ME 72 Final Design Report

Date: 3/19/25

Professor Mello

Terms: Fall and Winter

Team: Penguinators

Jabri Garcia-Jimenez

Jade Millan

James Muren

Sara Razavi

Jaylen Shawcross

I. Background

The 40th annual ME72 Engineering Design Competition was Bot Hockey, a challenge in which teams designed, built, and competed against other teams with three remote-controlled robots in a high-intensity hockey-inspired tournament. To make things interesting, the 20-foot x 12-foot rink had a ferromagnetic surface, allowing teams to use a magnetized chassis to improve traction and maneuverability. Hence, this competition required teams to balance speed, agility, and durability while designing robots that could maneuver, pass, and shoot a street hockey puck into the opposing goal while defending their own.

Preparing for this competition involved various challenges, including developing specialized puck-handling mechanisms, increasing traction, and integrating advanced control systems using platforms like Arduino. Additionally, there were strict size and weight constraints (16” x 16” x 16” per robot, combined team weight limit of 48.5 lbs). To create robots for this competition, teams had to balance mechanical design, electronics, and software.

Beyond the fun that comes from this competition, this competition provided students with an opportunity to apply real-world engineering principles through hands-on experience in manufacturing, machining, designing, and coding.

II. Robotic Vehicle Designs & Strategy

Our team adopted a specialized role-based strategy to optimize performance in the Bot Hockey competition. We designed three distinct robots, Enforcer, Goalie, and Striker, in hopes of mirroring the dynamics of an actual hockey game. Each robot had a specific function, which allowed us to create a well-rounded and high-performing fleet capable of both defense and offense.

First, the Enforcer was built to dominate bot-to-bot interactions by leveraging its high magnetic force and high-torque drivetrain. It was designed to disrupt and challenge opposing robots to maintain control of the rink. Hence, the Enforcer was amazing at offensive pushing and defensive blocking. It was the perfect balance between offense and defense. Also, its reinforced chassis and robust frame were optimized to withstand and deliver high-impact collisions, making it a force to reckon with on the rink.

Second, the Goalie was built as a last line of defense. It was designed to effectively block incoming shots via chicken wire while also using a trapping intake mechanism to capture and control the puck. Similar to the Enforcer, the Goalie was incorporated with heavy magnetism to anchor itself to the ferromagnetic rink. The Goalie was designed to mirror an actual real hockey goalie to protect the goal.

Finally, like any amazing hockey player, the Striker was built for speed, agility, and rapid scoring. The Striker was designed with a motorized intake system and a high-speed shooting fly-wheel mechanism. The Striker is able to shoot powerful and precise shots on goals. Hence, the Striker played a pivotal offensive role.

In building these specialized robots, tasks were divided into three teams: Mechanical design, manufacturing, and electrical or software teams. The mechanical design team was led by

James Muren. This team focused on designing and optimizing the robots' chassis, drivetrain, and intake systems to make sure that each robot was capable of its intended role. The manufacturing team was led by Jaylen Shawcross. This team focused on using precise machining and manufacturing techniques to bring these designs to life. The third team, electrical and software design, was led by Jade Millan. This team programmed the control systems to make a robot a robot. The rest of the team contributed to each of these groups, creating a collaborative environment that mirrored the teamwork that is needed to succeed in an actual hockey game. Through this structured division of labor, we were able to create a cohesive and competitive Bot Hockey fleet.

III. Design Process

A. Preliminary Design

Our preliminary design focused on simplicity. We initially envisioned a fleet of three robots sharing a common design, with modifications tailored to each specific role. The first robot designed and built was the Enforcer, which was simple but effective. We placed a major emphasis on reliability and high torque to push other teams. We considered several ways to leverage the magnetic floor to our advantage. Our initial idea was to use a high-power electromagnet, but we abandoned this idea due to the deformation we calculated it would cause to the robot's frame. We experimented with finite element modeling of several magnet geometries, before settling on the fourteen magnets which made their way into the final design. We deliberately chose a gear ratio that would permit us to push other robots around.

We envisioned a goalie which would have some means of blocking high shots and would be capable of trapping the puck. We discussed many materials to block shots, including netting, before finally deciding on chicken wire. Chicken wire is sturdier than netting, which meant it would require fewer supports and less substantial design changes to implement. Our trapping mechanism was originally a roller intake which moved the puck into a net. Though we did not use a net, the final trapping mechanism was similar to our initial design. Like the Enforcer, we anticipated that high torque and weight would be advantageous because it would allow us to push opposing robots out of the goal zone.

After we made our Striker the Goalie (see section on mobility demo for more information on this decision), it became necessary to create a new Striker robot from scratch. Using lessons learned from previous robots, we decided to use a flywheel shooter (more information in the mechanical systems subsection of the final design section). This robot was designed with maneuverability and speed in mind. First, we decided to use a three-wheeled West Coast Drive system for this robot, instead of the two-wheel system we used on the Enforcer and Goalie robots. This drive system places the center wheel slightly lower than the exterior wheels, allowing seamless turning. To make turning capabilities even better, we used omnidirectional wheels on the exterior. We also decided to use fewer magnets, debating between four and eight before settling on a design that would allow us to easily swap the number of magnets, enabling us to determine the optimal number through testing.

B. Final Design

Several major revisions were made to the preliminary design after the mobility demo and mock competition in order to produce the finished robots. We broke the direct drive on the roller mechanism during testing by bending the motor shaft, so we investigated alternate means of driving this mechanism that would protect the motor. We decided to use a bevel gear, which would allow the motor to sit in a more protected position inside the robot. Another major consideration was weight. In our initial design, we did not consider weight as much as other factors such as cost and reliability, which led to our robots weighing around 51 lbs after preliminary assembly.

As such, several weight-reducing measures were taken. We focused on removing material from the ¼ inch material to maximize weight savings while minimizing structural fragility. We were able to reduce gearbox weight by roughly 35% by removing unneeded material on the bandsaw. We also created new side plates for both the Enforcer and Goalie robots. These side plates were heavily pocketed using the water jet, then the Trak mill was used to drill and ream holes into which we press fit needle bearings. The CNC features of this machine were used to cut holes for the flange bearings. Instead of making new bellypans, we used the Flow water jet to create additional pocketing in our existing bellypans. This was done because the bellypans required more post-processing after being cut on the water jet than the side plates as they each have fourteen holes for magnets which need to be CNC'd on the mill. This also saved roughly 3 square feet of material compared to manufacturing new bellypans.

	
Figure Ia: pocketed Enforcer bellypan	Figure Ib: pocketed Enforcer and Goalie side plates

At the point we began manufacturing the new Striker, we realized that weight would be a premium. We designed its side plates using 1/8th inch aluminum, instead of 1/4, like the other robots. We created standoffs to ensure constant spacing between the inner and outer side plates which doubled as receptacles for our magnets. These were easily accessible to allow us to swap between using four and eight magnets in between matches depending on the next opponent we were facing. We did not want to pocket the ⅛ material of the side plates but pocketed the ¼ material of the gearboxes and the ⅛ material of the intake and transfer mechanisms. This allowed us to save weight while not compromising the structural integrity of the parts we expected to see experiencing the most impact.

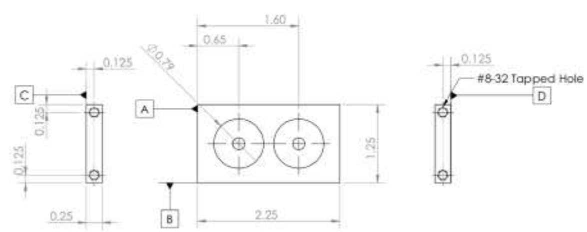


Figure IIa: standoff design	Figure IIb: machined standoffs

1. **Mechanical Systems**

We completely redesigned the Striker robot in light of revelations from the mobility demo. First, the high-traction 4-wheel drive was swapped out for a speedier and more maneuverable West Coast drive. Considering we already had 2 high torque robots, strategically we wanted to add flexibility to our scoring strategy by designing around a shooter mechanism.

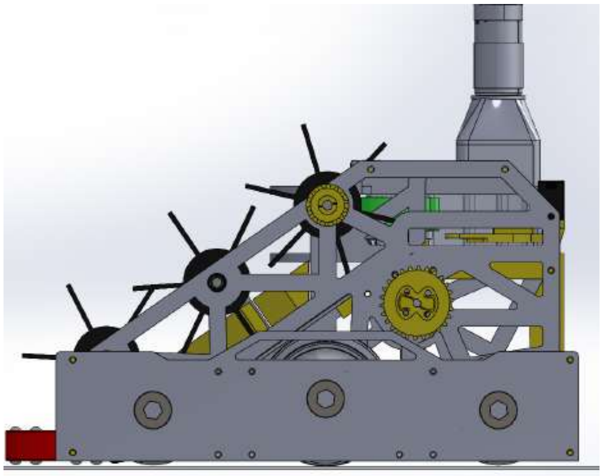
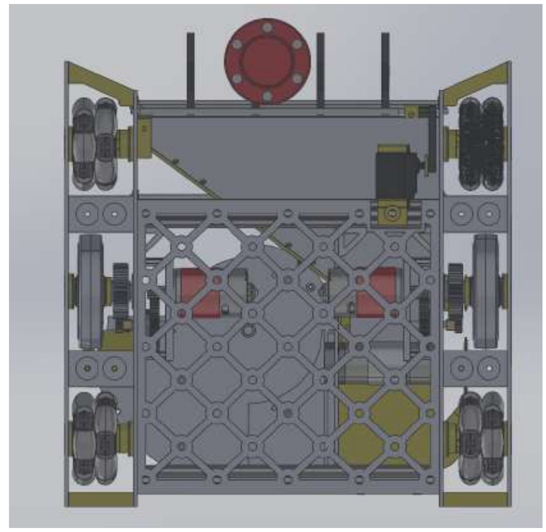
	

Figure IIIa: West Coast Drive with a 1mm center dropped wheel	Figure IIIb: Bottom view of new drivetrain with 4 omnidirectional wheels and two center traction wheels

We discussed a flywheel shooter mechanism at the very beginning of the design process but decided against it due to its complexity and weight. After attempting both a solenoid shooter (during the first term) and a combined roller intake/shooter mechanism (second term), we realized a flywheel was the most reliable option. We designed our flywheel to be driven by another RS 550 shop motor and to have a moment of inertia of 18.2 lb-in^2.

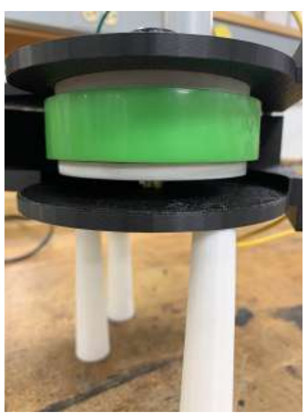
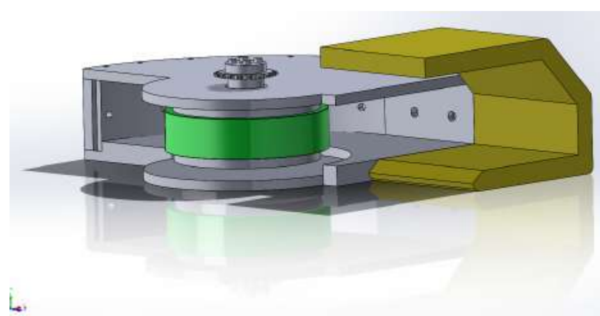
	

Figure IVa: prototype flywheel	Figure IVb: initial flywheel CAD

To facilitate shooting, we needed to design two additional mechanisms, an intake mechanism to capture the puck and a transfer mechanism to interface between the intake and shooter.

For the Intake, we took a unique approach by 3D printing TPU stars to allow for a seamless and flexible intake process. A big challenge was the 3-second limitation on puck possession, which meant that the intake needed to be both fast and reliable to avoid major penalties. After much deliberation, sketching, and CAD mockups we came up with a final design for the intake. It features a 3 stage rolling intake with a wide opening lip that tapers to the left side of the robot allowing the the puck to be discharged out of the right side with minimal interference with the robot. The ramp angle was chosen to be 35 degrees after a detailed sketch analysis in SOLIDWORKS, along with a TPU star diameter of 5 inches.

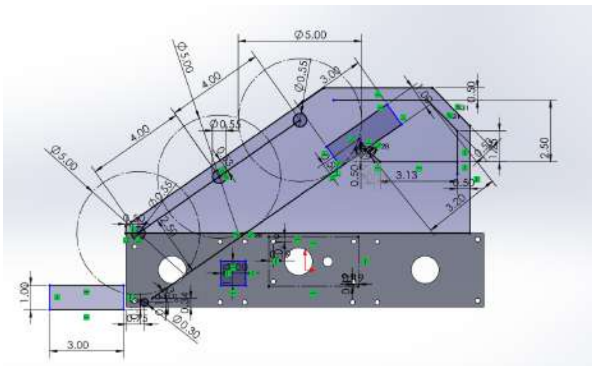
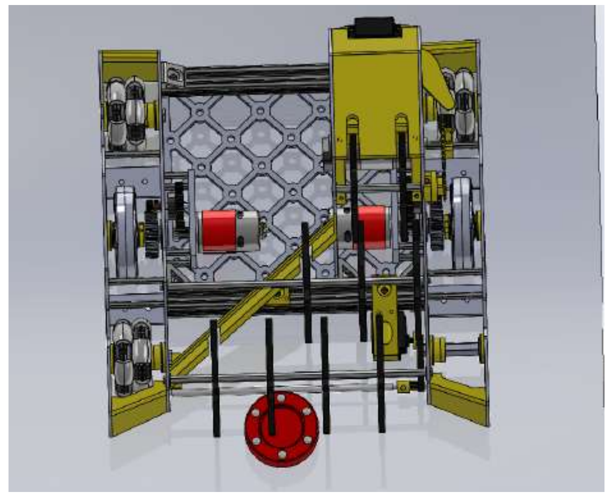
	

Figure Va: Solidworks sketch analysis of the intake ramp angle and fit geometry	Figure Vb: Top view of the tapered intake along with the 3 stages of TPU star rollers

Finally, there needed to be a transfer mechanism to push the puck into the flywheel for shooting. We opted for a simple puck-holding mechanism and servo finger to propel the puck sideways and into the flywheel. The puck holder was designed specially to minimize the chance of a puck jamming, while also elevating the puck a further 0.5 inches with an internal incline. This extra height helped the puck clear the robot's intake while shooting.

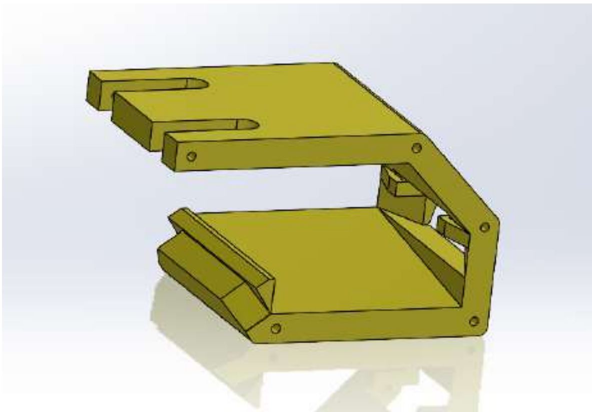
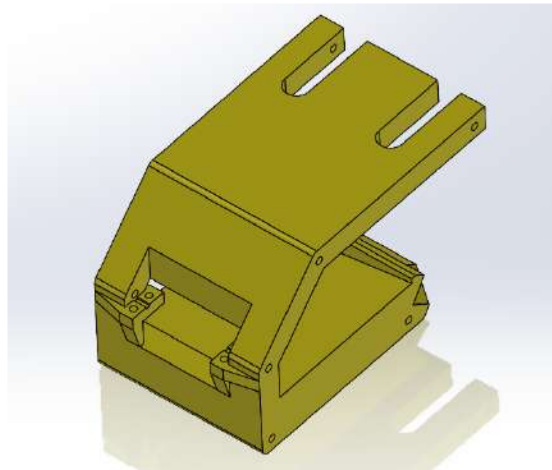
	

Figure VIa: Shows the 3D printed puck holder design in Solidworks with custom forks to avoid collisions with the TPU stars and an internal incline.	Figure VIb: Shows the backside of the puck holder that has a built-in servo mount to mount the finger servo.

The servo finger, while simple in concept, went through three full iterations to achieve a fully working design. The first finger design experienced consistent jamming issues due to hyperextension of the finger against the puck. The second iteration improved upon this by adding a triangular block brace that limited the range of motion of the finger and created a mechanical stop against the robot side plate. The final iteration added mounting holes to interface with a servo horn after we discovered that one screw into the servo was not enough to prevent slippage.

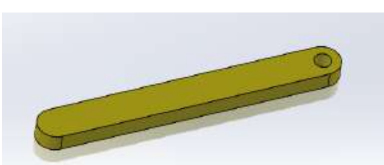
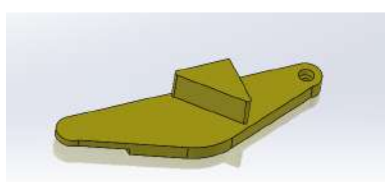
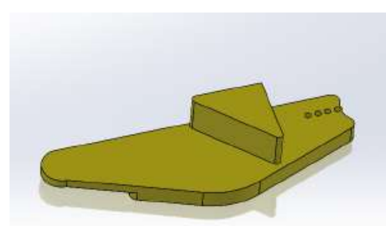
		

Figure VIIa: First servo finger iteration.	Figure VIIb: Second servo finger iteration with custom ROM limiting geometry.	Figure VIIc: Third and final servo finger iteration that added a servo horn mounting interface.

The Goalie went through many iterations of intake, transitioning from a roller to a hex rod lined with TPU stars meant to push the puck inside and trap it. The motor also changed positions now driving the shaft with a bevel year so that the motor's shaft is more protected. Initially using an RS550 motor to drive the intake system, we decided to switch to a NevaRest motor so that it has higher torque. Due to the motor's length, it rested on a mount so that it did not collide with the wheels. The TPU stars had low gyroidal infill to keep the points flexible and to allow the puck in, but a higher rectilinear infill near the core to keep it secure on the hex beam.

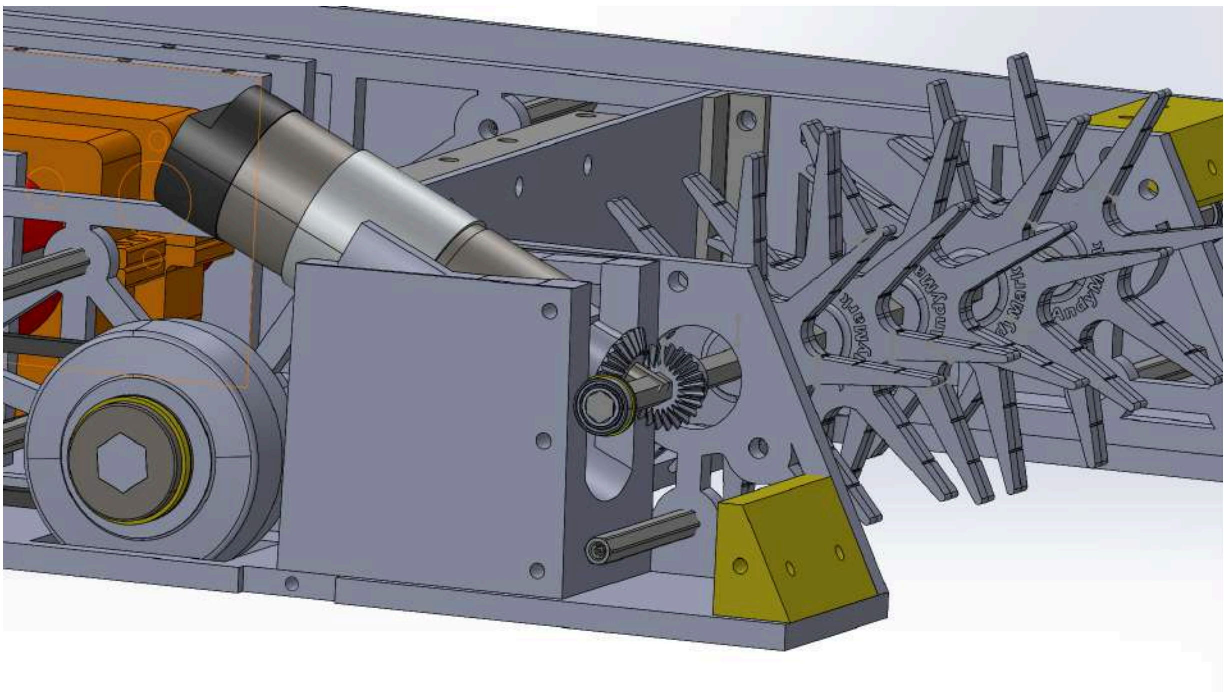


Figure VIII: Final Goalie intake design

2. Electronic Systems

The electronic systems used in each robot have varying complexity and features. The first electronics system to be discussed is the Enforcer circuit.

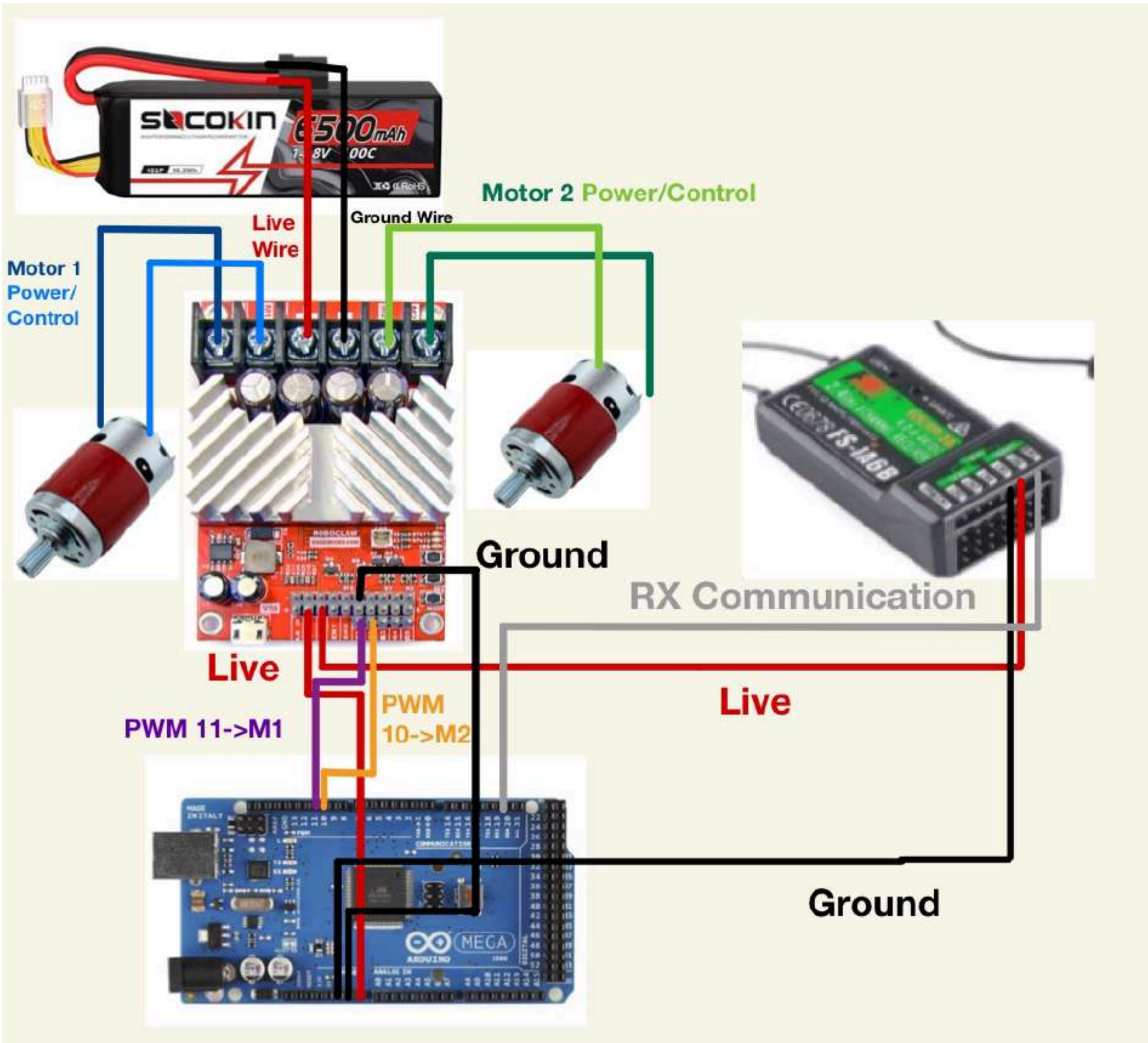


Figure IX: Final Enforcer Electronics Schematic

The Enforcer's electronics prioritize robustness and simplicity. The power is run from a 4S 14.8V Lipo battery into a 2x45a Roboclaw motor controller. This allows us to control the power output of each of the driving motors. The Roboclaw receives the direction and magnitude of the motor speeds from the Arduino Mega, sent via PWM signals. The Arduino Mega receives the driving information from the Flysky receiver, which is paired with a remote control transmitter. The Arduino connections to the receiver and Roboclaw are all with jumper cables, secured with hot glue. The motor and battery connections use 12-14 AWG wire. They are crimped and screwed to the Roboclaw and soldered to the motor ends. Each Roboclaw has two encoder power outputs that have a 5V VCC and ground terminal. These are ideal for powering passive electronics like a receiver and Arduino and help simplify our circuit by stepping down the battery voltage.

We opted to use an Arduino to process the receiver signals because it allows us to implement features such as incremental wheel balancing, a software transmission, a kill switch, and user-friendly features. We can see each of these aspects of the driving programming in the code stored on the Enforcer Arduino.

```
// PURE STRAIGHT
if (abs(leftRight) < TOLERANCE && continue_check) { // Give ourselves a small tolerance for driving straight
  rightInput = frontBack;
  leftInput = frontBack;
  continue_check = 0;
}
// PURE TURN
if (abs(frontBack) < TOLERANCE && continue_check) {
  if (leftRight > TOLERANCE) { // turn right
    rightInput = -leftRight;
    leftInput = leftRight;
    continue_check = 0;
  }
  if (leftRight < -TOLERANCE && continue_check) { // turn left
    rightInput = -leftRight; //leftRight is now negative in this if statement
    leftInput = leftRight;
    continue_check = 0;
  }
}
```

Figure X: Tolerancing in the Drivetrain

Due to the variability in joystick control, we introduced a tolerance on the joystick inputs, so that it's easier to drive the robots straight and also do a pure turn. These maneuvers are the most common we see during gameplay, and thus it's critical they are as easy to do as possible.

```
// set up killswitch with a small delay that skips over all driving
if (killSwitch > 0) {
  roboclaw.ForwardBackwardM1(ADDRESS, killSpeed);
  roboclaw.ForwardBackwardM2(ADDRESS, killSpeed);
  Serial.println(killSwitch);
  Serial.print("KILLED");
  delay(1000); // stops for a second
  continue_check = 0;
}
// set up gearing, default being low gear
if (drivetrain < 0) {
  overdrive = 1.0; // keep default
  Serial.println(drivetrain);
}
if (drivetrain == 0) {
  overdrive = 2.0; // average driving speed
  Serial.println(drivetrain);
}
if (drivetrain > 0) {
  overdrive = 4.0; // max operating voltage
  Serial.println(drivetrain);
}
```

Figure XI: Flysky Switch Features

The above software features are controlled via switches on the Flysky transmitter. The kill switch is either on or off and is used to kill all robot activity quickly via the transmitter. This is a critical safety feature on all three robots. The software gearing system is also a feature on all three robots and allows the driver to use a 3-stage switch on the Flysky transmitter to put the robot in high, medium, or low gears. At high gear, the motors receive slightly above maximum voltage for top speed and torque. Medium gear is ideal for most typical driving and maneuvering, giving the robot competitive speed and torque while not stressing out any key electrical components. Low gear is ideal for precise movements, or for driving the robot during gameplay stoppage, as it draws the minimal voltage needed to move the robot.

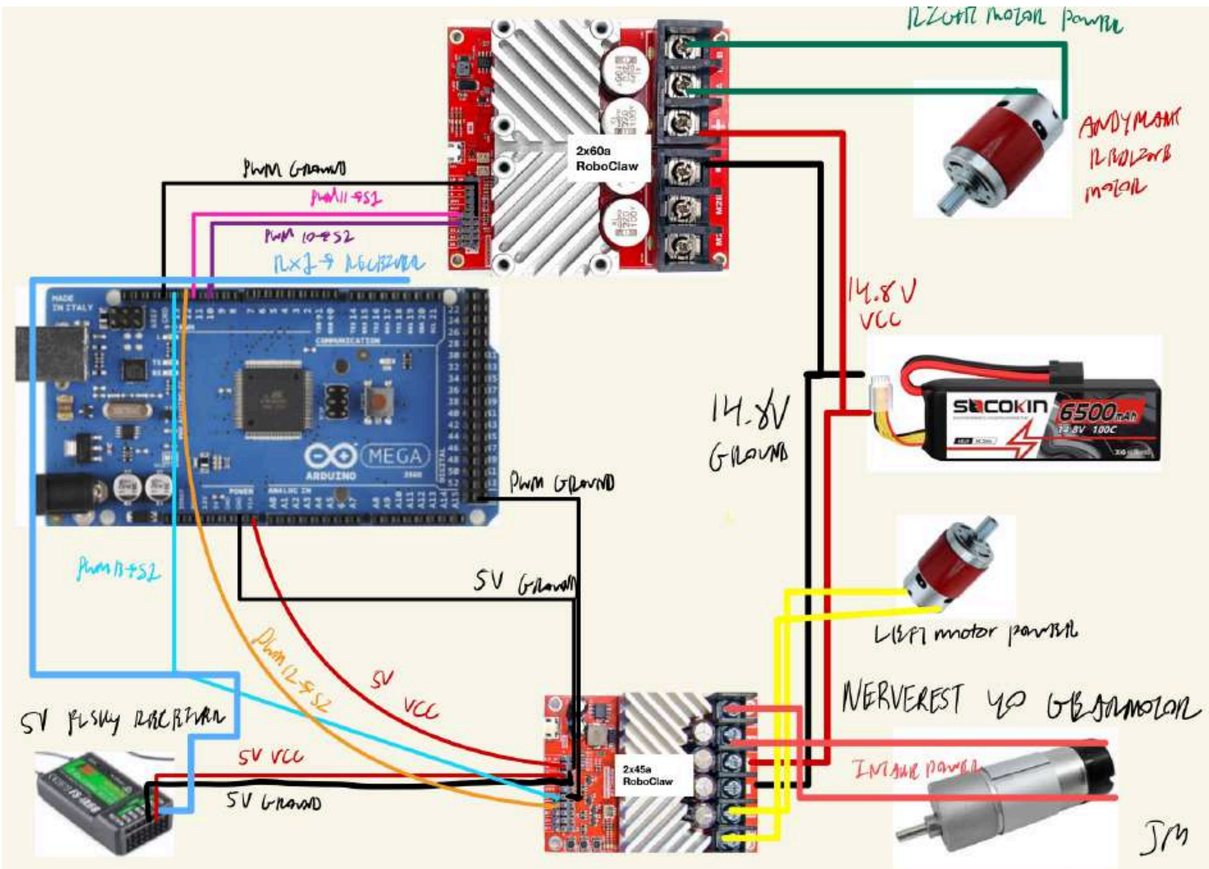


Figure XII: Final Goalie Electronics Schematic

The Goalie's electronics follow a similar method to the Enforcer's electronics, but there are a few small differences. First, we use both a 2x45a and a 2x60a Roboclaw. The 2x60a motor controller powers one of the drivetrain motors, while the smaller Roboclaw controls the other drivetrain motor and the intake motor. The drivetrain outputs are split up due to a hardware issue in the 2x60a Roboclaw in one of its output terminals. The intake motor is controlled via a switch and dial on the Flysky transmitter. The dial allows the driver to precisely control the speed and direction of the intake motor, allowing the intake to be spun rapidly to increase the likelihood of a steal from an attacking robot, slower to help maintain possession of the puck once trapped, or in reverse in case the goalie needs to leave the goalie box and a trap is no longer desired. A switch on the Flysky can also solely kill the intake, leaving it passive in between rounds or when no intake is desired or needed, but driving still is.

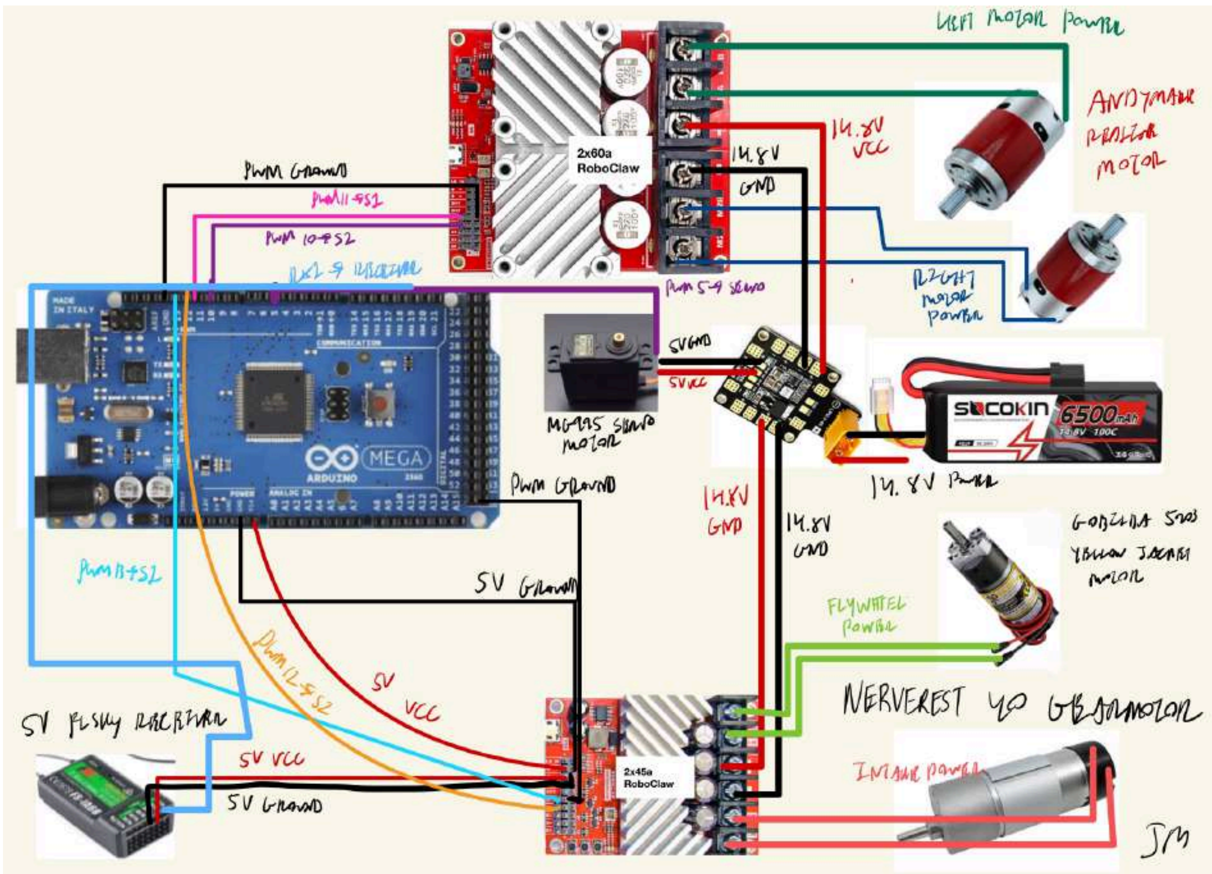


Figure XIII: Final Striker Electronics Schematic

The third and final robot is the Striker, with the most complex electronics circuit. The Arduino to receiver and Roboclaw connections are similar to that of the Goalie and Enforcer, as are the two Roboclaws being used. On the Striker, the two drivetrain motors are connected to the 2x60a Roboclaw for simplicity and robustness. The other Roboclaw controls the intake motor and flywheel motor. Both of these motors are programmed to spin in one direction for simplicity. The intake motor and flywheel are both killed via an aforementioned intake-only kill-switch. The flywheel speed is controlled via a dial on the Flysky transmitter. This variability in speed is valuable for testing purposes, as well as changing the range of shooting the puck. When not attacking the puck, the dial can be turned down to simply idle the flywheel to save battery power. A major change in this circuit is the introduction of a power distribution board. Due to the added complexity of five motors, this was necessary to ensure a simple way of powering everything. This board was especially useful for powering the servo motor, which assisted the puck's transition between intake and flywheel. A servo motor draws too much amperage (2A-3A) to be powered via the Roboclaw encoder power or the Arduino 5V power. This amperage draw could burn out the Arduino or the Roboclaw's logic battery. Therefore, we opted to use the power distribution board to step down the 4S Lipo battery to 5V. The Lipo battery can easily handle the amperage draw of the servo motor. The Arduino then connects via a jumper cable to the servo to tell it what position to turn to and when. This is controlled via a simple on/off switch on the Flysky transmitter. This means that all of the switches, joysticks, and dials on the Flysky transmitter were in use for the Striker.

```
// Balance the motor speeds. A negative balancer favors left, positive favors right
if (balancer < -TOLERANCE) {
  // Favor left side
  rightBalancer = abs(1 / (balancer / 10));
}
if (balancer > TOLERANCE) {
  // favor right
  leftBalancer = abs(1 / (balancer / 10));
}
```

Figure XIV: Striker Wheel Balancing

One of the most critical aspects of the code that improved our performance in the final competition was the wheel balancing on the Striker. By simply turning the dial on the Flysky, we can give the left or right motor proportionally more voltage. This was critical during the competition, as the Striker frequently saw shaky wiring connections, and one of the gearboxes had gears skipping due to faulty design/assembly. By giving the other motor and gearbox proportionally less voltage, we were able to keep driving the Striker relatively straight during the competition.

IV. Construction

A. Materials

For the majority of our structural components, we decided to use varying thicknesses of aluminum sheet metal due to its high strength-to-weight ratio. For structural components that undergo large amounts of stress (i.e. bellypans, gearbox plates, internal side plates) we used ¼" aluminum, and for other less critical components, we used ⅛" aluminum (i.e. front and back plates, outer side plates) to save weight.

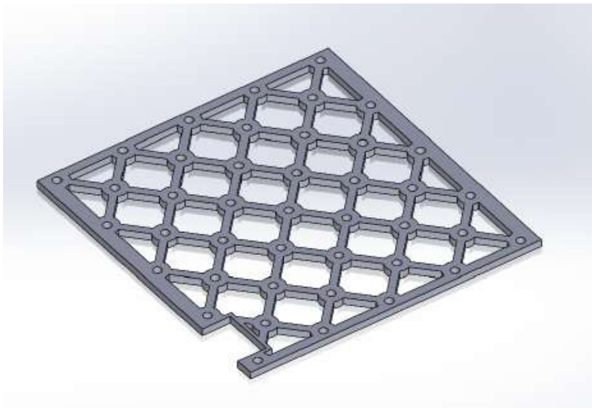
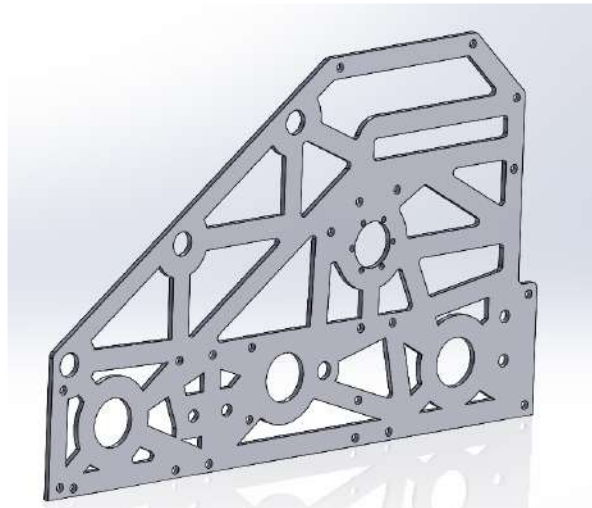
	

Figure XVa: Bellypan made with ¼” thick aluminum for structural rigidity.	Figure XVb: Side plate made with ⅛” aluminum for weight saving.

We reserved the use of steel for thin components that were expected to experience lots of strain (i.e. shafts). Specifically, the front shafts of the goalie and striker were in exposed positions so we decided to replace them with a steel shaft instead.

Unfortunately, even steel wasn’t rigid enough for this purpose, and both the striker and goalie shafts were bent during the official competition. Potential solutions to this design challenge are to use a thicker diameter roller on the front to increase the cross-sectional area and prevent deformations.

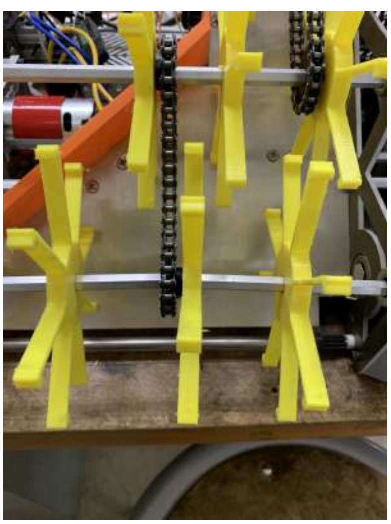
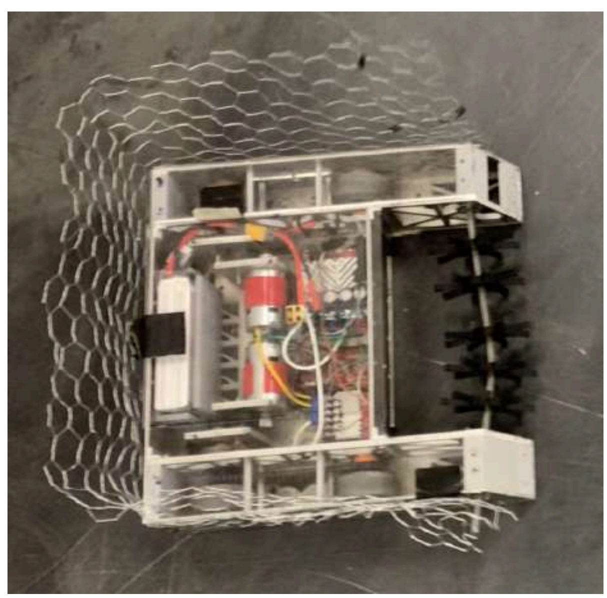
	

Figure XVIa: Aluminum shaft on the striker that bent after a collision during the mock competition.	Figure XVIb: Steel shaft on the goalie that was bent after a collision.

When it came to the 3D printed components of the robots, we tried and used a variety of 3D print filaments and settings. We can generally sort the 3D-printed parts we need into three categories: external (high strength), internal (lower strength), and flexible. The flexible 3D prints were made out of TPU 95A. The Shore Durometer of 95A was hard enough to hold shape under static conditions, but flexible enough to allow a puck to push its way through. For the intake stars, gyroidal infill was used on both the Goalie and Striker. This is because the stars would be constantly spinning, and gyroidal infill is strong in all directions, ideal for circular or spinning objects. This infill pattern was also used for internal prints made out of PLA.

Figure XVII: Example of Gyroidal PLA 3D Prints

Small gears, sprockets, and servo attachments for intake/flywheel mechanisms generally could hold up under about 20-30% gyroid infill with PLA. These parts generally weren't under much force and simply needed to hold their shape as mechanisms moved.

The external 3D prints underwent the most trial and error. We initially went with maximum infill PLA, but these parts were susceptible to shear and were quite weight-inefficient. Our next step was to try CF-PLA since we believed that the carbon fiber would make the prints much stronger. Instead, we found the parts *more* susceptible to bending and shear, as the carbon fiber made the prints more brittle and rigid. This could work for internal prints, but not external prints under a lot of impact. We then moved on to using ASA. ASA has one of the highest impact strengths for filaments and can handle bending and shear much better than PLA (ASA's tensile strength is 50-60 MPa higher than PLA's). However, ASA needs precise settings in order to print well due to its rapid cooling properties. When we finally printed the ASA successfully, we found it warped so much during the printing process that the parts were nearly unusable.

Figure XVIII: Example of ASA Warping

Due to the printing difficulty of ASA and the need for rapid prototyping, we moved on to using PETG for the external prints. PETG has a tensile strength of 20-30 MPa higher than PLA's. It's also more flexible than PLA and has a higher ultimate tensile strength, meaning it's more likely to bend or dent before cracking and shearing. We used the higher strength to our advantage and made PETG prints with 65% infill and a triangle infill pattern. Past 65% infill, the strength curve of 3D prints nearly flattens completely. With the triangle infill pattern, we resist shear stress directly while improving print speed due to its simple geometry. All of these factors combined to produce a lightweight, shear-resistant print that could be rapidly prototyped.

B. Machining

A variety of machining operations were used in the construction of the three robots. Most of the components, including the bellypans, side plates, gearboxes, and front and back plates of each robot were initially machined on the water jet. Additional post-processing took place on the mill. The mill was used to drill and ream holes for needle-bearing press fits on the side plates and gearboxes, to machine the bottom surfaces of all components to ensure a smooth fit with the surface, and to drill holes in the bottom surfaces of the side plates and gearboxes to connect to the belly pan. Several operations were also performed using CNC machining. Each belly pan (and, in the case of the Striker, the standoffs) featured 13/16 inch holes for magnets. Plunging with an endmill will leave a conical surface (instead of a smooth counterbore), which will prevent the magnets from sitting flush. As such, we used CNC machining to cut these pockets using a ⅜ endmill running at 12 in/min and 2400 rpm. We used the lathe to create shafts and bushings for the flywheel shooter. Other tools were also used, including the bandsaw for rough cutting, the pin grinder for cutting small steel pieces, and the soldering iron for connecting wires to electrical components.

V. Testing

A. Benchtop Prototype Evaluation

Our team used extensive benchtop prototyping when it came to iterating on the design of the electronics. These tests included configuring motor speeds and testing transmitter connections. We also tested things like wheel balancing and the kill switch before putting things on the robot. Testing software and electrical robustness and safety features on the benchtop were key to ensuring that the robot would perform reliably and that we wouldn't need drastic measures to stop a runaway robot. On more complex systems, such as the Striker, each electronic subsystem needed to be functionally tested before it could be added to the greater intake to transfer to the flywheel system. The servo transfer system underwent many iterations on the benchtop as we needed to find the optimal starting and ending position of the servo, how to set its reset position, and the best servo attachment for moving the puck. This type of testing wouldn't make sense out in the field or during a demonstration.

B. Field Testing

We took the mobility demo and Mock Competition as opportunities to test our magnet loading. During the mobility demo, we loaded 4 total magnets onto the chassis of the enforcer which demonstrated good pushing power and not much negative impact on driveability. For the mock competition, we upped the number to 12 magnets which gave the enforcer phenomenal pushing power and traction but began to impede its mobility. In the end, we decided on a magnet loadout of 8 magnets per robot according to these results. This number gave the ideal balance of traction and mobility.

Flywheel:

Initial testing of the flywheel revealed several difficulties. The original motor was too weak to launch the puck more than a few feet, the movement of the 3D-printed sprockets was not well-constrained, and there was too much friction between various components. As such, the flywheel mechanism was redesigned to address these concerns. The redesigned flywheel uses a Yellow Jacket motor from Gobilda, which provides a shooting range sufficient for full-court shots. We chose this motor because we had previous experience with it for flywheel applications in FIRST robotics and were confident it would perform as expected. The mounting system was redesigned to be more secure, an 8-degree ramp was added to increase range, and clamp hubs were added to constrain the movement of all rotating components. Due to spacing constraints, the redesigned mechanism only used one weight, which decreased the moment of inertia to roughly 10 lb-in^2. The needle bearings we purchased did not arrive in time for the competition, so we created bushings using brass on the lathe. These bushings were press-fit into the PLA. They did well at constraining movement while allowing free rotation, but heated easily and on one occasion popped out of the plastic. Due to time constraints, we were unable to print a replica of the damaged component, so we leveraged the thermal conductivity of the brass bushings. By applying heat to the bushing using a soldering iron, we were able to melt it into the surrounding PLA similar to the method used in ME13. To secure it we used epoxy, but it did not have sufficient time to fully cure before the competition. This system worked well during testing. To test the flywheel, we hooked the motor up to a 3S LIPO battery, and then fed the puck in by hand.

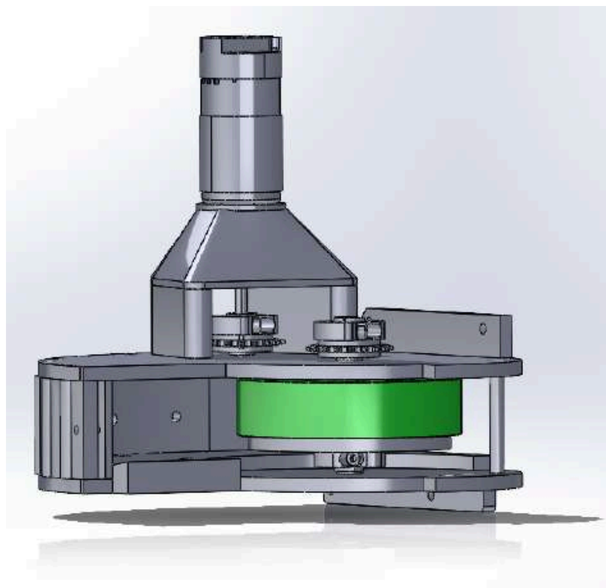


Figure XIX: final flywheel design

Intake:

The Striker's intake system used similar low gyroidal infill TPU stars as the goalie and required a lot of trial and error to find an effective design. Eventually, a design with long, narrow, thick points was tested and found to work well. Our initial intake system was unable to intake pucks off the ground, and barely able to intake pucks after they were hand-fed into the intake. We refined the geometry and spacing of the TPU stars. After the final flywheel iteration, one of the TPU stars rubbed against the flywheel so we used tin snips to reduce its length. The intake was attached using small flange bearings. The first stage of the intake used a steel shaft with the hope that it would be more resistant to bending than aluminum. The second and third stages used aluminum because these stages are not going to be impacted during collisions with other robots and to save weight.

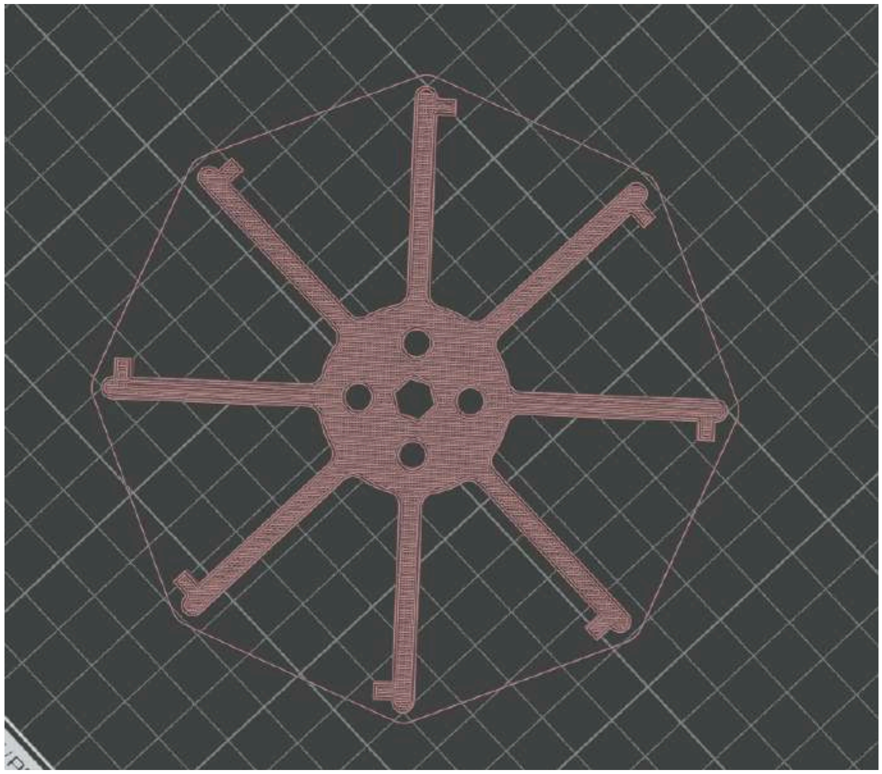


Figure XX: Striker TPU star for intake

C. Reliability Assessment

During demonstrations and live testing (testing where typical gameplay contact was involved) we found that one key aspect of reliability we didn't yet consider was the connection of all the electronics. Both the Enforcer and Goalie had wires taped in place if they couldn't be soldered or crimped/screwed. However, the Striker electronics were rushed and many key jumper cables were secured externally. This came to a head when the Striker was spun in place rapidly and a receiver to the Arduino cable came loose. This meant we could no longer kill the Striker from the transmitter, and that the Striker would continue to do the last action it received before the connection was lost: spin in place at top speed. While we managed to (somewhat violently) wrangle the Striker and unplug the battery, one of the intake shafts was damaged. This was an important lesson in the reliability of the jumper cable electronics connections. Following this, we immediately secured all final electrical connections with hot glue, ensuring that it would be near impossible for internal or impact forces to disconnect anything on the robots. We also found that the soldered motor connections were a key point of failure, as the Striker motor wires would occasionally come loose. This happened during the final competition as well, and we mitigated this issue by having extra wire and solder on hand to fix any connections. We ended up finishing the competition with three driving robots and zero runaway robot incidents as a result.

VI. Initial Performance

A. Mobility Demo

During the Mobility Demo, we initially tested the performance of two of our robots, the Enforcer and the original Striker (which later became the Goalie). The demo focused on evaluating maneuverability, stability, and shooting mechanisms. Through these evaluations, we later realized that, even though the then-striker excelled in speed and agility, it was stable and sturdy enough for effective defensive play.

From these observations, we made a strategic decision to repurpose the Striker as the new Goalie. The then-striker's sturdy frame and high-speed maneuverability allowed it to cover more ground and react quickly, which is also an essential trait for a successful Goalie. Also, its intake mechanism was easily adapted into a trapping system, which enabled us to capture and block incoming shots more effectively than if we were to use it as an intake mechanism.

This critical adjustment taught us many lessons. First, we learned the importance of mobility demos with preliminary designs as it allows us to identify performance mismatches and make the necessary adjustments before we finalize our designs. Also, by finding common ground between the purpose of a Striker, Goalie, and the bot we had at the time, we were able to reassign roles effectively. Finally, we learned the importance of flexibility and adaptability throughout the design process. By recognizing and acting on the then-striker's potential to perform better as a Goalie, we demonstrated how flexibility in strategy can lead to improved outcomes.

B. Final Design Review

We focused on the Striker for our Final Design Review, which was designed to have a combined intake and shooter mechanism but otherwise be similar to the Enforcer. We slightly modified the geometry of the belly pan to accommodate this mechanism while fitting within the space constraints placed upon us. It featured an extended belly pan and side plates, with identical front and back plates. The first attempt at the roller intake used pre-purchased rollers, which did not work for this application because the shaft and roller rotated independently of each other. The second iteration used a 3D-printed roller made in two parts, a rigid, center core of PLA and a flexible outer shell of TPU. Because TPU is flexible, it is compliant. This was designed to compress and provide a good gripping surface with which to intake the puck. The intake was powered via direct drive by an RS 550 motor from the Jim Hall Design & Prototyping Laboratory.

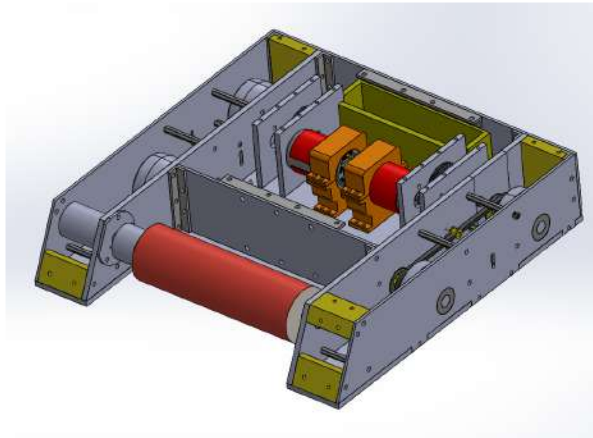


Figure XXI: Initial Striker design

After the mock competition, the robot which was intended to be the Striker was repurposed into the goalie and we designed a new Striker robot (more information about the second design can be found in the final design subsection of the design process section).

C. Mock Competition

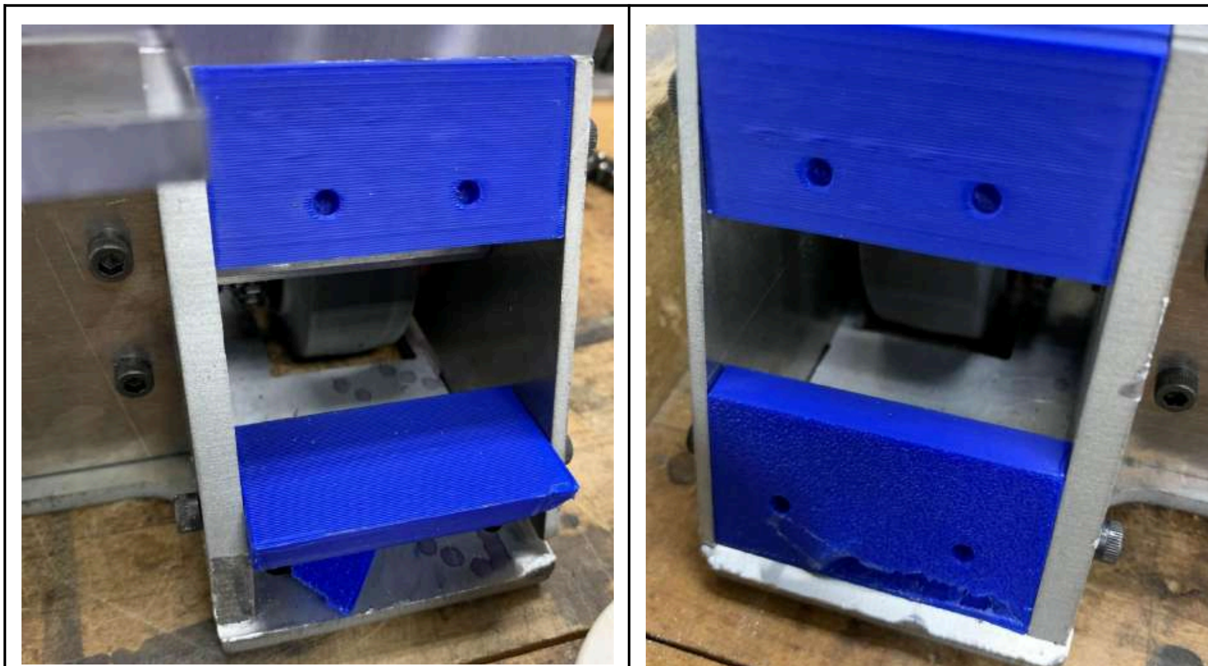


Figure XXII: damaged Enforcer standoffs

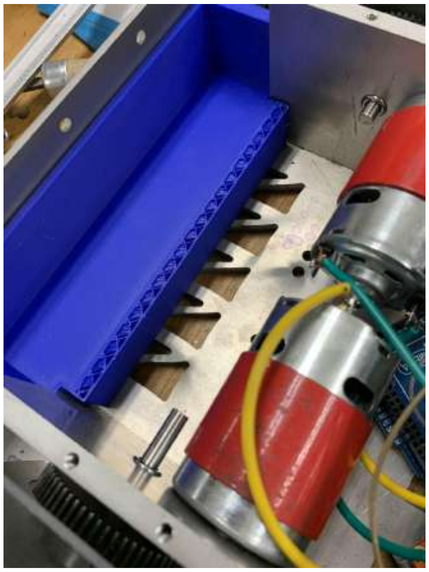


Figure XXIIIa: damaged battery mount	Figure XXIIIb: damaged external PLA

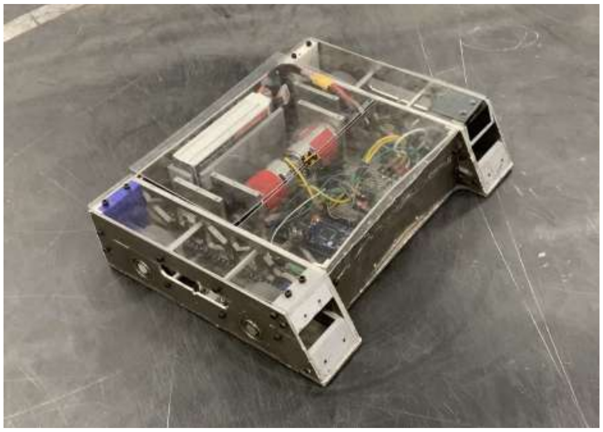
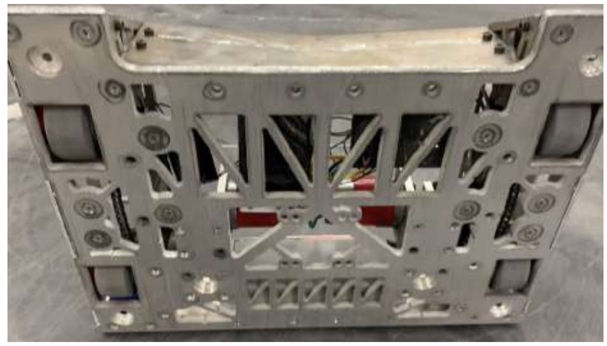
During the mock competition, we only played one round, so it was hard to see what failure points we may have. One key point of failure we saw was the shearing and breaking of the external PLA prints on the Enforcer, and the internal battery mount. Both of these issues we found could be remedied by switching to PETG (pictured above). We replaced all of the external PLA prints on the Goalie, Enforcer, and Striker with PETG. These prints only suffered minor dents after the conclusion of the final competition. Meanwhile, the battery mounts were replaced with PETG, and we switched to triangle infill to protect against the shearing. We also slightly changed the design to utilize small fillets, which helped keep the front of the battery mount attached.

Another issue we encountered was the improper placement of the goalie magnets. The magnets were placed asymmetrically due to time constraints. Initially, we thought we could correct this with wheel balancing. We soon found that even the wheel balancing couldn't make the goalie drive straight. When we fixed the magnets, the goalie worked. This was an important lesson in magnet security, as even one magnet coming off or being out of place could render a robot useless.

D. Final Design & Assembly Stage

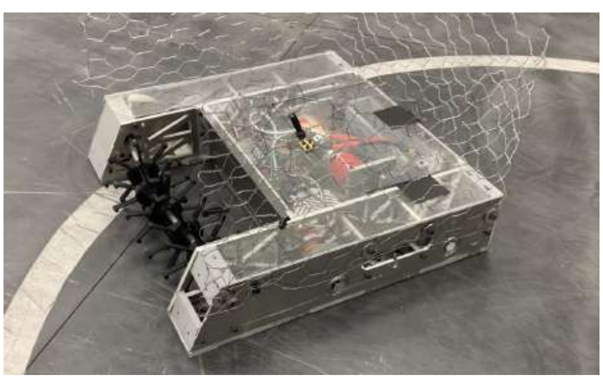
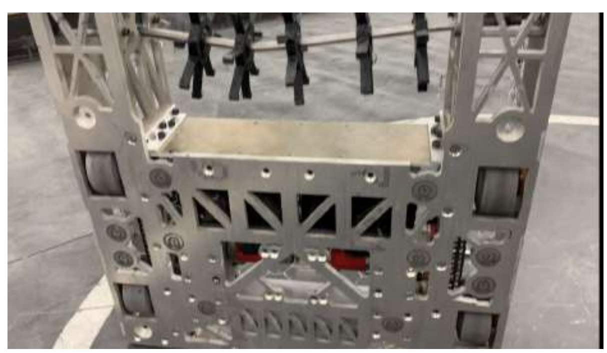
Enforcer:

The enforcer being one of our earliest and most reliable robots did not need many tweaks as the competition approached. The only concern was meeting the weight limit, so we disassembled and reassembled the robot in order to cut excess material.

<table>
<tr><td></td><td></td></tr>
<tr><td>Figure XXIVa: final assembly of the enforcer with handles cut out of the side plates.</td><td>Figure XXIVb: underside of the enforcer final assembly with a pocketed bellypan and 8 neodymium magnets.</td></tr>
</table>

Goalie:

Closely modeled after the enforcer, the goalie had a very similar final assembly phase, with weight being the main concern. However, the goalie also had a chicken wire net that was assembled via fasteners and washers on the exterior, as well as a trapping intake mechanism. However, due to the bent intake shaft, and a lack of replacement parts, we were unable to assemble a fully working intake by the competition and used the TPU stars to passively trap the puck. This worked quite well.

<table>
<tr><td></td><td></td></tr>
<tr><td>Figure XXVa: final Goalie assembly with the TPU star intake and chicken wire net.</td><td>Figure XXVb: underside of the goalie final assembly with a pocketed bellypan and 8 neodymium magnets.</td></tr>
</table>

Striker:
The Striker robot was our newest and least tested design, thus the final assembly stage was very involved. We had to make many on-the-fly decisions to have the robot ready to operate for the competition. For example, the intake was not working well to collect the puck despite testing multiple thicknesses and styles of TPU stars. We realized that the bottom servo roller which was intended to help the puck come up into the intake, was hindering the intaking process. We decided to remove the mechanism entirely and waterjet a new longer ramp that extended to the ground, which eventually fixed the issue.

For the flywheel, we also had to make a few last minute adjustments due to some parts not arriving through shipping. We custom-machined brass bushings to replace the needle bearings that did not arrive and used epoxy to help hold the brass bushing inside the 3D printed flywheel mechanism.

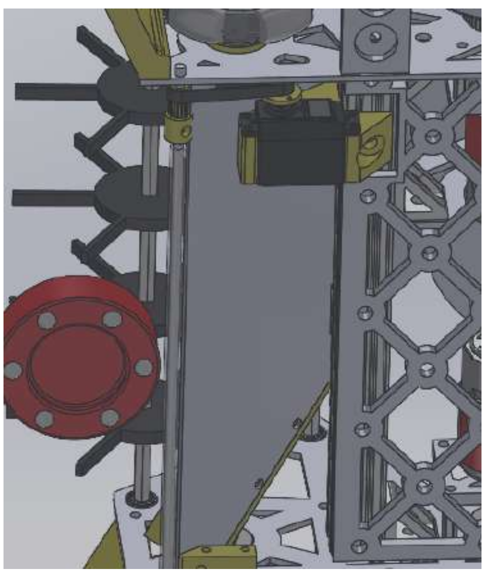
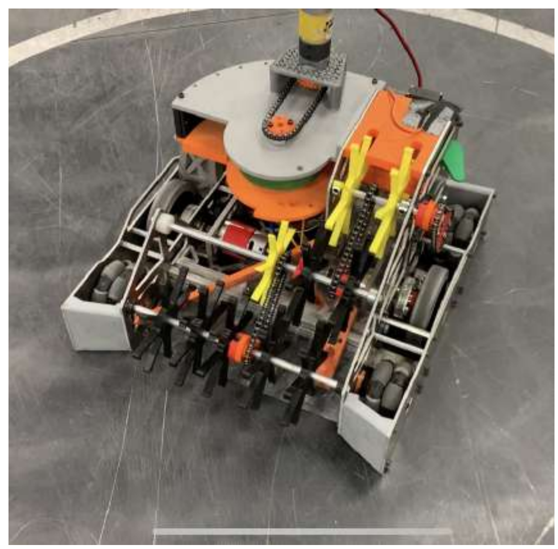
	

Figure XXVIa: servo intake roller mechanism that was intended to help lift the puck into the intake	Figure XXVIb: final Striker assembly with the roller mechanism removed and a longer ramp.

VII. Final Competition

A. Prior to and Start of Competition

Prior to the competition, we were able to get all of the features we wanted to implement on all of our robots working, save for the Goalie intake shaft which broke during testing. We decided that a passive Goalie intake could still work for trapping the puck, but we would have to be careful about leaving the Goalie box. We successfully tested the full Striker intake, transfer, and flywheel mechanism. We expected that we would be able to shoot effectively over the course of the competition. We also upgraded the previously damaged aluminum intake shaft to steel. While we didn't get as much driving practice as we'd like on the robots, we felt that with three working robots, we stood a chance in almost every match.

Unfortunately, during the first match, the Striker's intake shaft was bent again, even though it was steel. This rendered the Striker unable to intake the puck at all and therefore unable to shoot. We decided to remove the shooting mechanism so that it could avoid damage during the rest of the competition since it wasn't going to be used anyway.

B. Round 1

In our first round, we ran into the metaphorical buzzsaw that was the Puckboiz. We were having some issues with controlling our Striker and Goalie, and they scored a relatively quick goal on us. We were able to remedy these issues, but Puckboiz played solid defense and stalled for time, giving us the 0-1 loss. We felt good about our defensive capabilities but wanted to get on the board.

C. Round 2

Our next round came against Five Guys Plus Fries. We essentially had three working robots during this match, and we started to find our step. We played stout defense with the Goalie, and the Enforcer dominated the puck and the opposing team. It was starting to become clear that the Enforcer was our key to victory.

D. Round 3

The third round we played was against Wayne Botzky. We played a tough first 90 seconds, coming out to a 1-0 lead, but things seemed quite competitive. The Wayne Botzky attacker and the Enforcer were seemingly evenly matched if the Enforcer bot was a bit weaker. We were only able to score because the Striker set a pick on the Wayne Botzky bot, allowing the Enforcer to overpower their goalie.

Figure XXVII: Striker sets a Pick for the Enforcer

We soon found that one of the Striker's motors became disconnected, likely due to a subpar solder job and facing off against a much stronger robot. This meant that it was currently a 2v2, with our Enforcer and Wayne Botzky going head to head, and their goalie still on the field. We called a timeout to fix the Striker after getting a second score to go up 2-0 with 3 minutes left. Being fairly evenly matched, we didn't want to risk not using all of our robots, and also realized using our first timeout to fix an unoperational robot halfway through the round-robin is a good usage of time. It didn't make sense to risk a loss or tie since up to this point we were mostly only able to score thanks to the Striker playing interference. During this time, we found that screws on the Enforcer were coming loose due to impact, and so we tightened them with a hand drill.

Returning to the field, it was night and day. The Wayne Botzky goalie was unoperational, making it essentially a 3v1. The Enforcer was able to dominate without the help of the Striker, and even the Goalie got in on the action. We won big: 9-0, setting the highest score for the competition in the round-robin. We started to believe in our ability to not just make the semifinals, but make some noise in the postseason as well.

E. Round 4

The fourth and final round we played was against the Vroombas. Based on what we had seen prior to this match, a working Enforcer would all but guarantee us a victory and likely the second seed. A loss could put us at the fourth seed, and in a first round matchup against Puckboiz. At the start of the match, the Striker was again unoperational due to faulty electronics and the Goalie was experiencing inconsistent response to controls.

We jumped out to an early 1-0 lead in the first 30 seconds thanks to the Enforcer plowing through all three Vroombas robots into the goal. Essentially our only fully functional robot, after the goal was scored, the Enforcer became unoperational too. We then encountered a major issue, the Enforcer's motors and potentially the Roboclaw were starting to overheat. Additionally, one of the Goalie's motors became fully unoperational. We were out of timeouts and had to pull the Enforcer off the field. We quickly fell down 1-3 before the Enforcer became operational again thanks to power cycling and some cooling via compressed air. We put it back on the field thinking this was allowed since it started the match operational. We came back and took the lead 7-3. We were later informed that returning the Enforcer was not allowed, and were handed a forfeit loss 1-3, dropping us to 2-2 through the round-robin.

F. Semi-finals

We managed to secure the 2nd seed thanks to our overall strong performance and 2-2 record. We were up against Vroombas again, and this time we had three functional robots. During this match, while the Striker had little torque to fight against being pinned, the Vroombas had to split their resources to handle the Striker, meaning the Enforcer typically only had to go against two Vroombas. The Enforcer dominated the Vroombas easily, and we won 6-0.

G. Finals

At this point, our entire focus was on cooling the Enforcer and ensuring the Goalie and Striker were going to remain online. We knew we had a dogfight ahead of us and we were right. The Puckboiz puck handling made it difficult to knock the puck loose from them and play good defense. During a tight encounter, the Enforcer started to overheat and spun in circles just for a moment, but long enough to lose pressure on the puck. Puckboiz were able to weave around our Goalie and go up 1-0. They almost scored a second goal, but their handling was called a carry due to us hitting the puck directly and it not coming loose.

During the next couple of minutes, we played strong defense and were deadlocked in a scoreless battle until halfway into the match. We sent our Goalie out, and together with the Enforcer, were able to move the Puckboiz goalie out of the way and pin it with our Goalie. Our design strength was on display as we fundamentally overpowered the Puckboiz and were able to squeeze in a goal, tying the match 1-1.

The rest of the match remained scoreless, as both teams called timeout and we continued to unplug and cool the Enforcer. We pushed the game to overtime and played another two minutes. Eventually, the overheating caught up to us in the final seconds of overtime. The lengthy match and the long competition wore down the Enforcer, and Puckboiz scored off a strong faceoff in the final seconds of the match. We got second place, 1-2 (OT).

H. Takeaways

We performed much better in the competition than almost anyone on the team was expecting. Our superior torque and traction on the Enforcer and Goalie, as well as their heavy designs and utilization of magnets, made us both an unstoppable force and immovable object. Our reliability was also solid enough that we had three working robots for most of the time. We learned that reliability and power were the names of the game. Had we had all three robots working consistently, we likely would have only lost to Puckboiz once or twice, and zero times to everyone else. We lost a costly game to the Vroombaz that could have had us knocked out in the semi-finals due to their superior reliability. When it came to electronic reliability, wire connections and motor heating were factors that went under the radar for us. While Puckboiz were definitely the better team, our performance across the board would have been more consistent had we paid attention to these factors. Lastly, losing our shooter immediately was quite bad, as in the match against Puckboiz, a tie after overtime would result in a shootout. Since our Striker intake was broken, we had no shooter and likely would have lost the shootout eventually. That being said, we performed admirably and truly separated ourselves and Puckboiz into our own tier in terms of design, reliability, and robustness.

VIII. Budget

Colson Performa 2.5"x1.25"	4	$4.49	$17.96

2-1/2" Long, 10-32 Thread, Standoffs	12	$1.44	$17.28
#25 18 tooth socket	2	$12.00	$24.00
60 tooth 1/2" Hex Gear	2	$19.50	$39.00
2X 4S 6500mAh LiPo	1	$61.95	$61.95
20mm x 5mm N52 Magnets	15	$2.60	$39.00
60A Roboclaw	1	$0.00	$0.00
6mm Shaft	1	$3.09	$3.09
15 tooth gear	2	$7.99	$15.98
6mm ID 10mm OD Needle Bearings	4	$1.10	$4.40
Multipurpose 6061 Aluminum 90 Degree Angle, with Square Leg Edge, 1/8" Wall Thickness, 1/2" Outside Height (4ft) Length	1	$9.65	$9.65
Female Threaded Hex Standoff, Aluminum, 1/4" Hex, 2-1/4" Long, 8-32 Thread	10	$1.44	$14.40
Youme 4S Lipo Battery, 14.8V Lipo 4S 6500mAh 80C with Tr Plug Fit	0.5	$75.99	$38.00
25 Series Symmetrical Hub Sprockets, 500 hex, 18 tooth	2	$12.00	$24.00
Carbon Steel Spur Gears, Module 0.8, 60 Tooth	2	$22.67	$45.34
Clamping Shaft Collar - 1/2" Hex ID	6	$0.99	$5.94
Zinc-Plated Alloy Steel Hex Drive Flat Head Screw - M5 x 0.8 mm Thread, 12 mm Long	1	$10.05	$10.05
AndyMark 775 RedLine Motor	2	$16.50	$33.00
36 Inch Long 1/2" Rounded Hex Shaft - 6061 Aluminum	1	$5.50	$5.50
25H Chain - 10 Feet Long	1	$6.00	$6.00
QTY 10 - Flanged 1/2 Inch Hex Ball Bearings	0.5	$30.00	$15.00
Multipurpose 6061 Aluminum 1/4" Thick, 12" x 48" Sheet	1.17	$59.52	$69.64
Colson Performa 2.5"x1.25"	4	$4.49	$17.96
AndyMark 775 RedLine Motor	4	$33.00	$132.00
6mm Shaft	2	$3.09	$6.18
6mm ID 10mm OD Needle Bearings	8	$1.10	$8.80
15 tooth gear	4	$7.99	$31.96
60 tooth 1/2" Hex Gear	4	$19.50	$78.00
Multipurpose 6061 Aluminum 90 Degree Angle, with Square Leg Edge, 1/8" Wall Thickness, 1/2" Outside Height (8ft) Length	1	$15.57	$15.57

Carbon Steel Spur Gears, Module 0.8, 60 Tooth	4	$22.67	$90.68
Flysky FS-i6X 6-10(Default 6)CH 2.4GHz AFHDS RC Transmitter w/ FS-iA6B Receiver	2	$36.75	$73.49
Passivated 18-8 Stainless Steel Phillips Flat Head Screw	1	$10.68	$10.68
Needle-Roller Bearing	1	$6.81	$6.81
Melsan 2x4 Inch Adhesive Square Hook and Loop Tape - 12 Sets	1	$7.99	$7.99
1/2 in. Hex ID 1.125 in. OD Shielded Flanged Bearing	8	$3.00	$24.00
Multipurpose 6061 Aluminum Sheet, 1/8" Thick, 18" x 18"	1.6	$29.30	$46.88
20mm x 5mm N52 Magnets	15	$2.60	$39.00
Passivated 18-8 Stainless Steel Phillips Flat Head Screw	1	$10.68	$10.68
Needle-Roller Bearing	1	$6.81	$6.81
Melsan 2x4 Inch Adhesive Square Hook and Loop Tape - 12 Sets	1	$7.99	$7.99
Multipurpose 6061 Aluminum Hex Bar 7 mm Wide 3ft	1	$5.89	$5.89
Female Threaded Hex Standoff Aluminum, 1/4" Hex, 2-1/4" Long, 8-32 Thread	6	$1.71	$10.26
Female Threaded Hex Standoff Aluminum, 1/4" Hex, 1" Long, 8-32 Thread	8	$0.53	$4.24
Multipurpose 6061 Aluminum Hex Bar 1/2" Wide, 1/2 Ft Length	1	$6.28	$6.28
3.25" Omni-Directional Wheel	4	$8.99	$35.96
Colson Performa (4" x 0.875", 1/2" Hex Bore)	2	$7.49	$14.98
Compliant Wheel, 4 inch, nub bore	1	$10.00	$10.00
1611 Series Flanged Ball Bearing (6mm ID x 14mm OD, 5mm Thickness) - 2 Pack	1	$3.99	$3.99
2317 Series MOD 0.8 Steel Miter Gear (Set-Screw, 6mm Round Bore, 24 Tooth)	1	$9.99	$9.99
2317 Series MOD 0.8 Steel Miter Gear (Set-Screw, 8mm REX™ Bore, 24 Tooth)	1	$9.99	$9.99
1611 Series Flanged Ball Bearing (8mm REX™ ID x 14mm OD, 5mm Thickness) - 2 Pack	1	$5.99	$5.99
1611 Series Flanged Ball Bearing (8mm REX™ ID x 14mm OD, 5mm Thickness) - 2	3	$5.99	$17.97

Pack			
Steel Low-Profile Narrow-Base Weld Nuts1/4"-20 Thread Size, 1" Base Length (25 pack)	1	$7.83	$7.83
RoboClaw 2x45A Motor Controller	2	$179.95	$0.00
Low-Carbon Steel Hex Bar 7 mm Wide 3 ft Long	1	$8.18	$8.18
Servo Programmer for 2000 Series Dual Mode Servo	1	$9.99	$9.99
1311 Series Thru-Hole Sonic Hub (6mm D-Bore)	1	$7.99	$7.99
1311 Series Thru-Hole Sonic Hub (8mm REX™ Bore)	1	$7.99	$7.99
5203 Series Yellow Jacket Motor (1:1 Ratio, 24mm Length 8mm REX™ Shaft, 6000 RPM, 3.3 - 5V Encoder)	1	$44.99	$44.99
2000 Series Dual Mode Servo (25-4, Super Speed)	1	$33.99	$33.99
1309 Series Sonic Hub (8mm Bore)	2	$7.99	$15.98
18-8 Stainless Steel Socket Head Screw M4 x 0.7 mm Thread, 50 mm Long	1	$7.22	$7.22
		TOTAL	**$1,394.35**

Table I. End of 2nd term BOM

IX. References & Standards

Our design and manufacturing processes adhered to several established standards to ensure safety, performance, and regulatory compliance. Some key standards referenced throughout the development of our Bot Hockey robots are: Radio control standards, wire gauge standards, fastener and tap depth standards, and sheet metal standards.

First, for our robots, we used a Flysky FS-I6X radio controller. This unit operates on the 2.4GHz band and permits bidirectional communication between transmitter and receiver. It uses “multi-channel hopping” to switch between 16 available channels between 2.408 and 2.475GHz. The 2.4GHz ISM band is an unlicensed band allowed under Part 15 of Title 47. It’s often used by wireless LANs and meets the standards of IEEE 802.11. We operate the transmitter in an unrestricted area, and the model we have comes with its own FCC ID: N4ZFLYSKYI6X. Therefore, it meets all necessary regulations and considerations.

Second, for our calculated slipping conditions, we found that each motor reaches 8.6A. Our lowest-rated robot claw can handle 30A in each of its two ports. To ensure that the wires can handle all the current draw that may be needed by the robot claw, they would have to be 8-10 AWG according to the NFPA 70 National Electrical Code 2014 Edition.

Third, we used commercially manufactured fasteners, so they meet the standards for ASME B18.3. Also, for the depth of our tapped holes, we are using a depth of 1.0 inches at a #8-32 (0.164" diameter) fastener size. A common rule of thumb is to use a depth of at least two screw diameters but after 4 screw diameters, the marginal gain in strength no longer outweighs the cost to manufacture a deeper thread. In our case, this nominal range falls into 2*0.164 - 4*0.164 = 0.328" - 0.656". Knowing this, we can afford to cut down on our thread depth and save cost (time) manufacturing.

Finally, we used ¼" multipurpose 6061 sheet aluminum and ⅛" multipurpose 6061 sheet aluminum. According to the distributor, McMaster, the ⅛" sheet follows ASTM B209 standards, and the ¼" follows ASTM B221 standards.