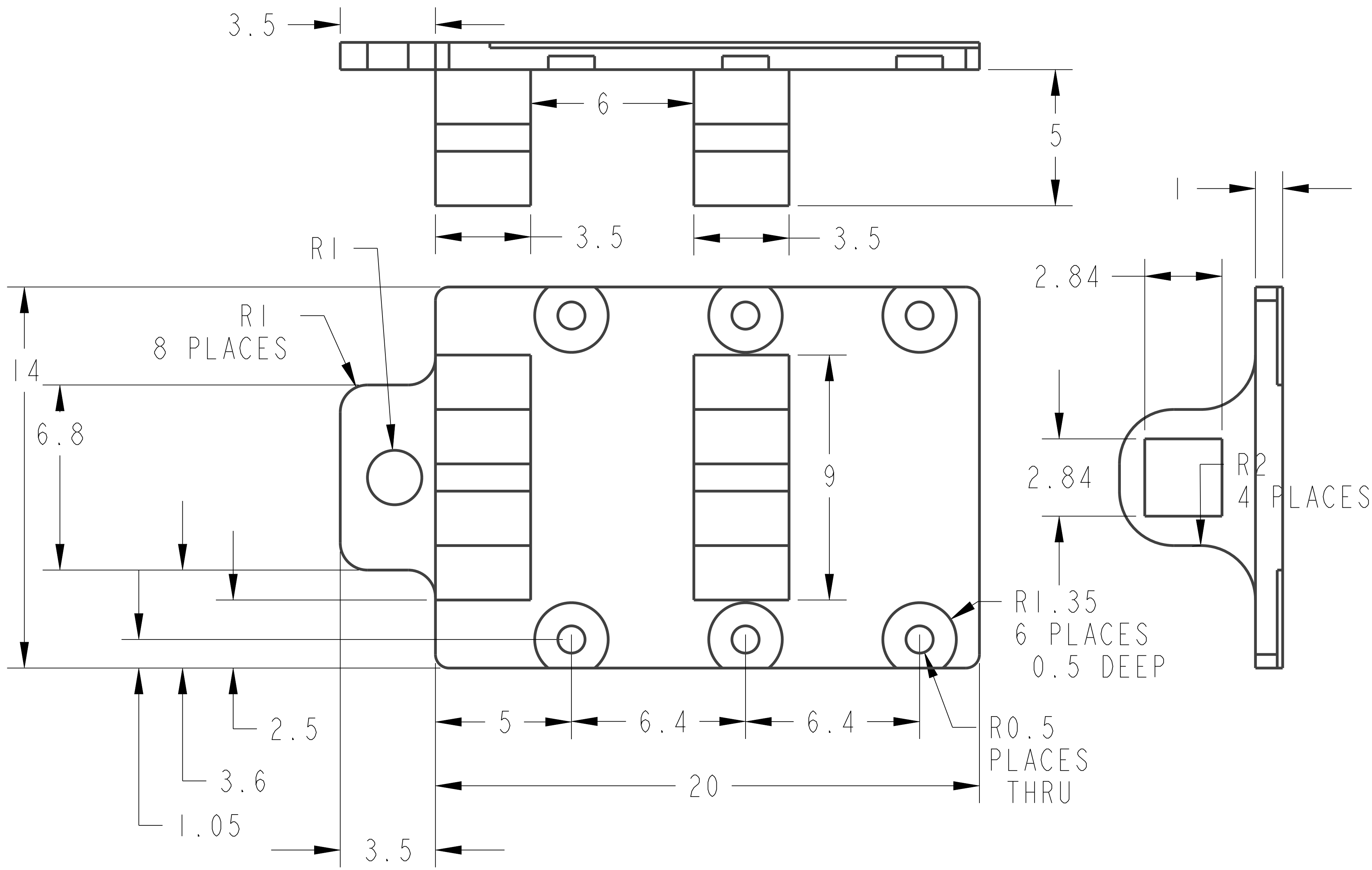
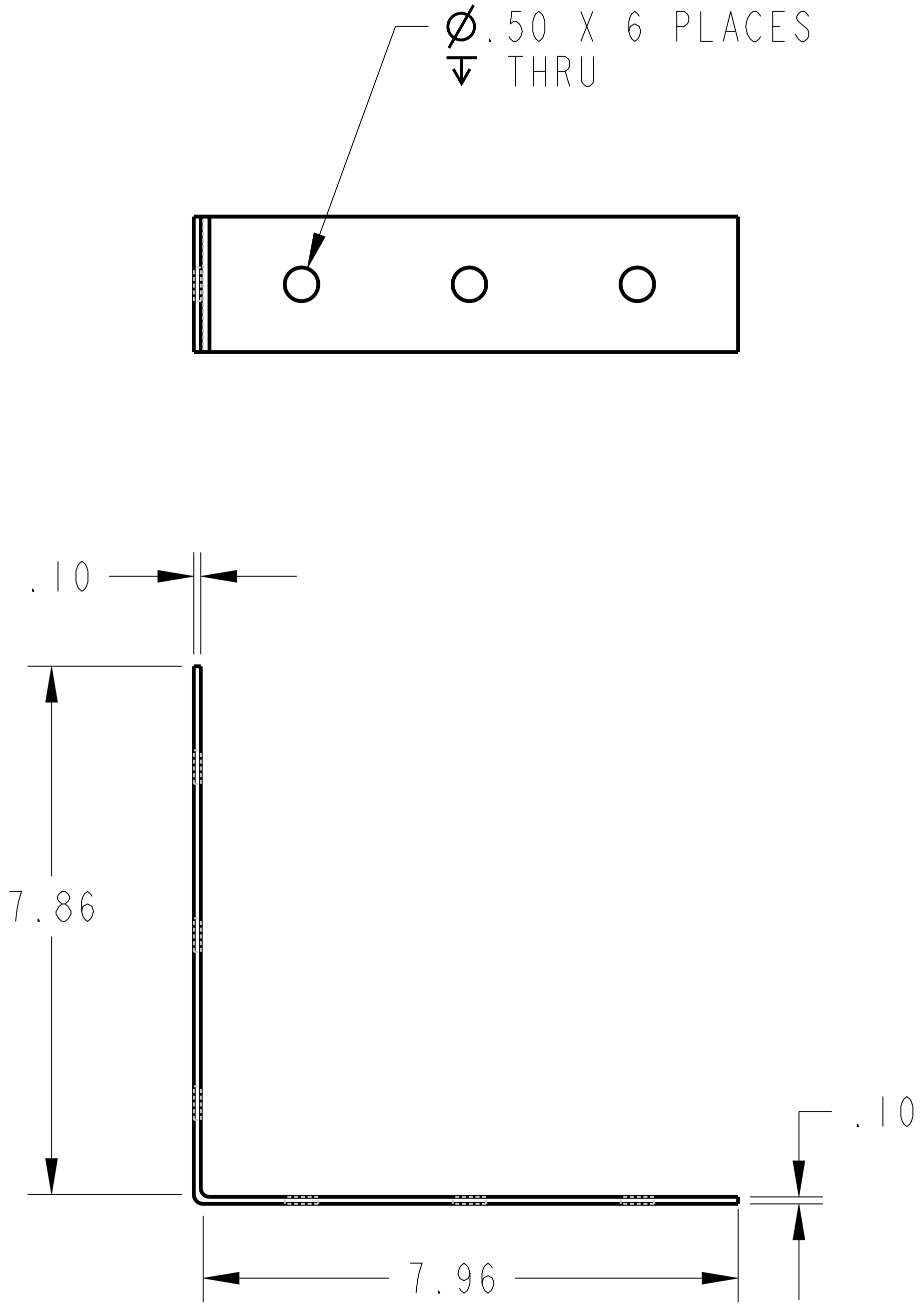
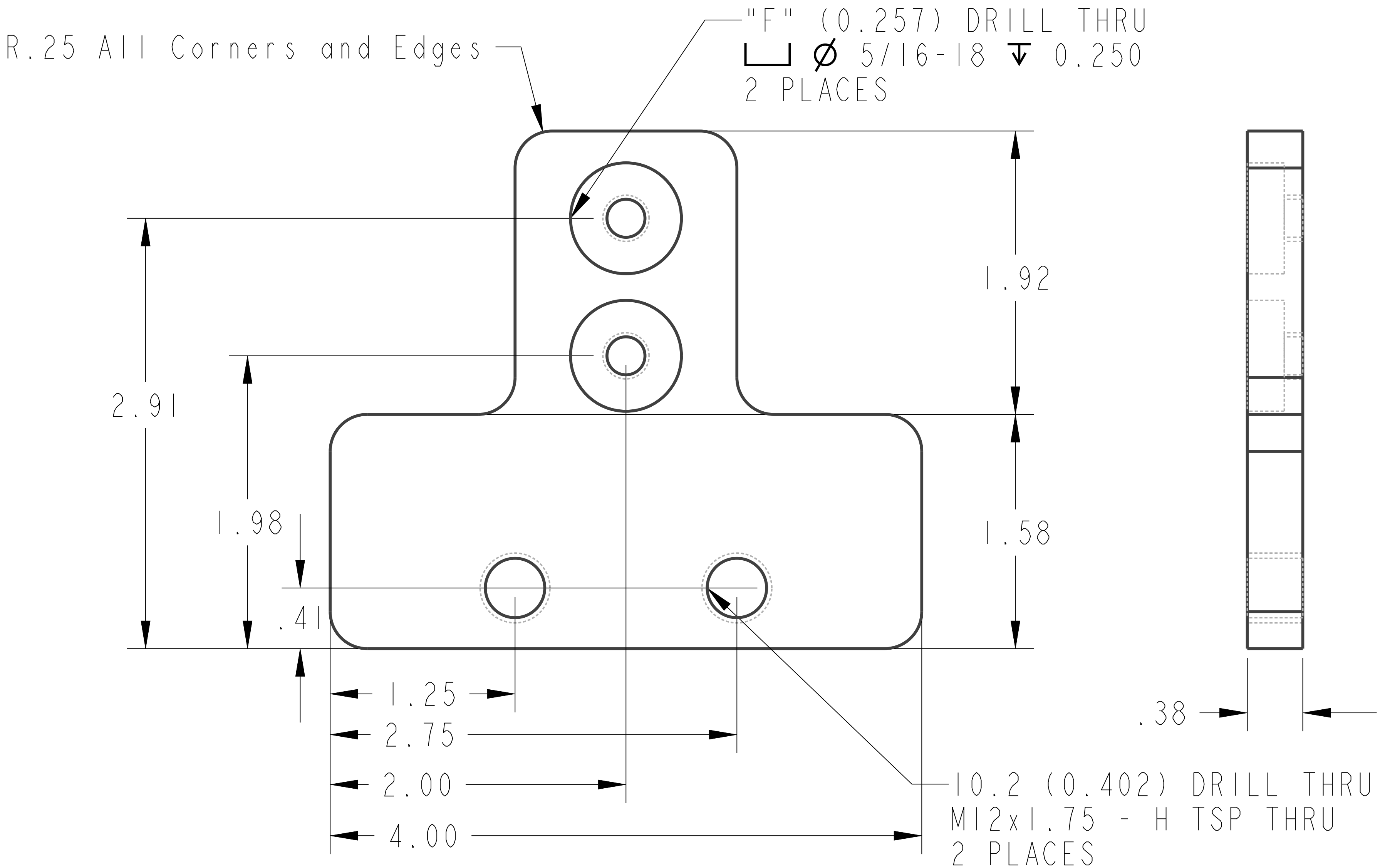


UNLESS OTHERWISE STATED DIMESIONS IN mm TOLERENCES: x.x±.1 x.xx±.01 x.xxx±.003 ANGLES ± .5°	PROJECT NAME Material Handeling Robot		PART NAME: CARRIAGE	
	DRAWN BY: PETER WATSON		DATE: 8/31/18	MATERIAL: PLA
	SCALE: 0.5	REV: 0	SHEET NUMBER: 1 OF 1	PART NUMBER: SP21-SD-R007



UNLESS OTHERWISE SPECIFIED	SIZE:	PART NAME:			PROJECT NAME:	
DIMENSIONS IN INCHES	A	FORK			SENIOR DESIGN	
TOLERANCES: X.X± .0.1 X.XX± .0.01 X.XXX± .0.003 ANGLES± 0.5°	DRAWN BY:		DATE:		MATERIAL:	
	ALEXANDER WOZNY		3/19/2021		STEEL	
	SCALE:	REV:	SHEET NUMBER:		PART NUMBER:	
	0.350	0	1 OF 1		SP21-SD-P-008	

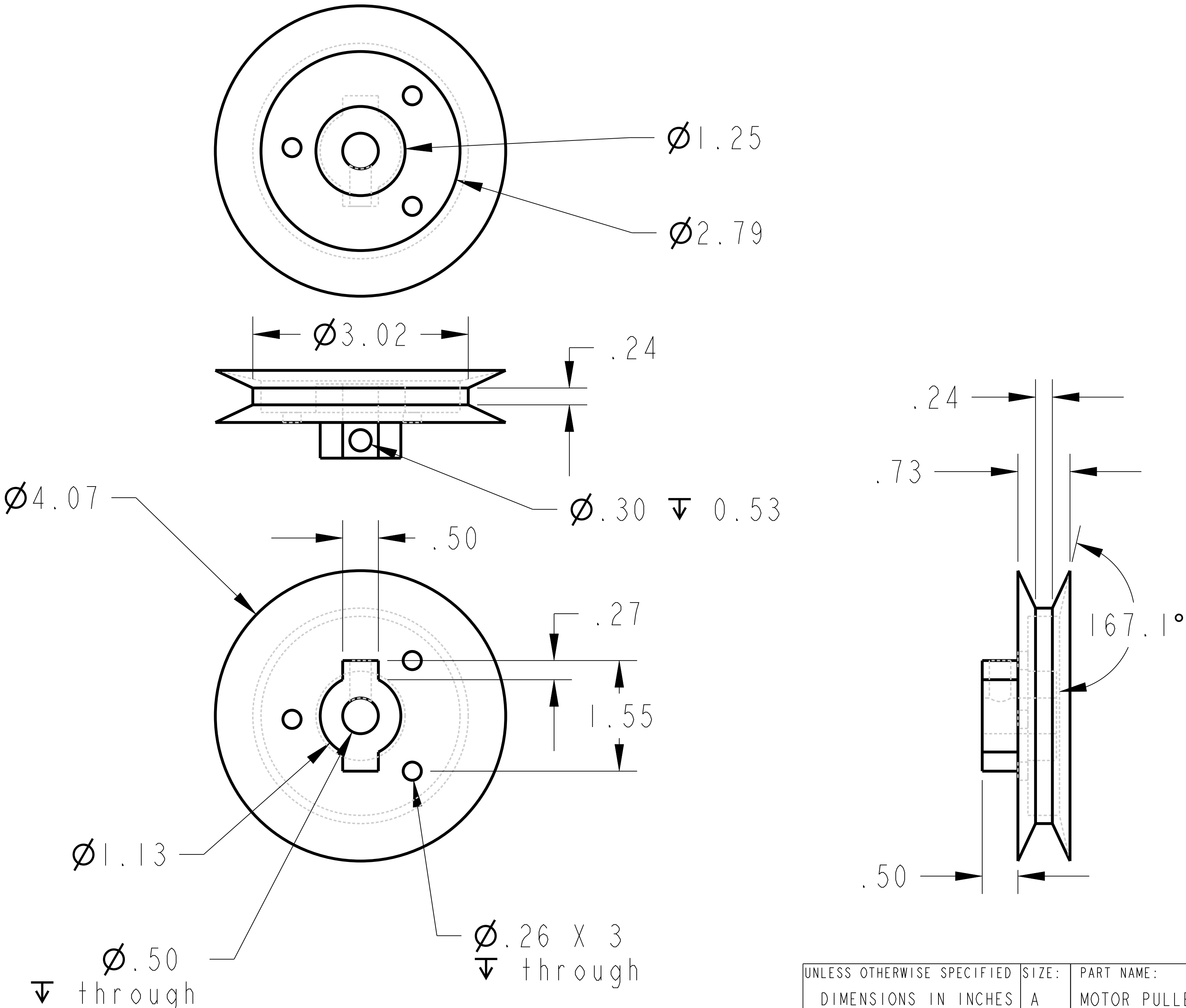


UNLESS OTHERWISE STATED
DIMESIONS IN INCHES
TOLERENCES:

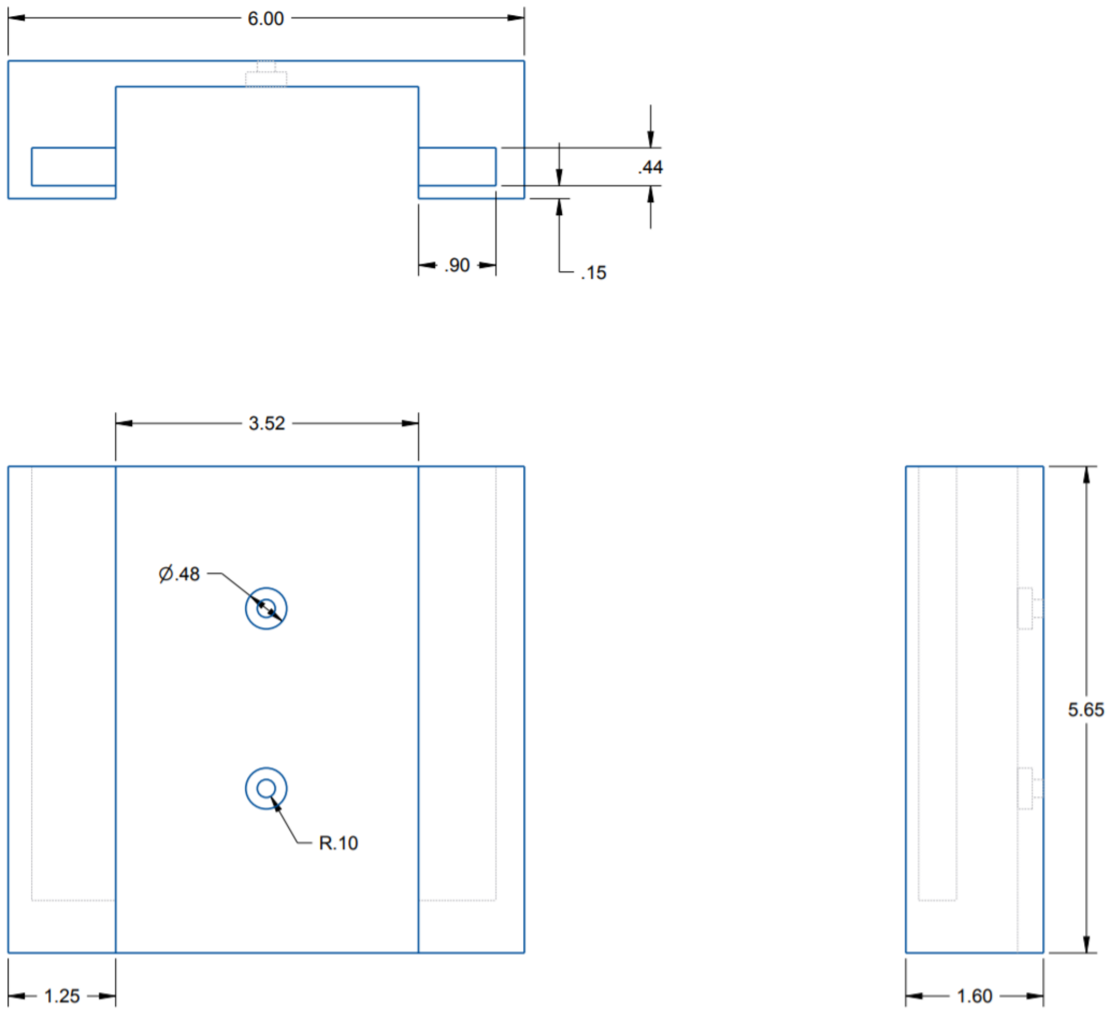
x.x±.1
x.xx±.01
x.xxx±.003

ANGLES ± .5°

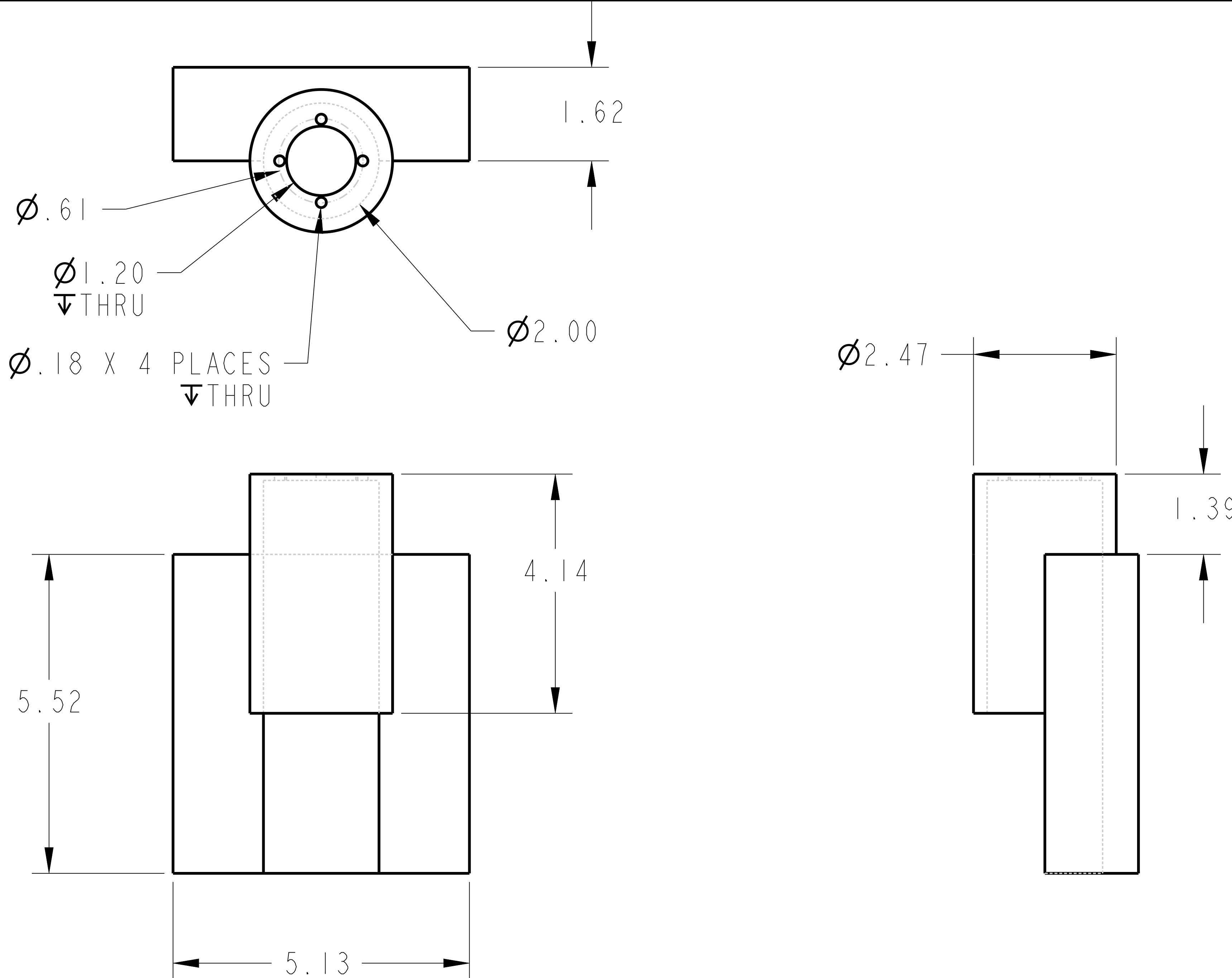
PROJECT NAME		PART NAME:	
Material Handeling Robot		Mast To chasis Connector	
DRAWN BY:	DATE:	MATERIAL:	
PETER WATSON	3/5/21	ALUMINUM	
SCALE:	REV:	SHEET NUMBER:	PART NUMBER:
1.00	0	1 OF 1	SP21-SD-P009



UNLESS OTHERWISE SPECIFIED	SIZE:	PART NAME:		PROJECT NAME:	
DIMENSIONS IN INCHES TOLERANCES: X.X± .0.1 X.XX± .0.01 X.XXX± .0.003 ANGLES± 0.5°	A	MOTOR PULLEY		SENIOR DESIGN	
	DRAWN BY:		DATE:	MATERIAL:	
	ALEXANDER WOZNY		3/19/2021	ALUMINUM	
	SCALE:	REV:	SHEET NUMBER:	PART NUMBER:	
	0.500	0	1 OF 1	SP21-SD-P010	



UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES TOLERANCES: X.X. ± .0.1 X.XX. ± .0.01 X.XXX. ± .0.003 ANGLES ± 0.5°	SIZE: A	PART NAME: Motor Slip		PROJECT NAME: Senior Design	
	DRAWN BY: Diandra Reyes		DATE: 3/19/2021	MATERIAL: PLA	
	SCALE: 1.000	REV: 0	SHEET NUMBER: 1 OF 1	PART NUMBER: SP21-SD-P-11	



UNLESS OTHERWISE SPECIFIED	SIZE:	PART NAME:		PROJECT NAME:
DIMENSIONS IN INCHES	A	MOTOR MOUNT		SENIOR DESIGN
TOLERANCES: X.X± .0.1 X.XX± .0.01 X.XXX± .0.003 ANGLES± 0.5°	DRAWN BY: ALEXANDER WOZNY		DATE: 3/19/2021	MATERIAL: PLA
	SCALE: 0.420	REV: 0	SHEET NUMBER: 1 OF 1	PART NUMBER: SP21-SD-P-012