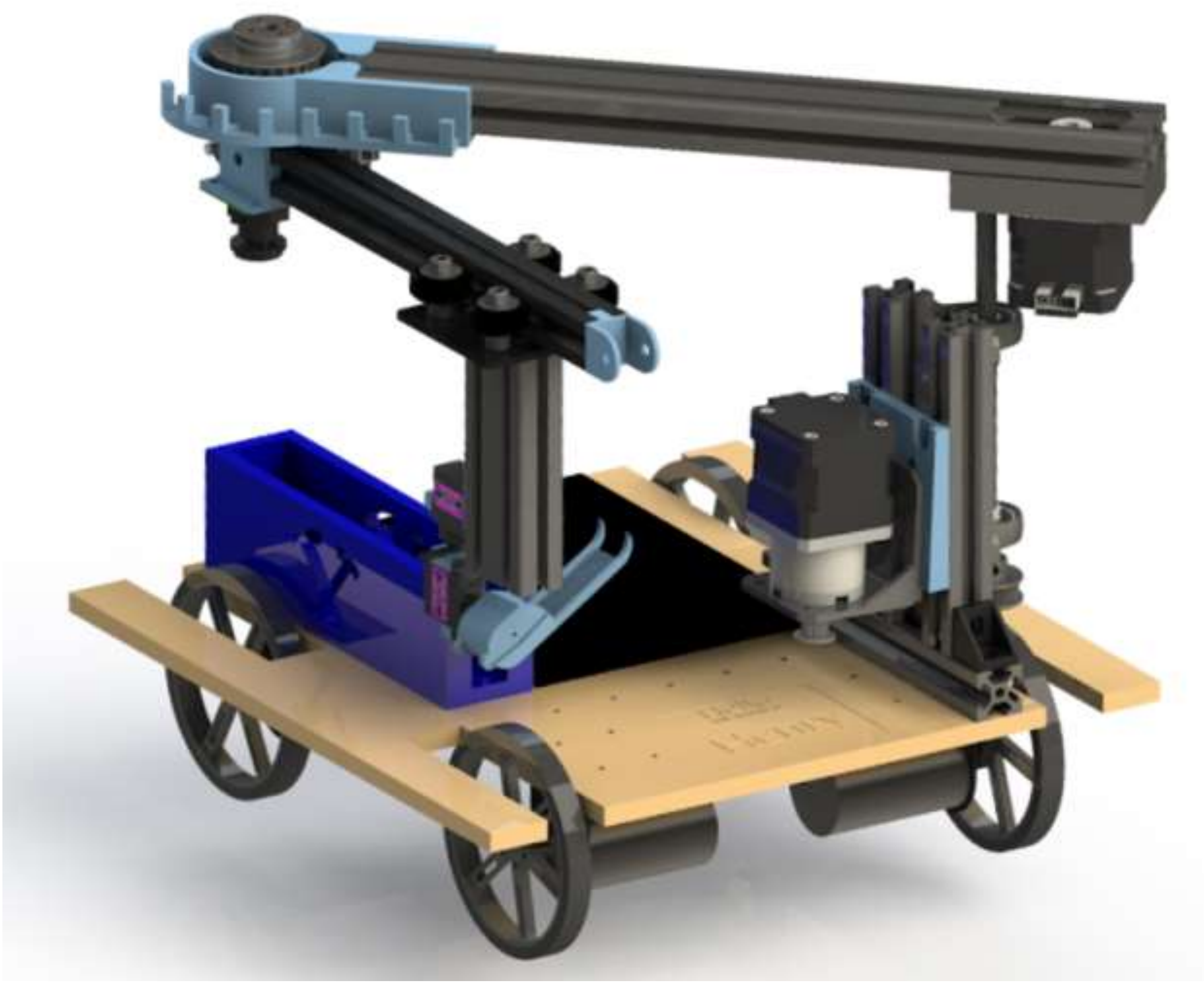
“Hello, My Name is Henry”

ASABE Agricultural Robotics Competition

Brigham Young University Agricultural Robotics

2023-2024 Design Report



1 INTRODUCTION

This report details the work done by the Agricultural Robotics Team at Brigham Young University in the design, implementation, and analysis of Henry, a robot competing in the advanced division of the 2024 ASABE Robotics Competition. The objective of this competition is for the robot to traverse a field of simulated strawberry plants, identifying and trimming unhealthy leaves and excess flower buds from the plants and mapping the field. This challenge highlights current innovations in the field of robotics, particularly in vision, mobility, and grasping technologies, which make agricultural robots increasingly suited to agricultural tasks.

Maximizing yields in strawberry cultivation involves several labor-intensive tasks that could benefit greatly from robotic innovation. For instance, ensuring that each plant has the correct number of berries is crucial for achieving the best possible yield. Robots equipped with vision and grasping capabilities could effectively identify and remove excess flower buds. Additionally, regular pruning of dead or damaged leaves is essential for allowing the plant to focus its energy on fruit growth. Robots can be programmed to perform this delicate task with precision and consistency, enhancing the plant's health and maximizing fruit production. By integrating these robotic solutions into strawberry cultivation, farmers could potentially achieve higher efficiency, reduce labor costs, and improve overall crop quality.

Figure 1-1 A simulated strawberry plant in the peat moss arena, with healthy leaves (dark green), unhealthy leaves (light green), and flowers (white)

Figure 1-2 A bed of simulated plants in the arena

This robotics competition simulates the strawberry cultivation process. The objective is to build a robot capable of pruning excess flower buds and unhealthy leaves from a simulated strawberry plant. The simulated plants are represented by 3D printed “plants” with thin printed stems. Printed leaves and flowers are attached to the stems with magnets. The leaves can either be dark green, signifying a healthy leaf, or light green, signifying an unhealthy leaf. The flower buds are painted white, and there can be several per plant. The arena is sixteen feet long and contains 24 plants arranged in two plant beds. The arena floor is covered with a layer of peat moss, simulating the soil of a garden environment.

For each plant, the robot must:

1. Record the number of healthy and unhealthy leaves and the number of flower buds in a CSV file (initial mapping).
2. Prune unhealthy leaves from the plant and remove all but one flower bud (trimming).
3. Re-record the new number of leaves and flowers on the plant to confirm the pruning operation was successful (final mapping).

Points are awarded for correct trimmings and mappings and are deducted for incorrect trimmings.

To add to the challenge, the robot has only five minutes to perform its work and must be small enough to fit in a one-foot cube.

Our robot uses a four-wheeled drive system with differential steering to navigate the peat moss field. The robot drives along the inside of the plant beds and navigates using ultrasonic sensors to maintain a consistent orientation to the plants. The robot has a gantry system that begins in a stowed configuration when at rest and deploys over the plants during operation. A camera positioned at the gantry's rotational axis uses a convolutional neural network to determine the location of all leaves and flowers of each plant. The gantry rotates and translates radially to position a claw-like trimming mechanism, which prunes the excess flowers and unhealthy leaves.

Figure 1-3 CAD rendering of competition

This report describes our design approach for the mechanical, electrical, and software components of our robot. We will also describe the testing we have conducted and the expected performance of the robot.

1.1 TEAM ORGANIZATION

The BYU Agricultural Robotics Team is organized into three main subteams, each headed by a Subteam Lead. These leads coordinate with the team management, consisting of the Project Manager and Chief Engineer, to ensure the project stays on track to achieve milestones for design and testing.

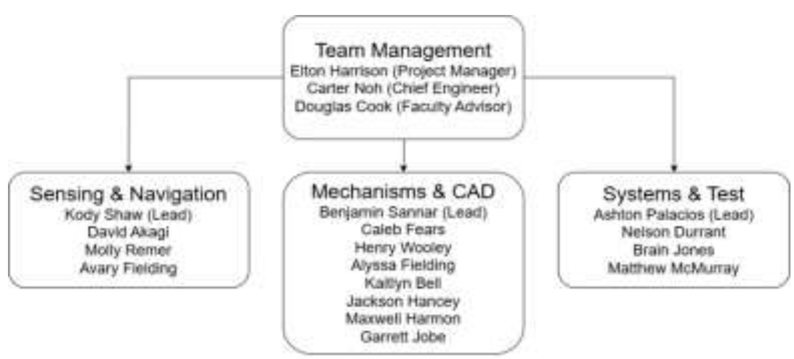


Figure 1-4 BYU AgRobotics Organization Chart

2 Conceptual Design

2.1 Competition Scoring

In the competition, robots participate in 5-minute trials. During a trial, a robot can earn points in three ways:

1. Navigation: Robots earn 20 points for reaching the far end of the field and 20 points for reaching the designated exit zone. 40 total points are possible for navigation.
2. Mapping: For each plant, the robot records the number of healthy leaves, unhealthy leaves, and flowers on the plant, before and after trimming. Each correctly reported number scores three points. Approximately 350 points are available for mapping: 216 for the initial mapping, and 144 for final mapping.
3. Trimming: Each correct trimming (removing an unhealthy leaf or excess flower) scores 8 points. Each incorrect trimming (removing a healthy leaf or the last flower) scores -8 points. Failure to trim something that should be trimmed does not result in negative points. A total of approximately 600 points is available for trimming in each round.

The total number of points accumulated in a 5-minute round is divided by the number of seconds the robot took to complete the round to determine the “points rate”. This value is capped at 5 to focus teams on designs that complete all the objectives. The points rate is then multiplied by the number of total points acquired in the round to obtain the final score.

2.2 Design Objectives

The best way to maximize the total score in a competition round is to collect all possible points in a short enough time to keep the points rate at its cap of 5. For approximately 990 points available, this means finishing the round in less than 198 seconds, or 3 minutes and 18 seconds. In this time the robot must:

1. Complete three maneuvers: approaching the first bed from the start position, turning around at the end of the first bed, and reaching the end position from the second bed.
2. Process 24 plants: travel to plant, initial mapping, all trimming maneuvers, remapping.

These goals were broken down into the following design objectives:

1. The robot’s drive system and navigation must perform fixed navigation maneuvers in under 10 seconds per maneuver.
2. The robot must be able to process plants at a rate of 7 seconds per plant.

a. Travel time between plants: 1.5 seconds
b. Initial Mapping: 0.5 seconds per plant
c. Harvesting: 4.5 seconds (approximately 1-1.5 seconds per harvesting event)
d. Final Mapping: 0.5 seconds per plant

2.3 Approach

2.3.1 Design Exploration

During the first two weeks of development, the team engaged in design-space exploration. We researched technologies that are being implemented in the agricultural robotics industry to develop an understanding of the state-of-the-art. This gave team members a mental inventory of proven ideas that could be adapted to meet our particular design objectives.

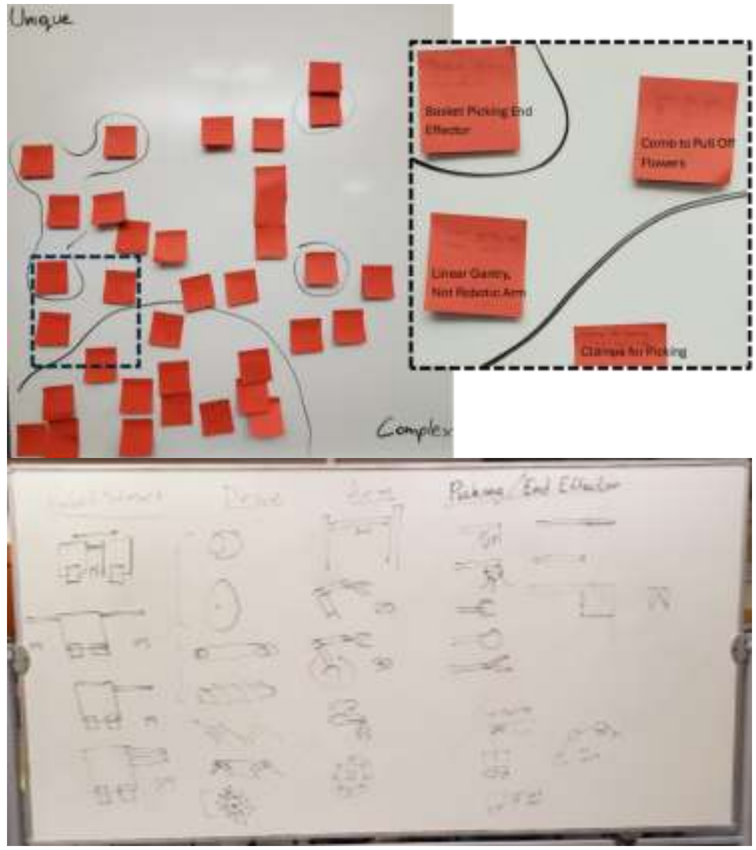


Figure 2-1 Concept sketches presented to subteams for feedback

After becoming familiar with existing solutions, an ideation exercise was used to map the design space. Team members listed design ideas on post-it notes, then arranged them on a plot along axes of uniqueness and complexity. The filled spaces were then marked in pen. As an exercise in divergent thinking, team members then devised ideas to fill all remaining gaps. The result was a design space map from which architectural elements could be selected or eliminated according to design requirements and team skills and resources.

Post-it note ideas were simplified into architectural elements. Applying the perspective of other subteams, infeasible concepts were eliminated, and promising ideas were allotted development resources.

2.3.2 Architecture Selection

Our design splits the robot into two main subsystems: a drive/navigation subsystem and a trimming/mapping subsystem. Separation of systems facilitated independent development of mechanical systems and parallel testing. Team members were assigned to independent design tasks, with members evenly divided between the drive system and two different trimming implement options. Each group was afforded freedom to develop a functional module with minimal coordination. As modules matured, design challenges became clear and each architectural element could be modified, added, or removed with minimal impact on other design groups.

2.3.3 Design Convergence

Teams were intentionally assigned to pursue redundant development paths, with independent teams developing different trimming and drive systems. As development milestones were met, redundant designs were evaluated for dependability. Systems that performed best were selected for the final design. At that point, teams were restructured to allot resources to the refinement of selected designs.

This approach led to several major design decisions and changes during development, including the following:

- Changed from a screw-drive concept to a 4x4 skid-steer drive system.
- Elimination of the whole-plant trimming ring concept in favor of single-stem trimming.
- Changed the robot's main structure from a plant-straddling configuration with the harvesting mechanism in the center of the robot to an offset configuration with the harvesting mechanism on a cantilever.
- Changed from using a depth camera for navigation to ultrasonic sensors.
- Eliminated the z-axis mobility of the end effector.
- Added a trimming implement storage and deployment system.

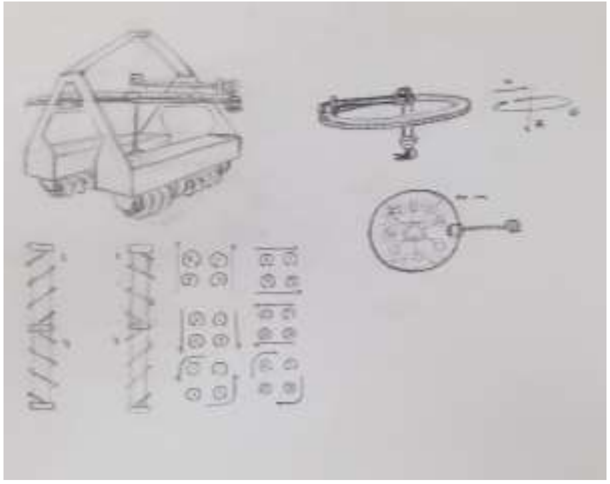


Figure 2-2 Initial concept sketch. Early designs featured a plant-straddling structure and screw drive

3 3 Final Design

3.1 Mechanical Subsystems

3.1.1 Drive System

The drive system provides the base structure of the robot and is the source of mobility for navigating the arena. The peat moss in the arena presents a challenge, as the drive system must be robust enough to withstand uneven and shifting terrain. Inspired by screw-driven tanks that traverse mud and snow, the first drive system designs used a helical screw mechanism for propulsion. However, this idea was abandoned after the screw drive proved ineffective in providing thrust in the light and shallow peat moss. Subsequent testing using tall, thin wheels proved much more effective and much simpler, as the thin wheels "cut through" the peat moss with minimal wheel slippage, which became our final design.

Figure 3-1 Final drive system design

This final design of the drive system consists of four 3.5” diameter wheels attached to four Geartisan DC 12V 50 RPM motors with a gear ratio of 1:17.4. The motors are mounted to the bottom of the base plate, a 11.75” square piece of 5/16” MDF. The wheels are inset into the base 1” to accommodate the ultrasonic sensors mounted to the outside edge (see Section 3.5). The wheels and motors were selected to meet the speed and performance requirements described in Section 2.2.

3.1.2 Gantry System

Trimming plants is a key functionality for the robot and is the largest source of points in a competition round. To ensure accurate trimming, our robot uses a cantilever deployment mechanism to position a rotating gantry directly above the bed of plants.

The gantry system is shown in figure 3.2. It consists of a linear cart on a rail of 20-20 extrusion, which itself rotates about its end. The whole gantry is suspended over the robot by a large cantilever. The gantry is designed to start in a folded position at the start of the competition to fit in the 12” by 12” box (figure 3.2a). After the robot is in position next to a plant bed, the cantilever deployment mechanism will rotate, positioning the camera above the row of plants (figure 3.2b). From this position, the robot travels along the plant bed. When the camera detects that it is aligned with the top of a plant, the robot stops. From here, the gantry is able to rotate around the plant, positioning the end effector to trim objects from the plant (figure 3.2c). When he plant has been trimmed, the gantry rotates back towards the robot, and the robot continues forward along the row.

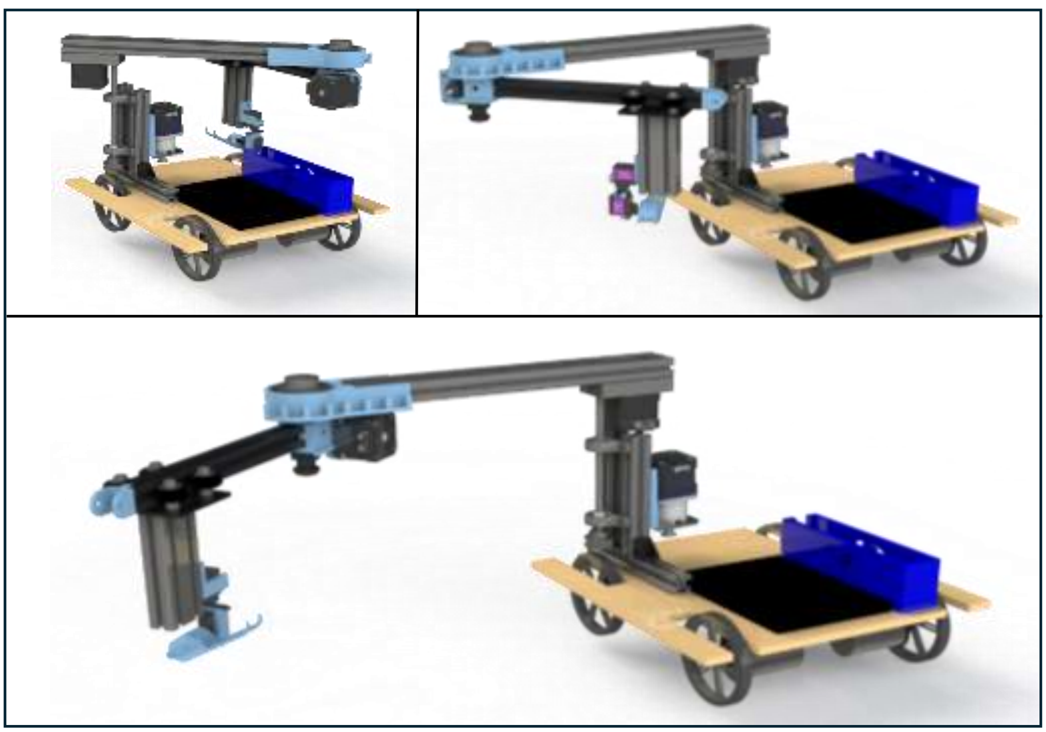
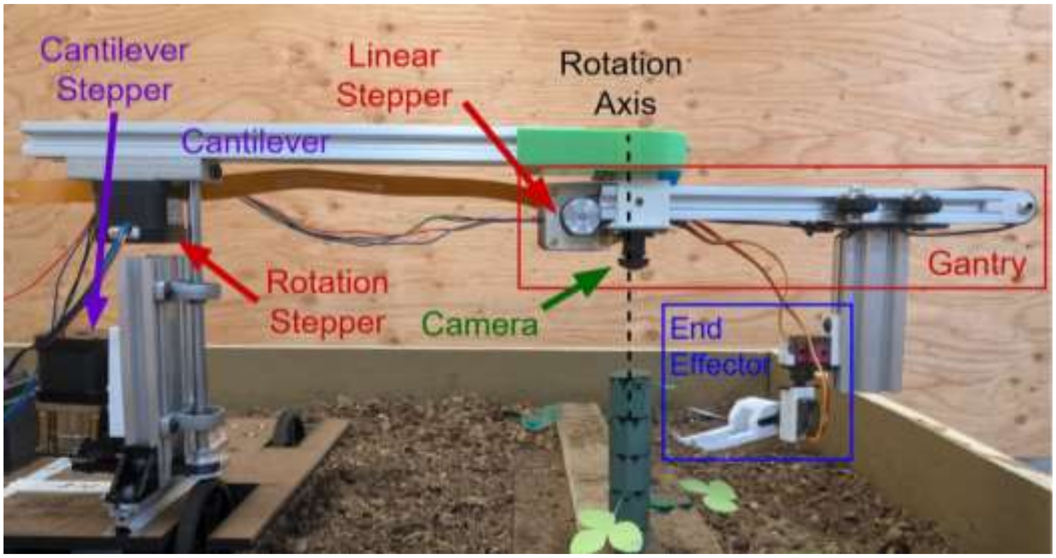


Figure 3-2 ***a)*** *The gantry and cantilever begin in a stowed configuration.* ***b)*** *The cantilever deploys the gantry over the plant bed****. c)*** *The gantry rotates about the plant to trim the plant*

The gantry deployment system spins about a steel axle that attaches to the corner of the robot. The axle is supported by a tower constructed of 20-20 aluminum extrusion and is driven by a NEMA 17 stepper motor. The stepper employs a 5.18:1 gear ratio to accommodate the large moment of inertia of the cantilever-gantry system.



The gantry is connected to the end of the cantilever by a strong bearing capable of supporting the high cross-loads from the weight of the gantry. This bearing forms the rotational axis of the gantry and is driven by a stepper motor mounted at the base of the cantilever. A belt runs through the cantilever to connect the stepper motor to the bearing.

The gantry's translation axis is driven by another stepper motor mounted to a housing under the bearing. The rotation of the stepper is translated through a belt to linear motion of the cart.

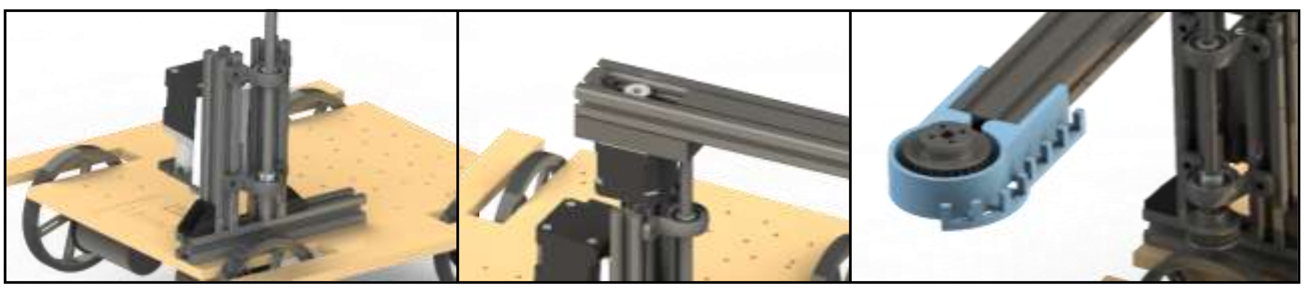


*Figure 3-3 The main components of the gantry deployment mechanism. **Left:** The 20-20 tower, supporting both the steel axis of rotation for the cantilever and the stepper motor that drives it. **Center**: The aluminum plate that interfaces the steel rod and second steppe's gear sits in a groove cut into the cantilever, and its belt runs through the cantilever. **Right:** the 3D-printed hub that houses the high-strength bearing. The cantilever mechanism hangs beneath this hub*

3.1.3 Trimming Mechanism

The end effector system lies at the end of the gantry system and is responsible for executing the trimming motion to remove flowers and leaves. The end effector consists of two tusk-like tines connected to the central body. When trimming a leaf, the tines are placed on the underside of the leaf, on either side of the stem. The end effector is then rotated upwards, pulling the leaf up while the stem passes through the tines. Thin strands of filament cross the gap between tines and are cut through the center. The strands are soft enough to allow the stem to pass through, but stiff enough to prevent flowers from slipping between the tines. This makes the trimming process very repeatable. However, it can be difficult to print, and the thin filaments break after a few uses, requiring us to replace the end effector after every round.

The gantry was originally designed to have the end effector at a fixed orientation, and a second, vertical linear actuator would move the end effector up and down to trim the leaves and flowers. However, this second actuator prove

d too bulky to be practical, so the system was redesigned to minimize the need for vertical actuation. To do this, the end effector was positioned around the middle of the stalk and attached to a servo rotating in the vertical plane. This allows the end effector to arc up and down. Next, the length of the tines was increased so that when the end effector is swept in an arc from the bottom of the plant to the top, the tines will reach any leaf or flower along the plant, regardless of the stem's length or height on the plant. This arcing motion eliminates the need for any vertical travel at the base of the end effector.

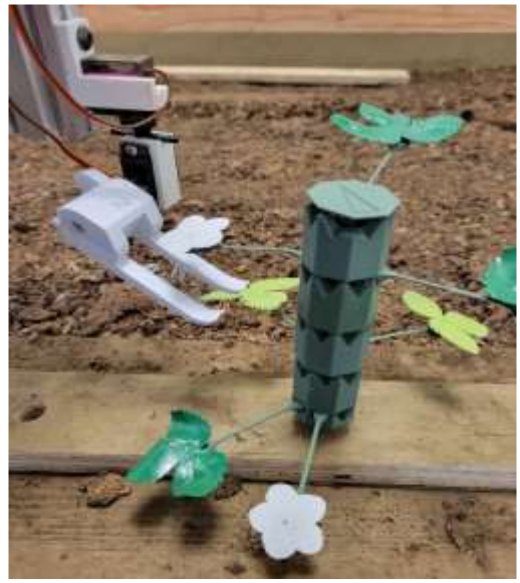


Figure 3-4 The trimming mechanism, consisting of a printed end effector driven by the "wrist"

Because of the unpredictable peat moss surface, sometimes the gantry camera fails to position the gantry exactly over the plant. When this occurs, the end effector, which normally points straight towards the center of the plant, gets off-axis. This leads to missed or false trims and damaged stems. To prevent this, a second "wrist" servo was built into the end effector system. This servo allows for the correction of the end effector's angle to make sure it can always align directly with the plant.

3.2 Electronics Design

3.2.1 Architecture Overview

The robot's electrical system accomplishes three main functions: (1) distributes power from the battery to the controllers, sensors, and actuators, (2) relays sensor data from the camera and ultrasonic sensors to the Raspberry Pi and microcontroller, and (3) relays motor commands from the Raspberry Pi and microcontroller to the drive system and robotic arm. To keep the wire

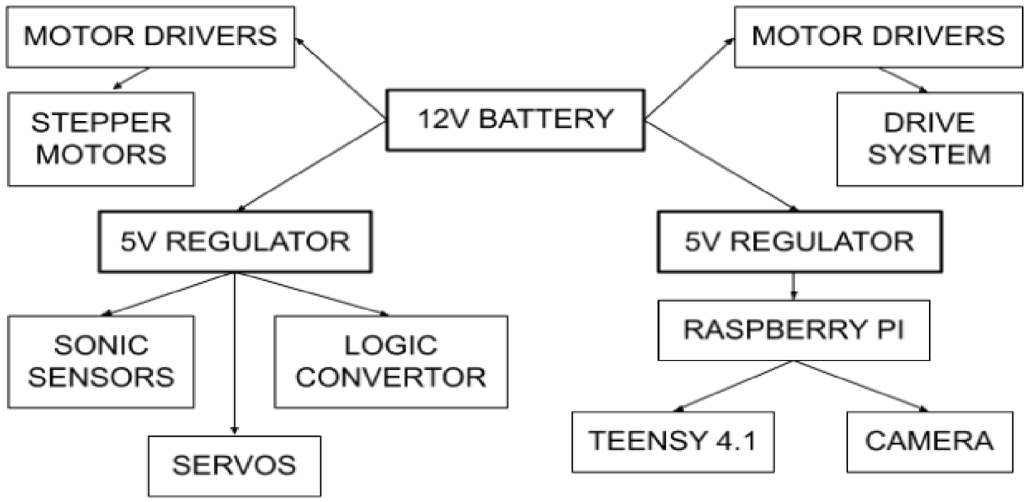


Figure 3-5 Electronics Power Distribution

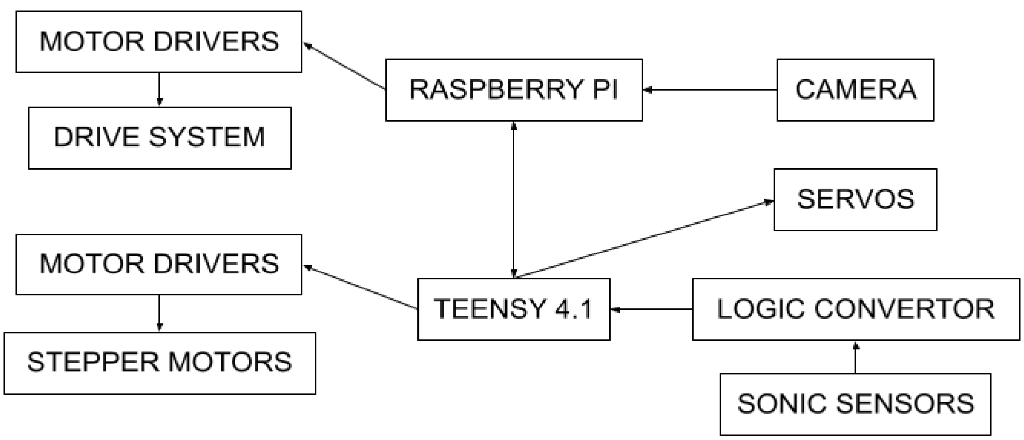


Figure 3-6 Electronics Communication Structure

management clean and easy to work with, we designed a simple PCB using Autodesk EAGLE that accomplished these functions. Figures 3.5 and 3.6 detail the flow of power and data through the electronics system.

3.2.2 Components

To power our robot, we selected an 11.1V 3S LiPo battery with a 5000mAh, 120C capacity, which will ensure sufficient power for all functions on the robot and will last an entire round. Three NEMA 17 stepper motors that control the gantry are controlled using an MP6500 stepper driver. The DC drive motors are powered by two RoboClaw 2x7A motor controllers, chosen for their high-power output.

3.3 SOFTWARE

3.3.1 System Architecture

The three design objectives for our software architecture were: (1) reliability, (2) modularity, and (3) repeatability. We selected ROS2 as the communications protocol for our system because of its compatibility across many devices and robust documentation. This allowed for reliability, modular testing, and easy replication through the ROS2 framework. A diagram of the system's communication architecture is shown in figure 3.7.

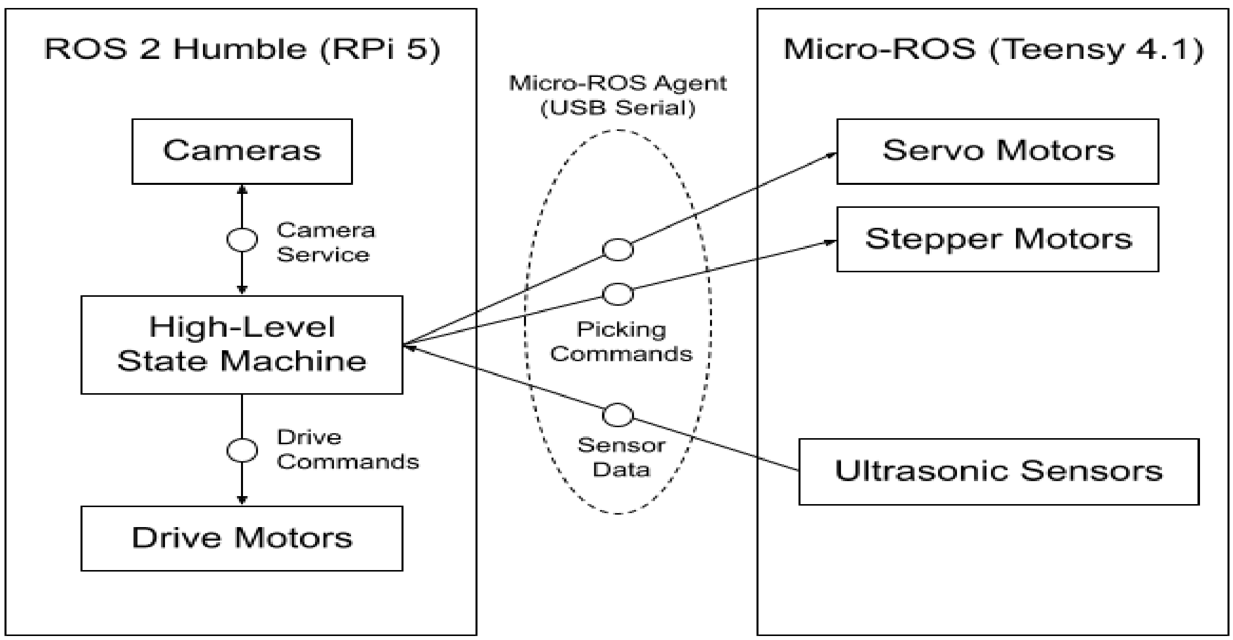


Figure 3-7 Diagram of ROS architecture

We implemented high-level action and mission planning controls on our robot using a simple state machine that runs in an independent ROS node on the Raspberry Pi. During operation the node receives data from the robot's camera and ultrasonic sensors, uses this data to decide on which action to perform next, and then sends those commands to the drive system and arm controls. Because there are two separate starting and ending positions, a flag in the node is manually set to indicate which fixed maneuvers the robot should perform at the beginning and end of the round. Details on operation and logic flow of the state machine are given in figure 3.8.

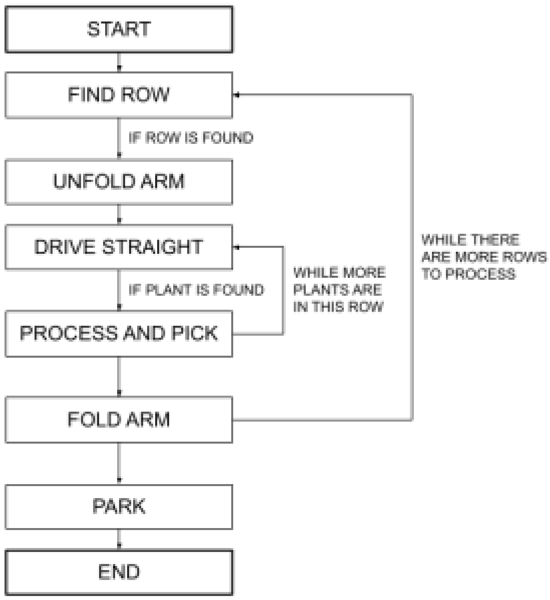


Figure 3-8 State diagram governing the robot's actions in the arena

3.4 Navigation

The robot's navigation tasks can be broken into two categories: fixed maneuvers and the row-following maneuver.

3.4.1 Fixed Maneuvers

The robot employs three pre-programmed maneuvers in navigation: one to approach the first plant bed from the start position, one at the end of the first bed to turn around and align with the second bed, and one at the end of the second bed to move to the end position. The motor commands for these maneuvers were tuned to consistently place the robot within 2"and 15° of the right-side plant bed, from either starting position. This allows the trimming mechanism to easily reach the plants.

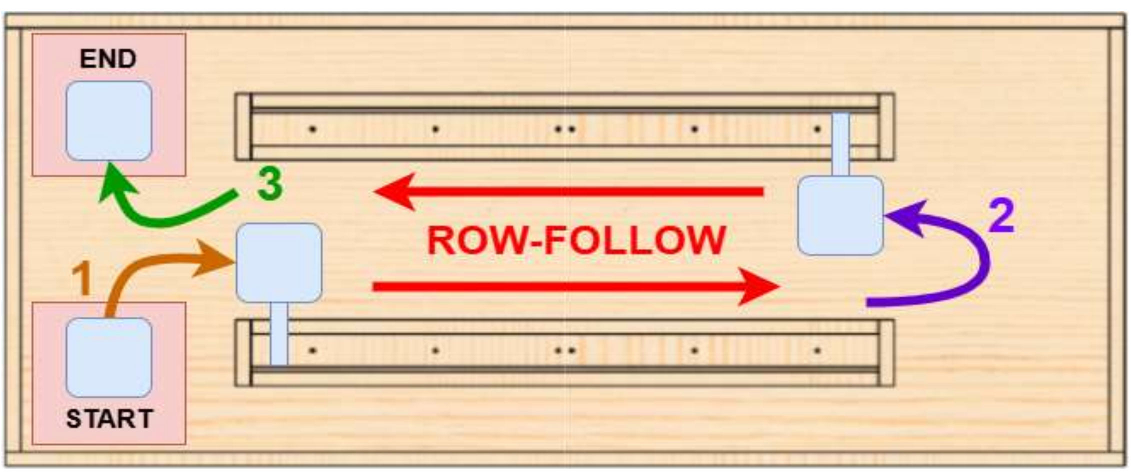


Figure 3-9 Fixed maneuvers and row-following maneuver shown on a shortened arena

3.4.2 Row-Following Maneuver

When the fixed maneuvers position the robot close to the start of a plant bed, the robot's next objective is to move between plants with enough precision to very closely align the gantry with each plant. The robot must maintain a set distance from the plant bed and remain parallel to it.

The peat moss in the arena adds uncertainty to all movements, so fixed maneuvers will not suffice. Instead, the robot uses ultrasonic sensors in a simple feedback control loop to maintain its position and orientation while traveling between plants. Two ultrasonic sensors are placed underneath the base of the robot on the right side, each pointing perpendicular to the direction of motion. The sensors detect the distance from the edge of the robot to the wall of the plant bed, which sits approximately 0.75" above the peat moss. The robot's position from the bed can be found as the average of the readings from the two sensors, and the angle of the robot relative to the bed can be found with the difference between the two readings.

The sensor readings are used in a simple proportional feedback control system. As the robot moves, the controller adjusts the motor commands to reduce the error in position (how far the robot is from the desired position) and orientation (the angle of the robot). This control strategy has proven very effective: tests have demonstrated that this approach corrects up to three inches of position error within six inches of travel.

3.5 Image Collection & Processing

3.5.1 Camera Selection

The camera sits just a few inches above the top of each simulated plant, with its visual axis aligned with the rotation axis of the gantry. The camera must accomplish several important tasks:

1. The camera senses the tops of the plant stems and sends a signal to the drive system to stop when the gantry is aligned with the plant.
2. Once the robot has stopped over a plant, the camera takes a picture of the plant. From this image, it detects and counts the instances of all healthy leaves, unhealthy leaves, and flowers. This data is sent to the Raspberry Pi for mapping.
3. The pixel locations of each object to be trimmed and the plant stem in the image are also reported to calculate joint positions for the trimming system to enact the harvesting mechanism.

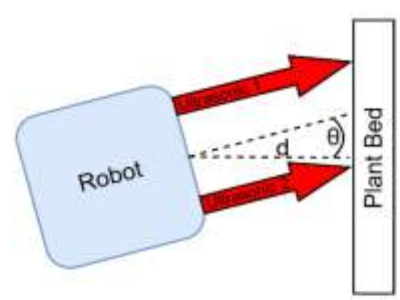


Figure 3-10 Two ultrasonic sensors are used to determine the distance and angle from the

To complete these tasks, the camera had to meet several design requirements:

1. The camera must have a wide field of view so it can see all objects on the plant from a short distance away from the top of the plant.

2. The camera must also be able to focus in the near field and have sufficient depth of focus to see all parts of a plant clearly.
3. The camera must interface easily with the Raspberry Pi 5.

The Arducam OV5647 was selected early in the design process for its small size, low cost, and swappable lenses. The team purchased a set of lenses varying from a 60° to 160° field of view, and after several rounds of experimentation, it was determined that the 120° lens was most suitable to our application, able to see the entire plant while not introducing too much image distortion.

3.5.2 Image Preprocessing

Each image taken by the camera goes through a preprocessing routine consisting of resizing to 480x640 pixels, then undistorting to correct for the effect of the wide-angle lens. The resulting image preserves realistic geometries, making it suitable for obtaining precise positions of the flowers and leaves.

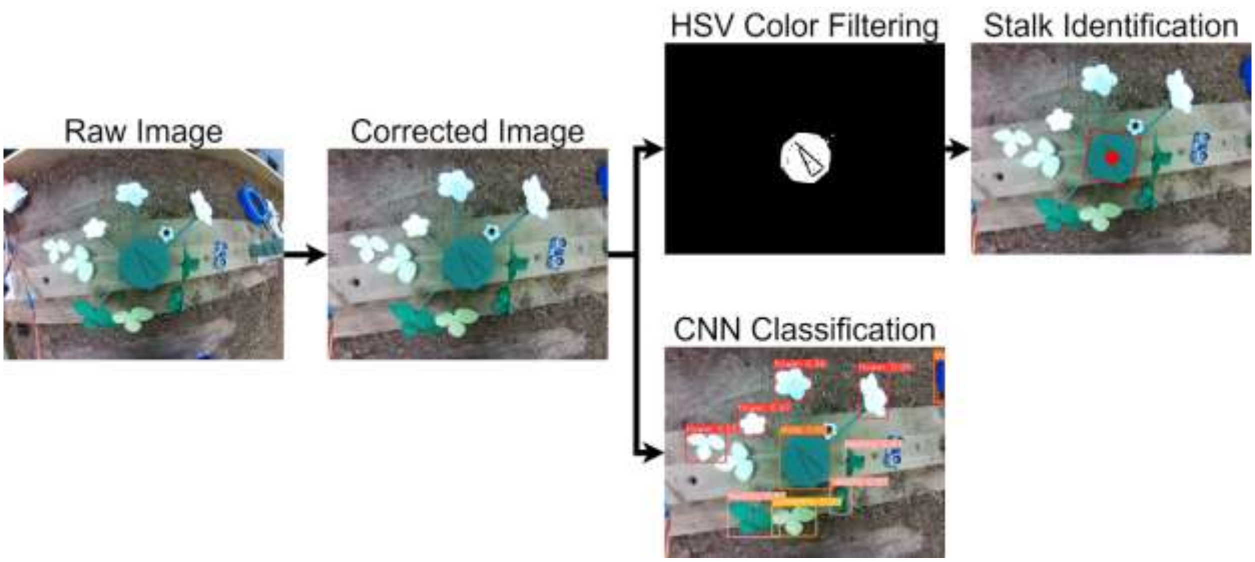


Figure 3-11 A sequence of images, from raw to undistorted to two branches, one with color filtering and one with CNN detection

3.5.3 Object Detection

Our robot has two detection tasks it must perform. First, the camera must process images in real-time as the robot is navigating to detect the center of each plant and tell the navigation system to stop moving. Classical computer vision color filtering techniques are a good choice for this, as they take very little processing power. This process involves converting to HSV space and binarizing to isolate the plant stalk. One of the weaknesses of this approach is that HSV filter values are sensitive to lighting, so adjustments will need to be made at the competition venue to account for venue-specific lighting conditions.

For the mapping and harvesting operations, the camera must be able to recognize the three categories of objects on the plant and determine their locations, while distinguishing leaves and flowers on the plant from those that might have fallen to the ground. Convolutional Neural Nets (CNNs) are the current state-of-the art in object detection and are an excellent fit for this problem. We used YOLOv8-nano, a CNN model developed by Ultralytics, and trained it on a dataset of several hundred images of plants, leaves, and flowers. The CNN has proven to be effective at distinguishing objects on the plant, with a successful identification rate of over 95%. It can distinguish objects on the ground at an 80% success rate. Further training will be done to improve the model before the competition.

The objects detected in the image are counted by category and sent to the Raspberry Pi for mapping, and the centers of the flowers and sick leaves to be removed are sent to the gantry system for trimming.

3.6 Trimming

The trimming operation takes place after the camera has located a bounding box for each object on the plant to be harvested. The Raspberry Pi receives this data in pixel coordinates, and for each box, it uses the box data to calculate three values: the rotational angle of the gantry, the linear position of the gantry cart, and the servo angle of the end effector. When these values are commanded to the stepper motors and servo, the end effector is put in a position where its trimming axis is aligned with the object to be trimmed and the center of the plant, ensuring a clean trimming motion.

Because of the uncertain navigation system, it is unlikely that the center of the gantry system will be perfectly aligned with the center of the plant as it is intended to be. The algorithm that calculates these values was designed to be robust to offsets in the location of the plant center and is able to find correct trimming commands as long as the plant center is within one inch of the gantry axis.

Once the gantry commands have been calculated, they are sent to the gantry, which positions the end effector. The gantry then executes a pre-programmed trimming motion, which lifts the object upward and off the stalk.

3.7 Mapping

The camera located at the gantry axis is used to image each plant before and after trimming, and a CNN is used to identify the number and type of each leaf and flower on the plant. In addition to its use for trimming operations, this information is also stored in .txt files to act as a semantic map of the field. Separate .txt files are created for the initial mappings and the final mappings. Each .txt file forms a table of comma-separated values. Every plant on the field gets one row in the table, with a column each for the reported number of healthy leaves, unhealthy leaves, and flowers. At the end of the trial, the two .txt files are saved to a USB drive to be exported.

While a relatively simple operation, mapping is very easy to ruin. If a single row in the table is omitted by accidentally skipping a plant, all subsequent rows will be incorrect when compared to the true state of the field. Mapping constitutes about one third of the available points, so it is crucial that at the very least, the structure of the table is maintained. Every operation upstream of the data recording, from proper gantry alignment through trimming, must ensure that something is reported for each plant.

We have implemented a basic mapping and data recording script, but it has yet to be integrated with the camera identification systems. This will be a priority in future system testing leading to competition.

3.8 Parts List

Table 3.1 gives an abbreviated Bill of Materials containing the most important XX components on the robot. A complete Bill of Materials consisting of all YY parts is provided in the appendix.

Item Description		Quantity
Base Subsystem		
	Pololu Wheel for Standard Servo Splines	4
	Greartisan DC 12V 50RPM 1:17.4	4
	Ultrasonic Sensor	4
	LiPo Battery 11.1V 5000mAh	1
Gantry Deployer Subsystem		
	Stainless Steel Rod 5/16"(8mm) Diameter 300 mm	1
	High-Load Face-Mount Crossed-Roller Bearing	1
	Nema 17 5.18:1 Planetary Gearbox	1
Gantry Arm Subsystem		
	2020 Aluminum Extrusion	250 mm
	V-Slot® NEMA 17 Linear Actuator (Belt Driven)	1
	Camera mount, 3D printed, 31g	1
	Arducam OV5647 Camera Sensor	1
Picking Claw Subassembly		
	Servo Motor	2
	Fork, 3D printed, 8g	1
PCB		
	Raspberry Pi 5	1
	Teensy 4.1	1
	MP6500 Stepper Motor Drivers	3
	RoboClaw 2x7a Motor Controller	2

Table 1 Abbreviated Bill of Materials

4 4 SYSTEM PERFORMANCE

4.1 COMPONENT & SUBSYSTEM TESTING

Our design philosophy focused on integrating frequent small-scale tests into the design process at the component and subsystem level to evaluate basic functionality. This allowed rapid iteration and refinement of ideas without needing the robot or subsystems to be fully assembled.

For mechanical systems, we focused on “human-in-the-loop” testing, where prototypes would be positioned and actuated by hand to validate that the part worked as intended. This worked especially well in the design of the end effector, which went through over ten iterations to refine its trimming ability. For software systems, processes were developed and iterated using simulated data to the extent possible. The

Figure 4-1 “Human-in-the-loop” testing on the end effector to refine its design

The image processing algorithm was developed using images taken by hand, and later refined once a camera and mounting position were selected. The navigation control system was developed in simulation and tuned once the full robot was assembled.

Prototype subsystems were assembled and tested in parallel to individual components as each component developed. This ensured that the component designs converged onto a single subsystem design and simplified the integration process.

4.2 Full System Validation

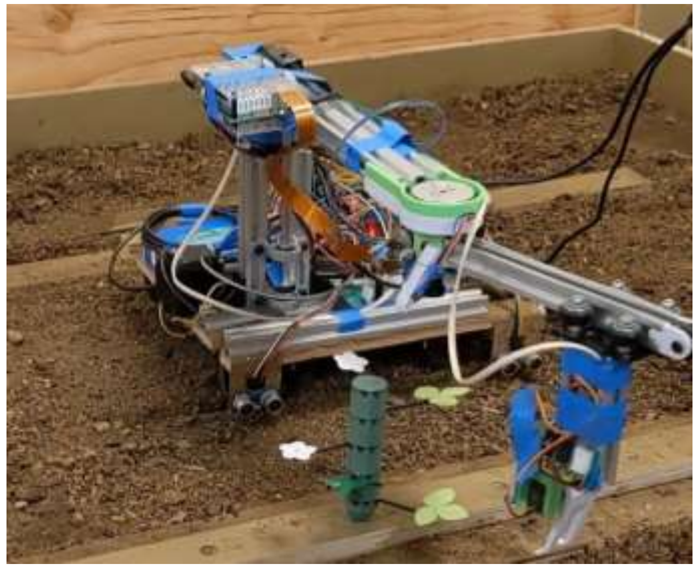


Figure 4-2 The first full-system test was successful in trimming a single plant

Early in the design process the team set a Go/No-Go milestone at the end of April 2024 to decide whether sufficient progress had been made to justify spending money to register and travel to competition. The robot would need to demonstrate successful integration of all subsystems and ability to autonomously execute all basic tasks. If this milestone was not met by the end of April, the team would not attend the competition.

On April 16th, 2024, the team conducted a full-system test of the robot. The robot started in the corner of the arena, navigated to the first plant bed, aligned the gantry with a single plant, correctly identified each leaf and flower on the plant, and successfully trimmed the correct objects. This was a significant achievement in the robot's development and indicated a high likelihood of success at competition.

The use of a milestone with a hard decision point proved to be an exceptional motivator for the team. In future years, we plan to add more significant milestones throughout the competition year to drive improvements to our design process.

4.3 Future Testing

While basic functionality has been demonstrated, as of July 1st, 2024 the robot is far from ready to compete. Several improvements have been made to the robot's hardware and software since the April milestone that must still be validated, and a full run of the entire competition round must be completed. Future testing leading up to competition will consist of the following:

- Run several single-plant tests to verify functionality of all subsystems.
- A series of full-round tests will be conducted at low-speeds to verify that the robot can complete a full round without encountering errors or going off course. The focus is on reliability and repeatability for the state diagram, sensors, and actuators.
- Full-round tests will continue to be performed at progressively higher speeds. The goal of these tests will be to improve the robot's performance until it can correctly and consistently complete the course as quickly as possible while providing reliable performance.

5 Conclusion

In this report we have given a high-level overview of the mechanical, electrical, and software design of Henry, our robot competing in the 2024 ASABE Robotics competition. We discussed the design philosophy that drove our initial design exploration and final design refinements, and briefly mentioned some of the challenges faced along the way. Most of the details of the design process, from preliminary sizing analysis to final dimensions, have been omitted in favor of brevity and clarity. We are confident that the quality of our engineering will show through in our robot's performance at competition.

The BYU Agricultural Robotics team is in its second year competing in the ASABE Robotics competition. We have grown a great deal this year, both through our successes and failures. We have learned how to maximize the information we gain from prototypes to improve our designs, how to design effectively for integration, and how to communicate and coordinate effectively as a growing and diverse team. We hope to apply what we learned this year to become greater, more influential engineers, both in competition years to come and for our lives.

We would like to thank the BYU Mechanical Engineering Department and Wiedman Center for their generous financial support - the growth and development that they enable is priceless. We would also like to thank our advisor Dr. Douglas Cook for his encouragement, feedback, and support throughout this competition year.

6 Appendix

6.1 Bill of Materials

Item Description	Quantity	Unit of Measure	Unit Price	Total Price
Base Subsystem				**206.665**
Pololu Wheel for Standard Servo Splines	4	unit	7.95	31.8
Greartisan DC 12V 50RPM 1:17.4	4	unit	14.99	59.96
DC Gear Motors Mounting Bracket	4	unit	8.99	35.96
6mm Bore Set Screw D-Hub	4	unit	6.99	27.96
2020 Aluminum Extrusion	150	mm	0.0118	1.77
Ultrasonic Sensor	4	unit	1.28	5.12
Ultrasonic Sensor Mount	4	unit	1	4
12 x 12 X1/4 MDF board	2	unit	2.75	5.5
Battery Mount, 3D printed, 91g	1	unit	9.1*	9.1
LiPo Battery 11.1V 5000mAh	1	unit	25.495	25.495
Gantry Deployer Subsystem				**276.628**
2020 Aluminum Extrusion	260	mm	0.0118	3.068

	2020 Corner Bracket	2	unit	3.99	7.98
	M8 x 16mm Flat Head Hex Bolts	8	mm	0.725	5.8
	M8 Threaded Slide	8	unit	0.55	4.4
	Stainless Steel Rod 5/16"(8mm) Diameter 300 mm	1	unit	6	6
	8mm Ball Mounted Pillow Block Bearing	2	unit	2.25	4.5
	High-Load Face-Mount Crossed-Roller Bearing	1	unit	169.96	169.96
	NEMA 17 5.18:1 Planetary Gearbox	1	unit	38.29	38.29
	NEMA 17 Stepper Motor Mounting Bracket Kit	1	unit	5	5
	GT2 Timing Belt Pulley 16 Teeth 5mm Bore	1	mm	1.1	1.1
	GT2 80T Pulley Synchronous Wheel, modified	1	unit	11.99	11.99
	6mm GT2 Timing Belt Rubber 300 mm	1	unit	6.04	6.04
	Motor Spacer	1	unit	2.3*	2.3
	Bearing Hub, 3D printed, 52g	1	unit	5.2*	5.2
	Cantilever Beam Motor Bracket, Milled	1	unit	5	5
Gantry Arm Subsystem					**119.53**
	2020 Aluminum Extrusion 250mm	250	mm	0.0118	2.95
	V-Slot® NEMA 17 Linear Actuator (Belt Driven)	1	unit	93.99	93.99
	Low Profile Screws M5- 25mm	*4*	unit		
	Low Profile Screws M5- 8mm	*4*	unit		
	Aluminum Spacer - 6mm	*2*	unit		
	Aluminum Spacer - 3mm	*1*	unit		
	Double Tee Nuts	*2*	unit		
	GT2 (2mm) Timing Pulley - 30 Tooth	*1*	unit		
	Eccentric Spacers - 6mm	*2*	unit		
	Solid V Wheel Kit	*4*	unit		
	Smooth Idler Pulley Kit	*1*	unit		
	Idler Pulley Plate	*1*	unit		
	Motor Mount Plate - Nema 17	*1*	unit		
	Cable Ties	*4*	unit		
	M3 Button Head Screws - 8mm	*4*	unit		

V-Slot Gantry Plate (20mm)	*1*	unit		
GT2-2M Timing Belt	*1*	unit		
V-Slot® Linear Rail - 20x40	*1*	unit		
Allen Wrench - 1.5mm	*1*	unit		
Allen Wrench - 2.5mm	*1*	unit		
Allen Wrench - 2mm	*1*	unit		
Allen Wrench - 3mm	*1*	unit		
NEMA 17 Stepper Motor	*1*	unit		
Camera mount, 3D printed, 31g	1	unit	3.1*	3.1
Pulley mount, 3D printed, 5g	1	unit	.5*	0.5
Arducam OV5647 Camera Sensor	1	unit	18.99	18.99
Picking Claw Subassembly				**20.48**
2040 al extrusion	100	mm	0.03	3
Servo Motor	2	unit	7.99	15.98
Fork, 3D printed, 8g	1	unit	0.8*	0.8
Servo to Servo Mount, 3D printed, 3g	1	unit	.3*	0.3
2020 to Servo Mount, 3D printed, 4g	1	unit	.4*	0.4
PCB				**347.24**
Raspberry Pi 5	1	unit	80	80
USB-A to USB-C	1	unit	0.71	0.71
USB-A to micro-USB	2	unit	1.59	3.18
Custom PCB	1	unit	12	12
Teensy 4.1	1	unit	31.5	31.5
2-pin screw terminals	20	unit	0.16	3.2
5V DC Buck Voltage Convertor	2	unit	14.99	29.98
MP6500 Stepper Motor Drivers	3	unit	8.49	25.47
RoboClaw 2x7a Motor Controller	2	unit	79.95	159.9
4-Channel Logic Level Convertor	1	unit	1.3	1.3
*$0.10 per gram PLA Plastic				970.543

6.2 Engineering Drawings

Table of Contents

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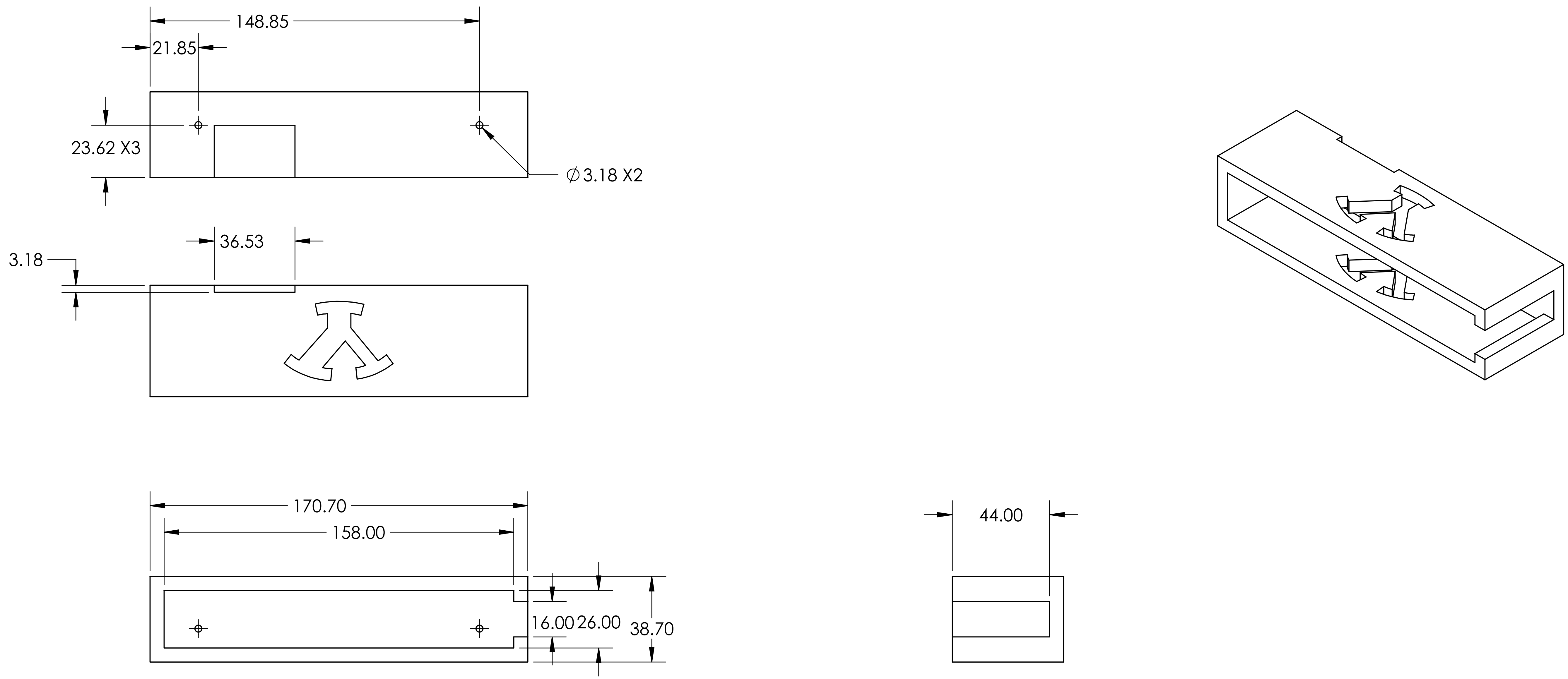

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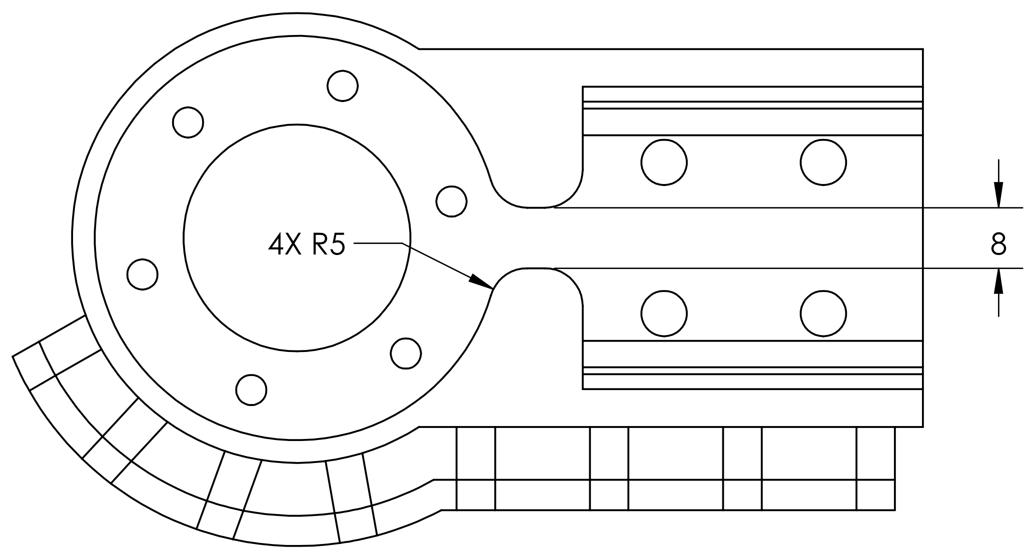

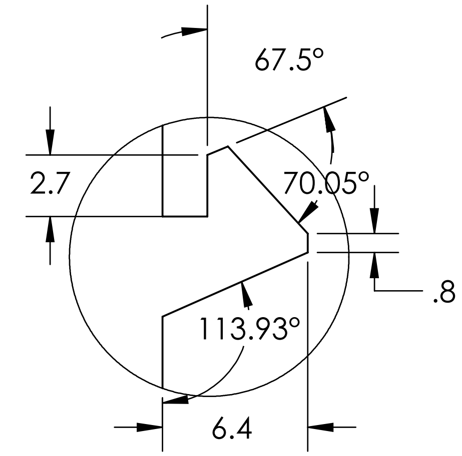

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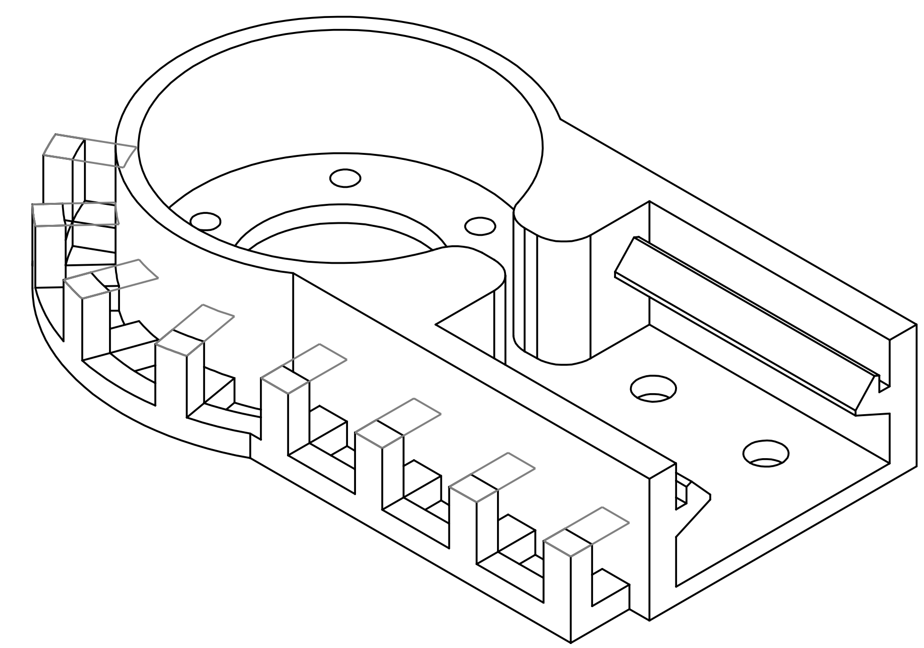

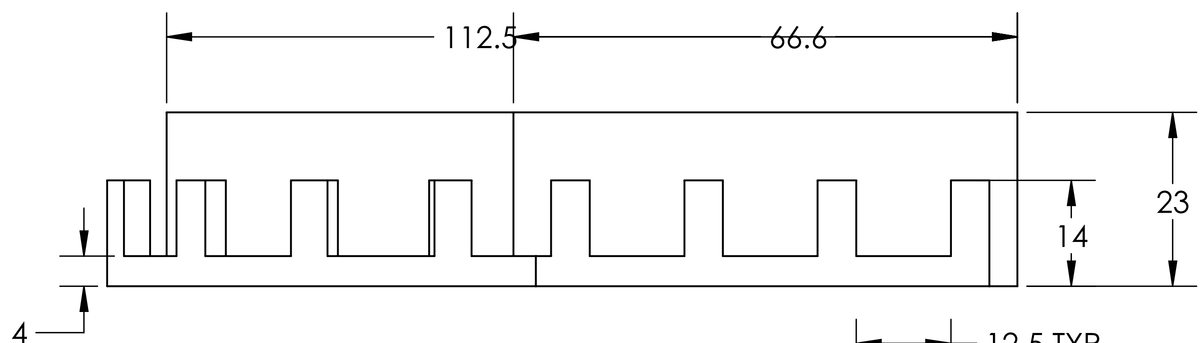

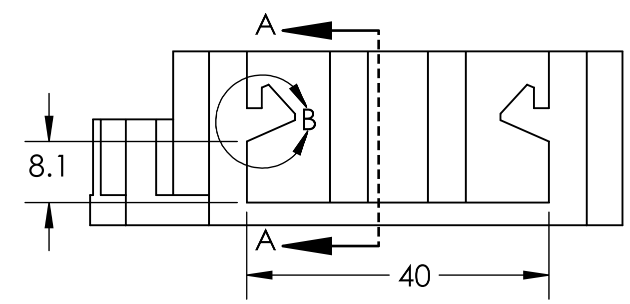

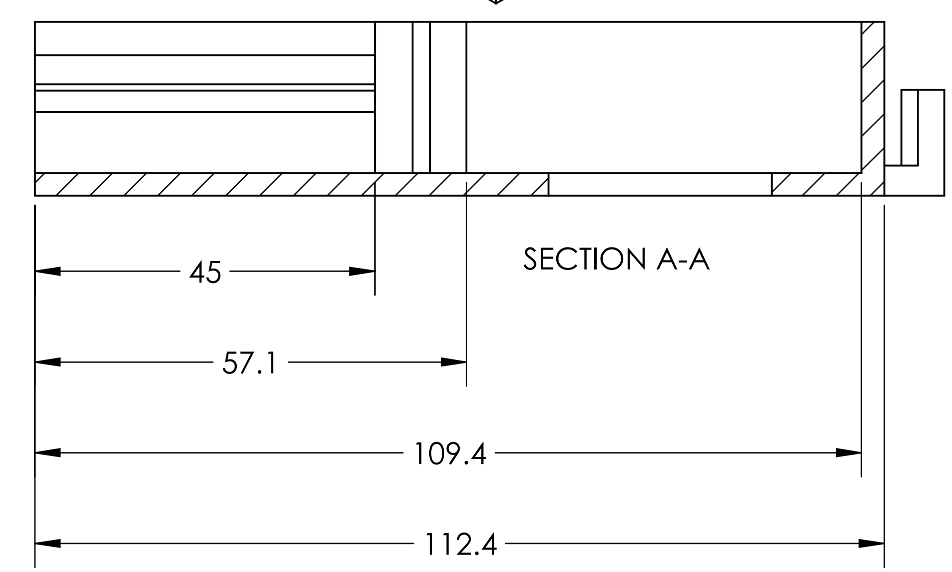

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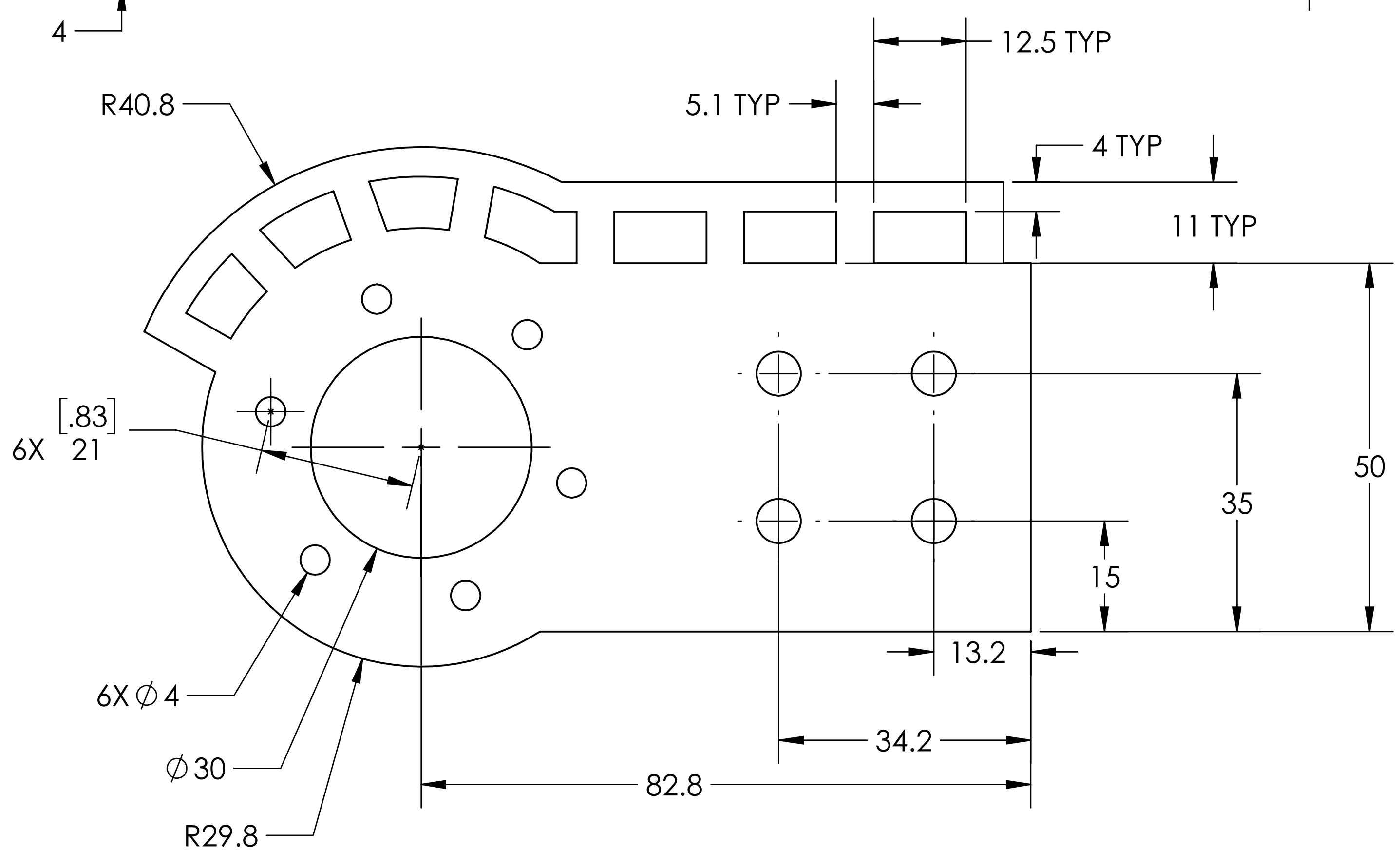

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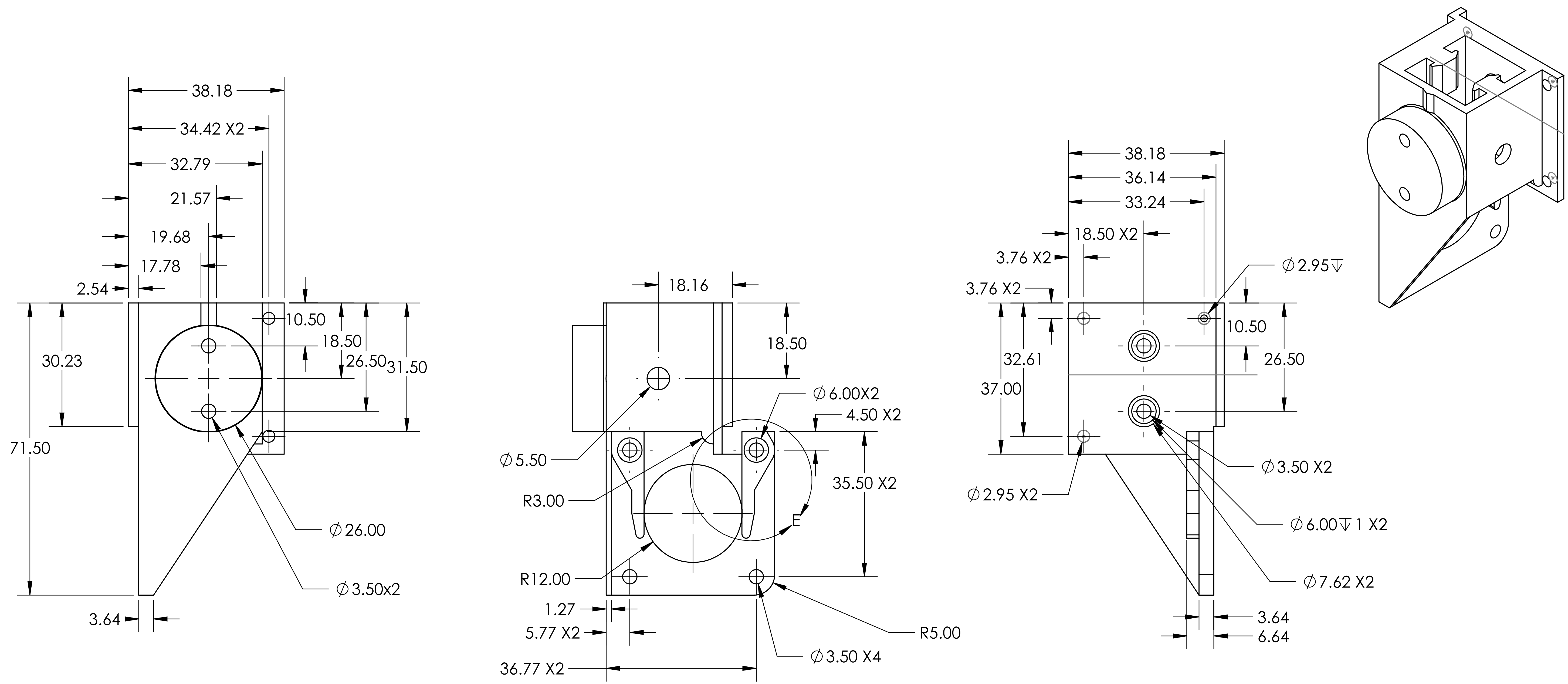

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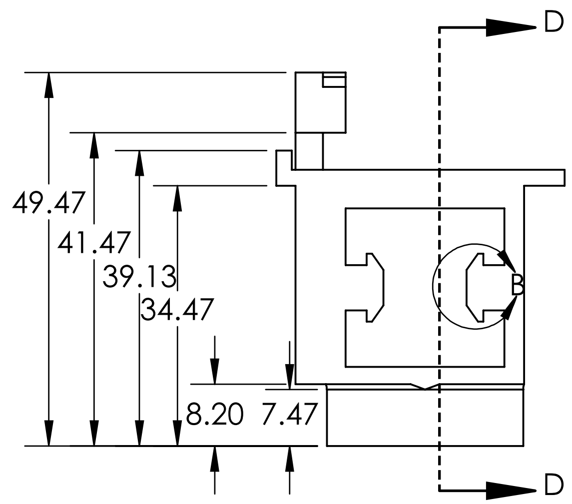

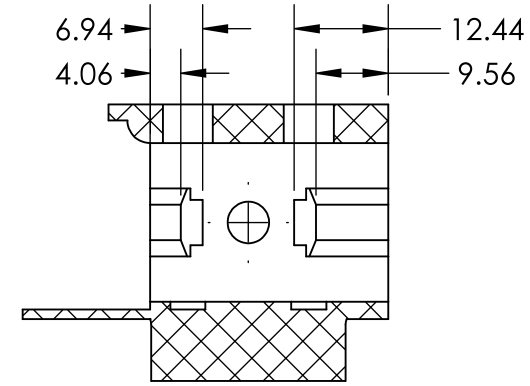

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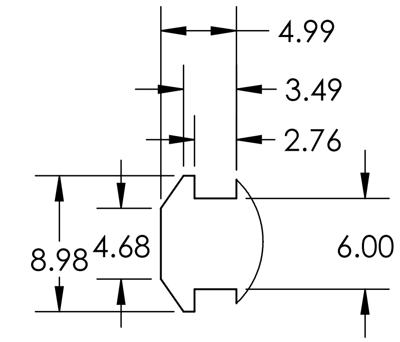

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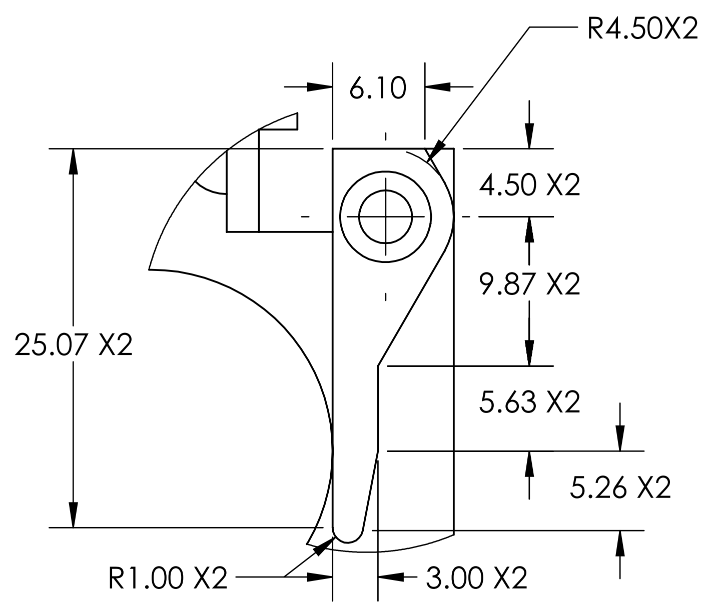

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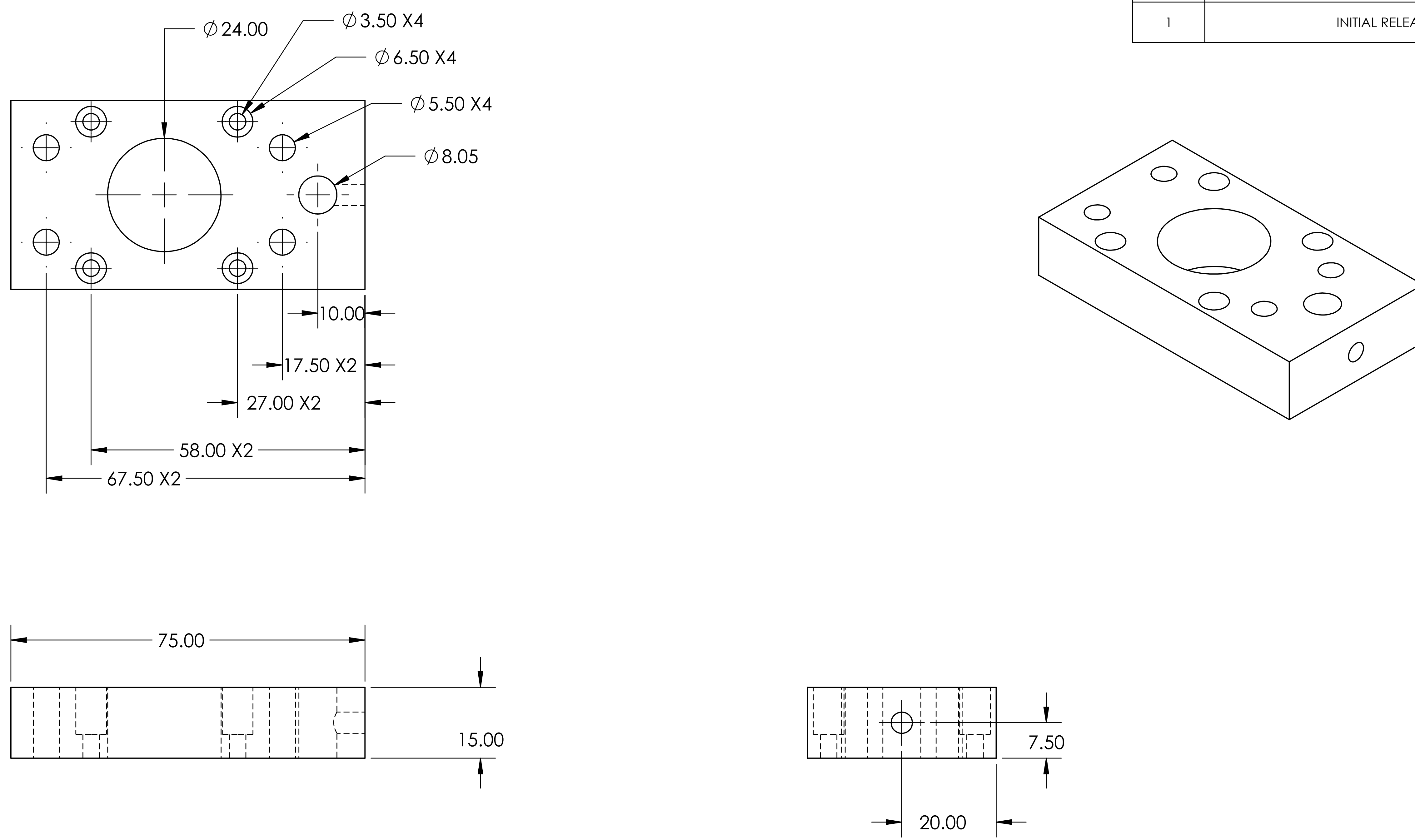

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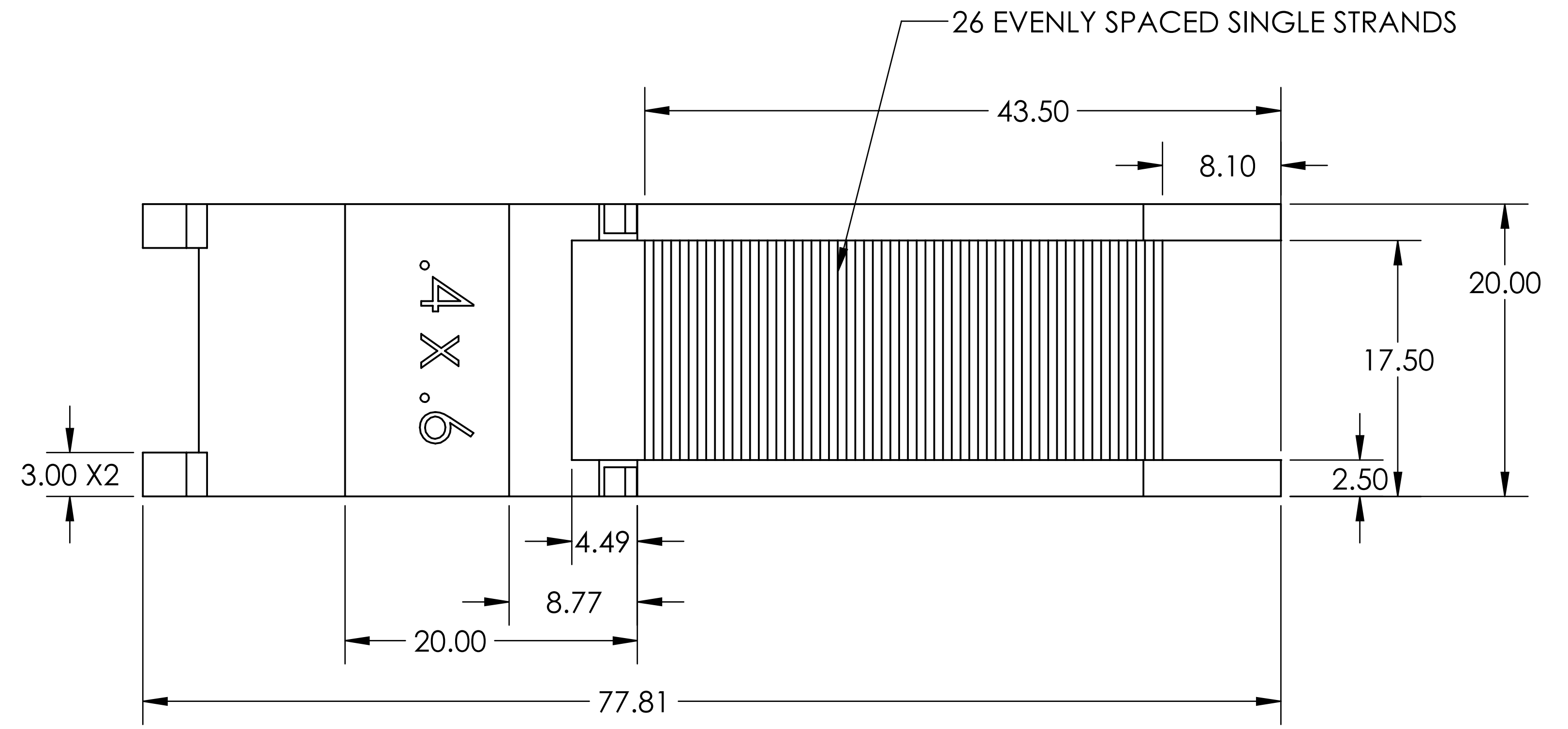

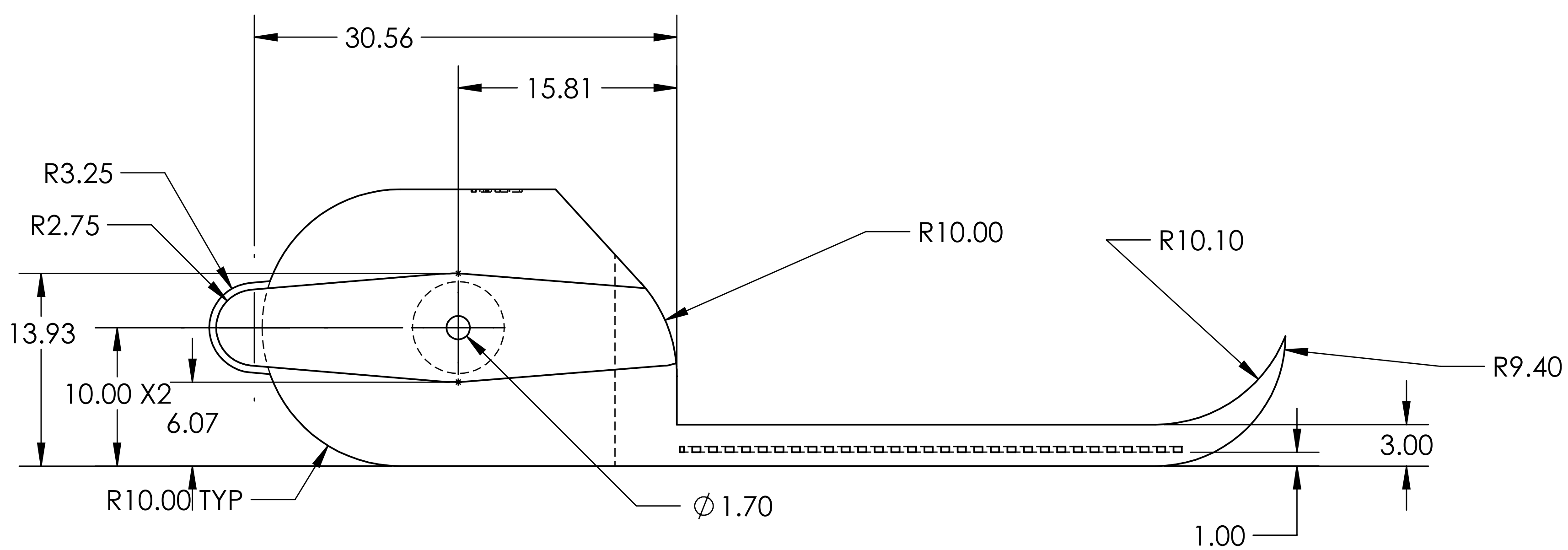

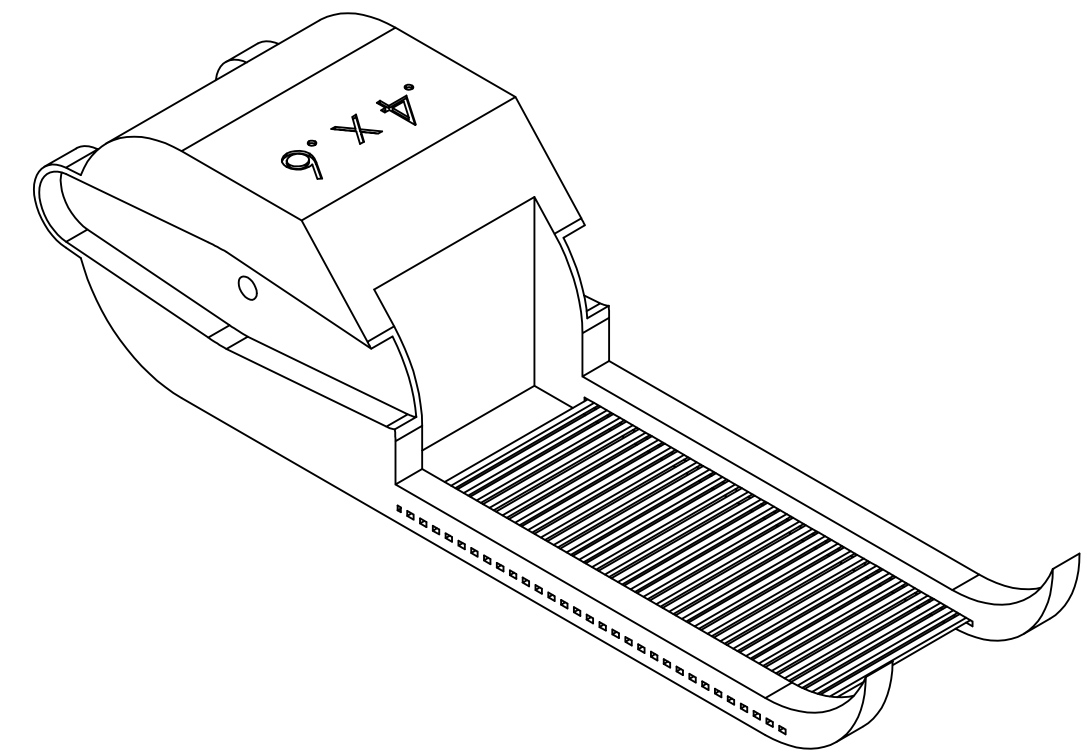

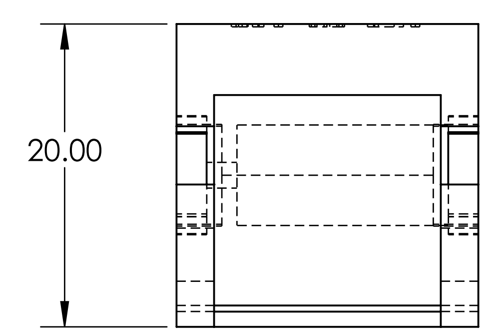

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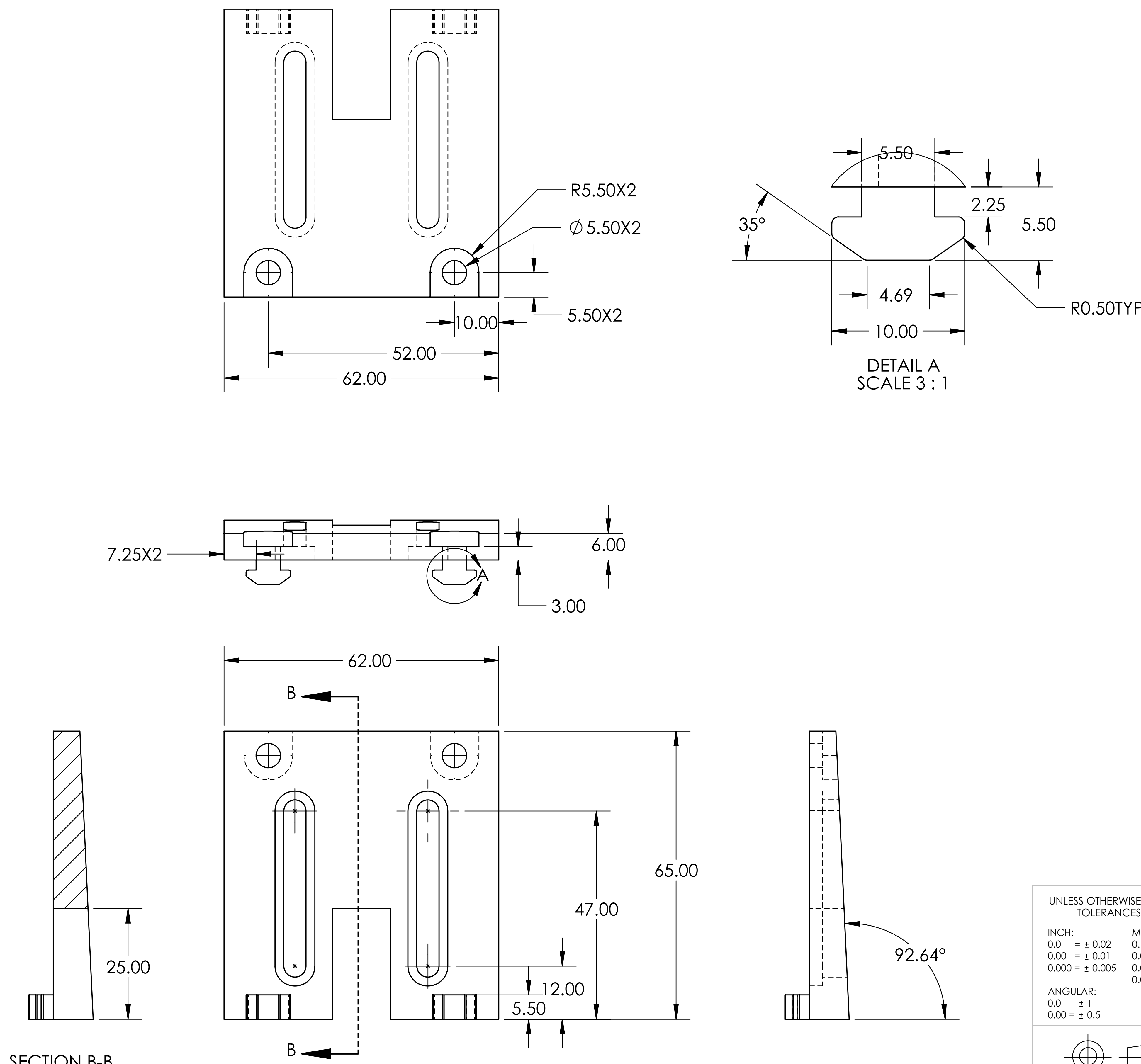

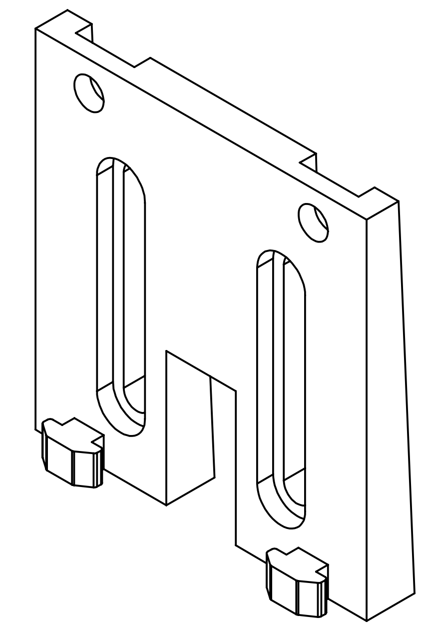

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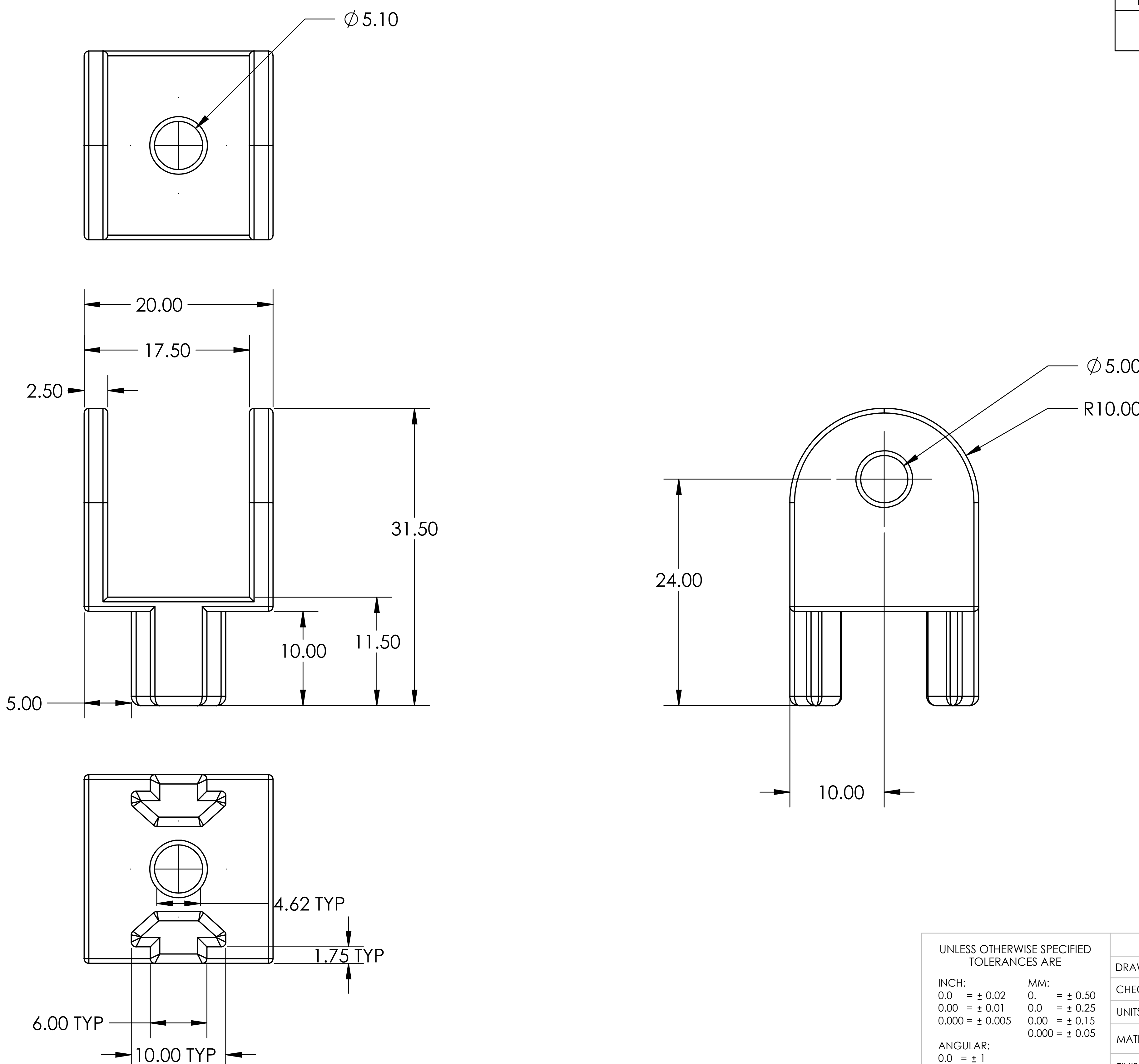

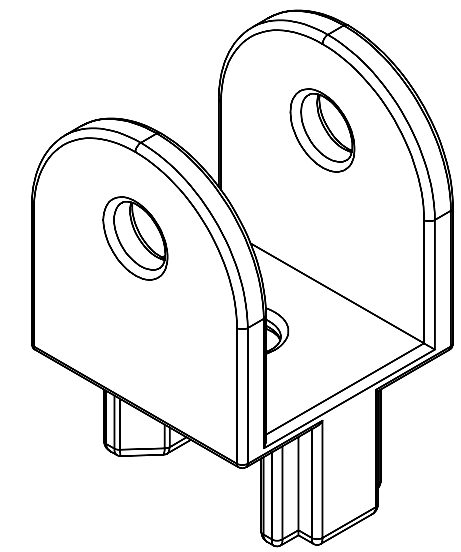

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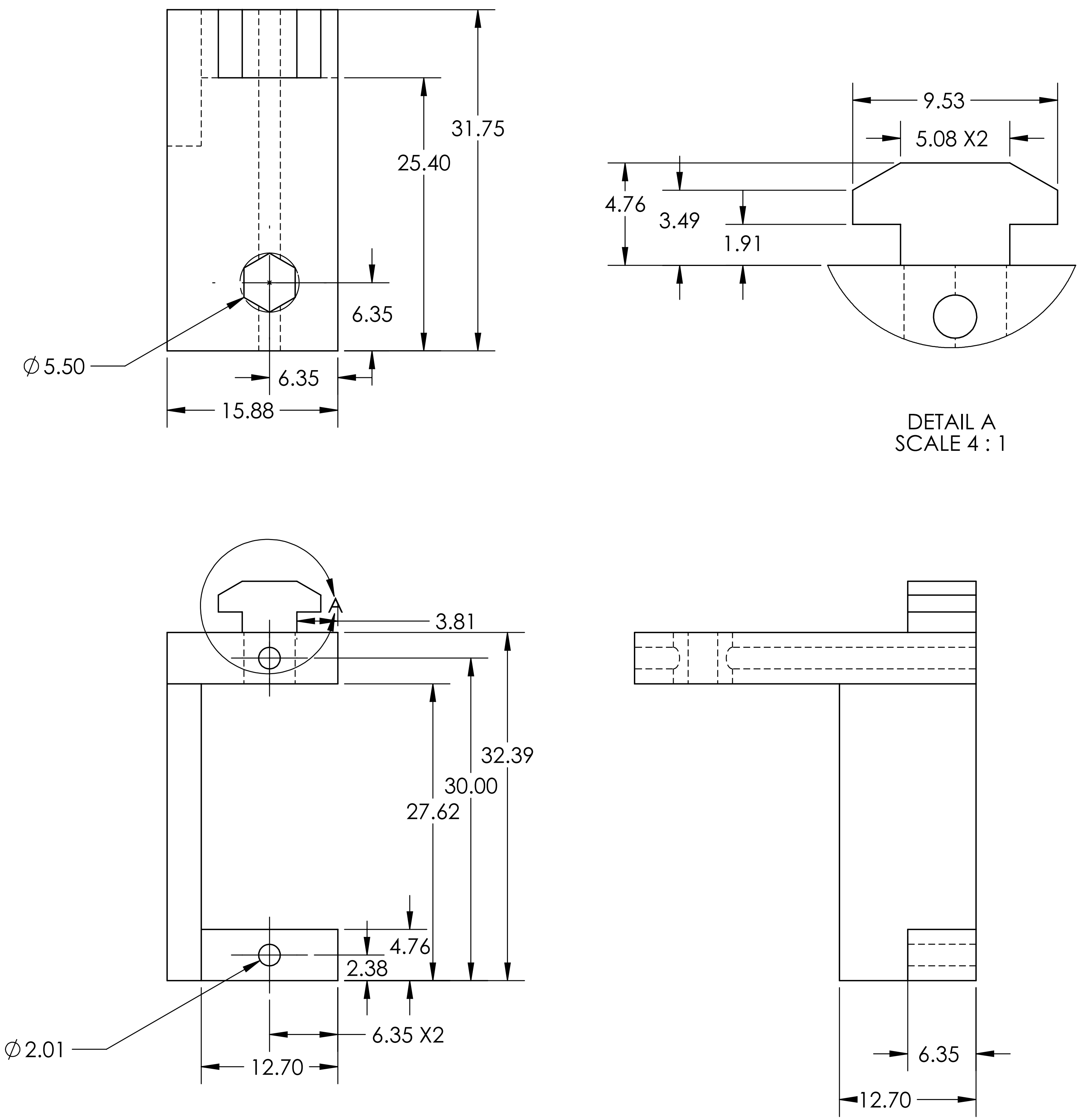

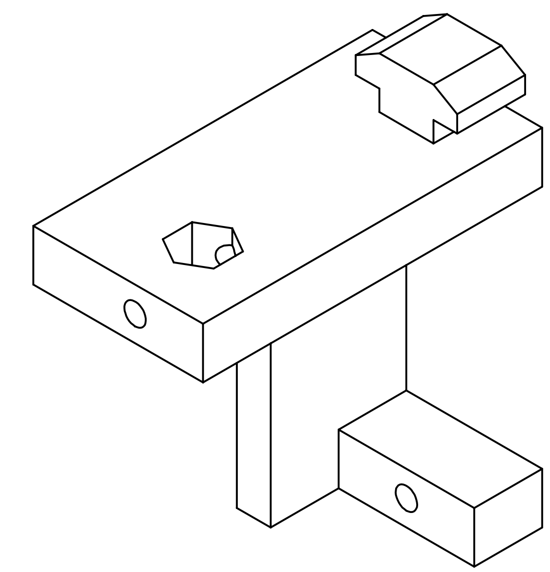

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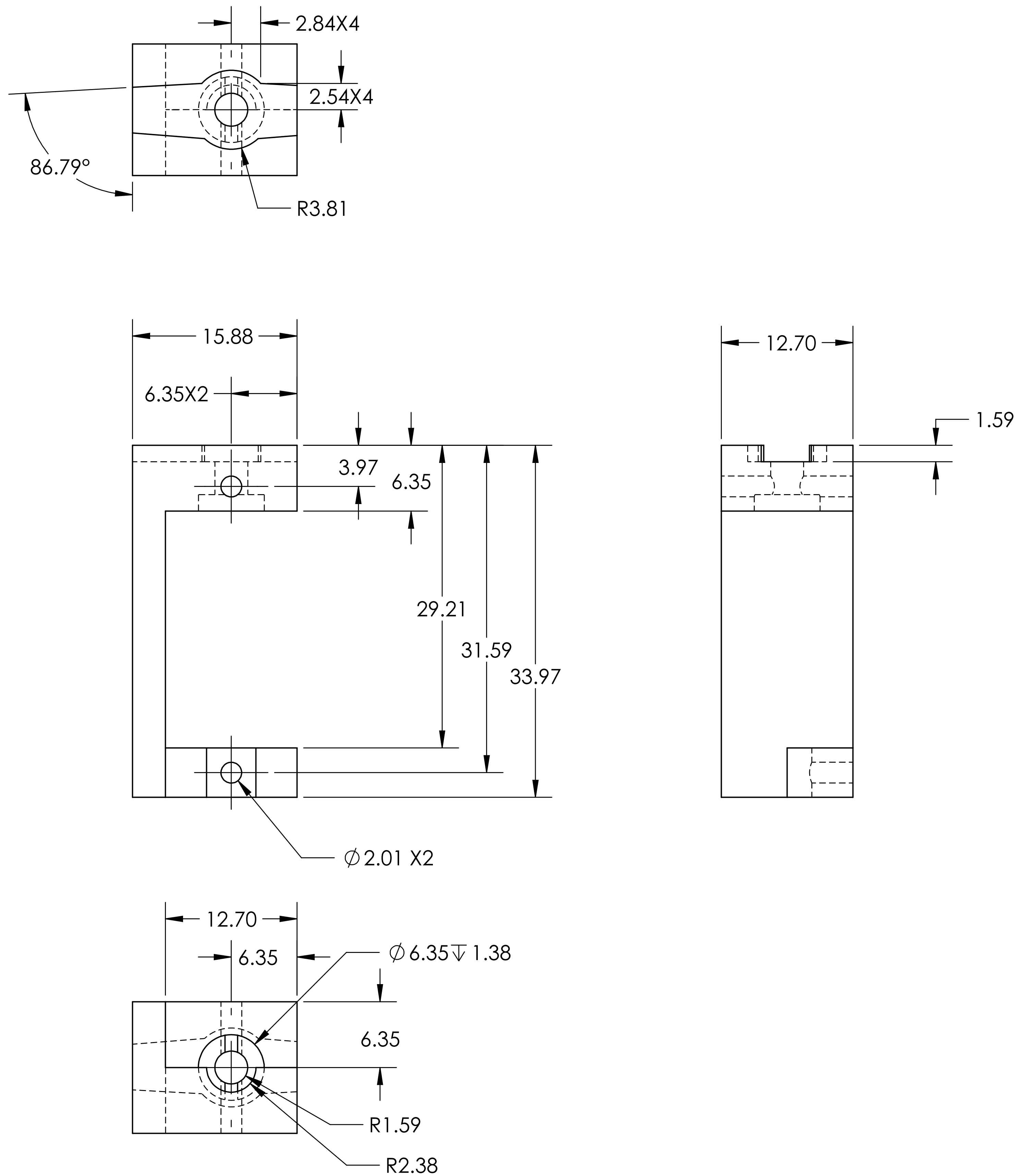

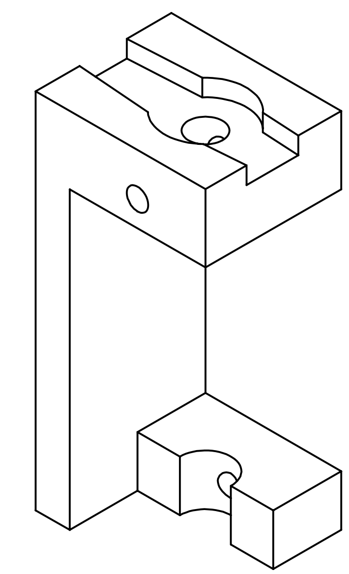

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COMMENTS		

BYU ENGINEERING
IRA A. FULTON COLLEGE OF ENGINEERING

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