University of Southern Indiana
Pott College of Science, Engineering, and Education
Engineering Department
8600 University Boulevard
Evansville, Indiana 47712

Designing and Building a BattleBot-Style Combat Robot for the 2023 Illinois Robobrawl

Jake Mitchell
Richard Meyer
Johan De Gracia

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Approved by:

Department Chair: Paul Kuban, Ph.D. . Date

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Abstract

The purpose of this project was to design and build a functional BattleBot-style robot that complies with the University of Illinois Urbana-Champaign's 30 lbs. combat robotics division rules and regulations to compete in the annual Robobrawl held in April of 2023. The robot designed for the competition had a vertical spinner driven by v-belts, a high-density polyethylene compliant outer armor ring, two independently driven wheels to allow zero-point turn capability, frame geometry that allowed the robot to be driven upside down, and an electrical system with two shut-off switches, one for the weapon and one for the drive system. Detailed in this report is an in-depth look at the design, manufacture, and testing of the project robot. After these sections are recommendations for changes to the design to make it more effective in the future.

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1.0 Introduction

BattleBots are remote-controlled fighting robots that are designed to withstand deliberate attacks by other competitors. BattleBots combine both mechanical and electrical engineering aspects into one project and are governed only by rules set in place for safety and fairness. For this reason, they are looked at as both a challenge and a place for almost unlimited creativity. Robobrawl, a BattleBot competition at the University of Illinois Urbana-Champaign, offers collegiate teams, as well as hobbyists, the opportunity to test their mettle. This report includes the objective of the project and the deliverables detailed in Section 1. Background information about BattleBots, the motivation for this project, and specific information about the competition for which the BattleBot is being designed are detailed in Section 2. The following section, section 3, is a review of similar projects others have done. Sections 4 through 7 discuss aspects of the critical design. The project budget, disposal plan, lessons learned, and future work are discussed in sections 8, 9, 10, and 11 respectively. Section 12 concludes the paper.

1.1 Objective

The objective of this project is to:

Design and build a functional BattleBot-style robot that complies with the University of Illinois Urbana-Champaign's 30 lbs. combat robotics division rules and regulations to compete in the annual Robobrawl held in April of 2023.

1.2 Deliverables

The deliverables for this project are the following:

- Functional Combative Robot
- Senior Design Report, Presentation, and Poster

2.0 Background

Remote-controlled combative robots battling it out in arenas of Plexiglass to the "death" is not a new event. The earliest record of the sport goes back to the first-ever competition of "robotic battles" held at a science fiction convention in 1989 [1]. Today, the popular television show *BattleBots* is the most well know representation of the sport [1]. The show's popularity has resulted in robots built to compete against other robots in physical combat to be commonly referred to as

"BattleBots". Figure 1 below shows an image of the popular BattleBot "Tombstone" from the television show. Combat robots of this nature have an active weapon, drive train, and protective armor, and are remotely controlled by a person from outside the arena. Competitions have weight limits that can range from 15 pounds to 250 pounds and the goal is to use their offensive weapon to strike the opponent, avoid the opponent's weapon, and win the match. Matches are decided by either eliminating the opponent by rendering them immobile or by gaining the most points in a judge's decision should both robots survive the match.

Figure 1: The BattleBot called "Tombstone" from the show "BattleBots" [2]

2.1 Motivation

The motivation for this project is to participate in the Robobrawl competition. To compete, the team needs a robot that both meets the requirements and is equipped to handle the nature of the competition. The hosting university has a rulebook that outlines the requirements for the robot. Several outstanding requirements are a weight limit of 30 pounds, a weapon weight of at least 20% of the robot's total weight, and the inclusion of electrical switches that turn the entire robot off in case of an emergency [3]. While store-bought robots are inherently designed with safety in mind, they are often made of plastic, lack any real power in the drive system, and certainly do not have any weapons capable of inflicting damage. The robot that is intended to be entered into the combat competition must be built by the team to overcome these limitations. As the robot is going to be designed and built for rough use, the skills and ideas learned along the way will be applicable for designing robots for use in other rough environments. These would include robots that are used for things such as bomb disposal, minefield sweeping, or even space exploration. [3]

2.2 Competition Rules and Details

The competition is held on the campus of the University of Illinois Urbana-Champaign. The double elimination tournament style bracket begins with the first match starting on the morning of March 31st, 2023. The battle rounds, which last 3 minutes, are fought in a 16-foot x 16-foot steel-plated arena. The round winner is decided by either rendering the opponent inoperable such that they cease motion for 10 seconds or by most points awarded by the judges should the round last the full three minutes. A concept of operations for the project can be seen in Appendix A. There are competition rules and requirements set in place for safety and fairness, and all teams must abide by them. The requirements of the overall design that most critically impact the design decisions are the following [3]:

- The total weight of the robot must not exceed 30 pounds
- The communications systems must fail in a manner that does allow the robot to move
- All electrical power supplies must have a manual disconnect switch that can be accessed in 15 seconds or less
- All robots must have one operational indication light per power source in an easily visible location
- All robots must have an active weapon that moves independently of the drive train and composes 20% of the final weight

2.3 Factors that Impact Design

Designing a BattleBot to be both effective and meet the competition rules requires consideration to be given to all aspects of the robot. Rather than considering the robot as one large system, it was broken down into five smaller subsystems that were designed to come together to form the entirety of the robot. The five main subsystems that the robot was divided into are the: frame, armor, drive train, electrical, and weapon. There are several factors that impact the design and effectiveness of these subsystems, which includes the following:

- Weapon Style
- Electronic Component Selection
- Material Selection
- Armor Design

- Drive Train Design

2.3.1 Weapon Style

The style of weapon chosen has a direct impact on the robot's overall effectiveness. A weapon that is too hard for novice teams to control effectively or that is more than adequate to inflict damage to the opponent, but risks damaging itself as a result of its power are all impactful to the overall robot's capability in the ring. A balance must be found between the weapon's damage, durability, and controllability. In remote-controlled combat robotics, there are two archetypes of weapons, kinetic weapons, and control weapons. Kinetic weapons impart an impulse load on the opposing robot to destroy the opposing robot's components. Control weapons lift, push, and hold the opposing robot. Control type robots use gravity or the arena itself to damage the opposing robot. It was decided a kinetic weapon, specifically a vertical drum spinner, would be the better option as control robots often use pneumatic systems which would require more interior components than a kinetic weapon.

2.3.2 Electronic Component Selection

The electrical system is another aspect of the robot that must be carefully considered. As previously mentioned, losing movement for more than 10 seconds results in an elimination in a match. For this reason, the electrical system of a BattleBot must be evaluated from a perspective of adequacy to move the robot, durability in the ring, and even overall weight so as to not put the robot over the weight limit. The design considerations for the motors were finding those with the proper torque and revolutions per minute needed to meet team set goals of speed and torque, as this will impact the size of the motors themselves, the gearing needed from the motor, and the size of the battery. Overly sized motors will add additional weight and require a larger battery to meet their current draw. Additionally, all electrical components must fit securely inside the frame of the robot making size considerations important. As mentioned, the battery must provide the proper voltage to the motors and store enough energy for a robot's entire electrical system to run for the whole round. Motors and a battery alone are not enough to have a functional robot, as there must be a way of varying the power to the motors for the robot to have mobility other than directly forward at a fixed speed. There are several different ways this can be done, such as with a microcontroller, but each has its advantages and disadvantages that must be considered. Lastly, in order to have remote control of the robot, a receiver must be included in the electrical system that can relay driver inputs to the devices controlling the power going to the motors. Consideration must be made to control aspect, as the wireless control system cannot violate any FCC regulations regarding radio control.

2.3.3 Material Selection

The material selection for all components has a large effect on the cost, weight, and effectiveness of a BattleBot. Lighter engineering materials such as aluminum and magnesium have the advantage of a high strength-to-weight ratio but come at a greater cost than steel. However, steel is much tougher than aluminum and magnesium. Additionally, steel and aluminum also come with a wide variety of physical properties, such as heat treatments and tempers; therefore, their intended use must be considered in order to ensure the material is capable of doing its job. Polymers and composites also have their place in the design of a BattleBot. The selection of what type to use, how to use it, and where to use it must also be considered in order to achieve a BattleBot design that not only meets all weight and safety requirements but also is capable of holding its own in the ring.

2.3.4 Armor Design

Armor design is an important aspect of building a BattleBot for several reasons. The first is that an ineffective armor design can quickly result in damaged components and a lost match. Another reason deliberate consideration to the armor design must be given is that the weight of the overall robot is limited. A robust armor design that provides extremely secure protection can have the tradeoff of a substantial increase in weight that must be made up by taking weight from other areas of the design. Consideration must be given to the materials the armor is made of to maximize its effectiveness-to-weight ratio. The expected attacks the armor will most likely be subjected to are also important to consideration. For instance, while flame weapons were not allowed at this particular competition, an armor design that protects from a weapon that shoots fire will be different than that of one where it is guaranteed that the robot would not face an opponent with a fire weapon.

2.3.5 Frame Design

The frame design is important as it must house all internal components and provide mounting locations for all other subsystems. Consideration must be given to the frame shape and frame material, as this will significantly impact the frame weight. Additionally, consideration for how all other subsystems will attach and fit into the frame where applicable is important for accessibility to assemble and fix components between matches. A larger volume frame comes with more room to mount components and access them but at the cost of taking up a larger percentage of the available weight. Lastly, consideration must be given to the specific level of protection the frame provides to the internal components. As an example, the design of a frame for a robot that may face a competitor with a flame/fire weapon, although as previously mentioned is not allowed at RoboBrawl competition, is different from that of robot who will not face any fire weapons.

3.0 Similar Projects

To tackle a task that no team member had any experience in, the starting point for the project was to conduct research into BattleBots and how others had built theirs, as this is a good starting point for any project. Research was conducted into numerous BattleBot designs from professional to amateur. Three designs that stood out were those of other collegiate teams. An examination of their robot designs was done to ascertain aspects that were viewed as positive and negative.

3.1 University of Cincinnati Team

A team of students in 2021 from the University of Cincinnati designed a 15-pound BattleBot as their capstone project, an image of which can be seen in Figure 25 in Appendix B [4]. This team used two brushed DC motors with gearboxes to achieve their desired drive speed and wheel torque [4]. The frame of their robot was made of aluminum plate cut on a waterjet and bent to shape with bolted-on aluminum plates at the top and bottom. For a weapon, they chose to use a steel lawnmower blade that spun horizontally at the front of the robot. The common term in BattleBots for this style of weapon, in which a bladed/bar is spun horizontally, is called a horizontal spinner. Their weapon was powered by two brushed DC motors that transmitted power to the weapon via a timing belt. The robot's outer armor was made of ultra-high molecular weight polyethylene that was attached to the frame using 3D-printed compliant mechanisms.

3.2 University of Miami Team

A team of engineering students from the University of Miami set out with the goal of designing and building a 250-pound BattleBot as their capstone project. They designed a BattleBot they called "Toolbot" (Figure 26 in Appendix B) [5]. This BattleBot used two brushed DC motors connected via a chain drive system to power a set of two wheels per side. The frame was steel angle-iron made into a box with plates bolted on all sides. For armor, this team used aluminum diamond plating which they bolted overtop of the frame plates. The weapon, which is considered in BattleBot terminology to be a drum spinner, was made of a large steel bar that was milled down to form long protruding edges [5]. The weapon was powered by a brushless DC motor connected via a sprocket and chain.

3.3 Florida State University Team

A team consisting of senior engineering majors from Florida State University chose to build a 220-pound BattleBot as their 2002-03 senior project [6]. An image of their completed BattleBot can be seen in Figure 27 in Appendix B. This BattleBot used two weapons, a pneumatically powered flipper arm and a rear-facing drum spinner. The flipping arm also doubled as a self-righting mechanism for their robot. Another design choice made by this team was to use a chain drive system with two powered wheels per side. Each set of wheels received power from a brushed DC motor. The frame itself was essentially a box made of metal sheets welded together [6]. For armor, they welded right triangles to the sides of the frame and covered them with steel plates. The top piece of the armor was attached to two long pieces of flat bar steel that ran the length of the BattleBot. The triangular-shaped armor was used to create a buffer zone between the sensitive internals and the outermost part of the robot while also being sloped to deflect opponent attacks [6].

4.0 Critical Design Overview

After a review of similar projects that others had done, a basic idea for a robot that incorporated design aspects that were viewed as advantageous was created. It was determined the robot would have two powered wheels with zero-turn mobility, as this design choice limited the weight of the drive system as only two wheels and two motors would be needed. Additionally, gearboxes were chosen to be used because of their robustness and less potential for failure as opposed to other methods like chain-drive. It was also determined that the frame would be made of aluminum because of its high strength-to-weight ratio. The style of weapon that was chosen to be implemented is that of a vertical drum spinner, which is a weapon that has multiple blades and rotates perpendicularly to the ground. It was decided to make the weapon out of a low carbon steel for its durability, weldability, and machinability. For armor, high-density polyethylene was chosen to be used because of its lower density than metals and high toughness. It was also determined to add additional shock absorption by adding compliant mechanism between the armor and frame. Figure 2 shows a SolidWorks sketch of the critical design, which when modeled with weight representations for all know components came out to 28.0 pounds. Below this, in Figure 3, is an image of the completed and fully assembled robot, which when fully assembled weighed 27.1 pounds. In order to design and build the robot, it was divided into subsystems that were designed independently but mesh together when assembled.

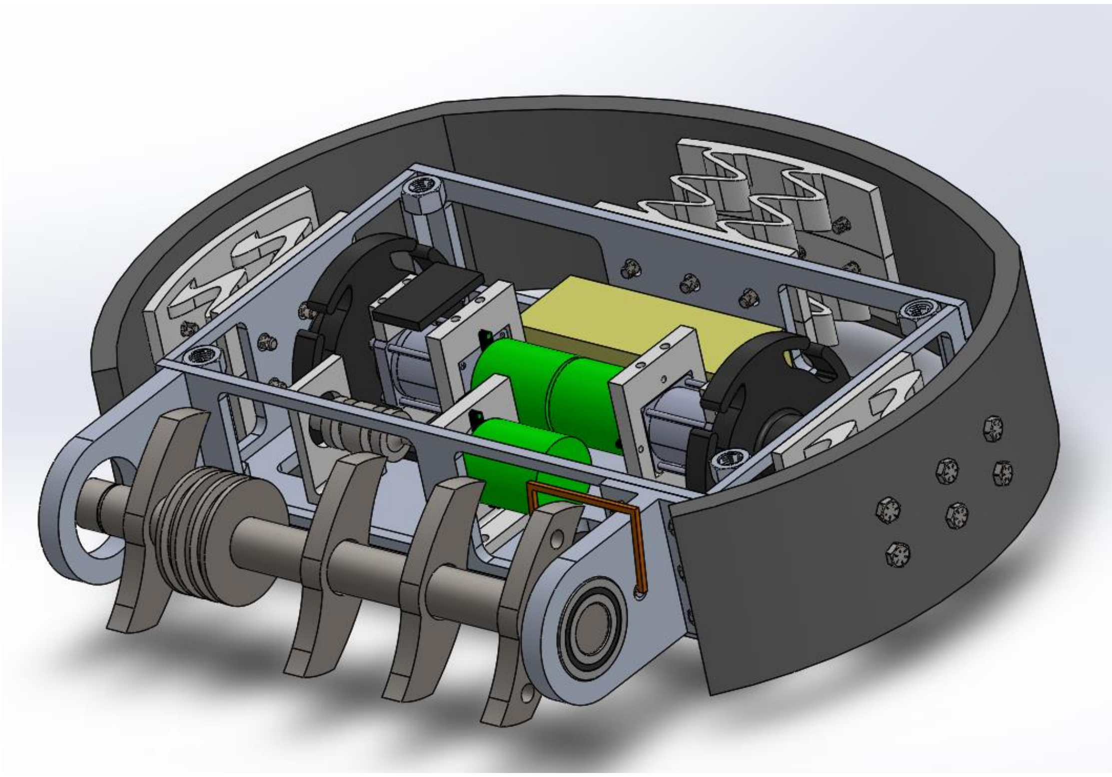

Figure 2: A Solidworks sketch of the critical design of the robot

Figure 3: An image of the completed robot

5.0 Subsystems Critical Design

The entire robot was separated into 5 major subsystems based on functionality: frame, weapon, armor, electrical, and drive. A full system Hierarchy can be seen in Appendix C. Each of these subsystems had their own critical design.

5.1 Frame

Weight is the driving factor of the frame design. Two systems that will not see much change in weight allotment are the electrical and weapon systems, comprise 16 pounds of the 30-pound weight limit. The remaining 14 pounds are divided between the armor and the frame. It was decided to minimize the frame weight to allow for more weight to be allocated to the armor. Aluminum was chosen as the frame material over steel because aluminum weighs less. There is a strength tradeoff using aluminum but the frame at this point only houses components, not protect them so strength is not as important. The frame design started as an 18-inch x 18-inch x 5-inch box but after modeling the bottom plate and finding the top plate weighed 3.5 pounds alone, it was decided to scale the frame down to a 14-inch x 14-inch x 5-inch box. The completed Solidworks model weighed 10.31 pounds. Upon further reflection it was decided to scale the overall volume down further to a 14-inch x 8-inch x 3-inch box. This design, when modeled in Solidworks, weighed 6.67 pounds.

In addition to the overall decrease in volume, to further decrease weight, voids were added to the frame in locations without theoretical mounting points. The voids further decreased the strength of the frame and created stress concentrators, but the tradeoff was a decrease in weight that allowed the armor to be more robust. To allow for easy access to interior subsystems the top and bottom plates were made removable while the four sides were welded together for strength.

One of the requirements for the subsystem is the frame shall have mounting points for the electrical and armor systems. The top and bottom plate will be mounted with ½-inch bolts with the sides of the frame being welded together. The back plate and side plates will mount to a compliant armor connection, while the bottom plate will mount the entire electrical system which is the battery, the electronic speed controllers, the gearboxes, and the receiver. Armor mounting locations were added to the design of the frame once the armor's design had been finalized.

With a decrease in overall volume, the concern over whether the electrical components could fit in the frame arose. Using product specifications from the seller's website, volumetric representations of the components were made and approximately placed within the frame. The result, seen below in Figure 4, shows all major components fitting within the frame with excess room.

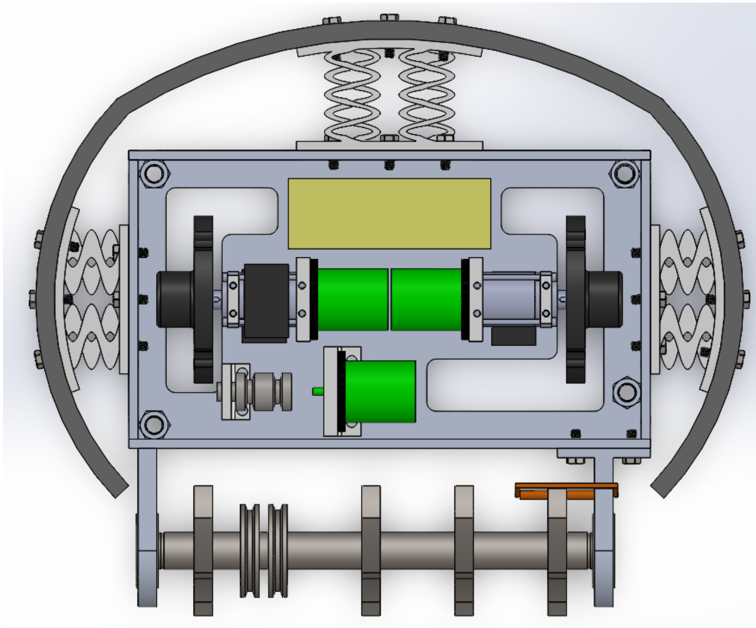

Figure 4: An image of frame with representations of components for the electrical and drive system

With the holes in the frame plates and an extended cantilever plate edge, it became a concern over whether the 10 pounds of electrical components were going to deform the bottom plate and affect the performance of the robot. A gravitational force study was performed in SolidWorks on the internal parts of the robot and the results below in Figure 5 shows that the farthest unsupported edge of the bottom plate deforms 1.45e-3 inches downward, which is less than 1 millimeter.

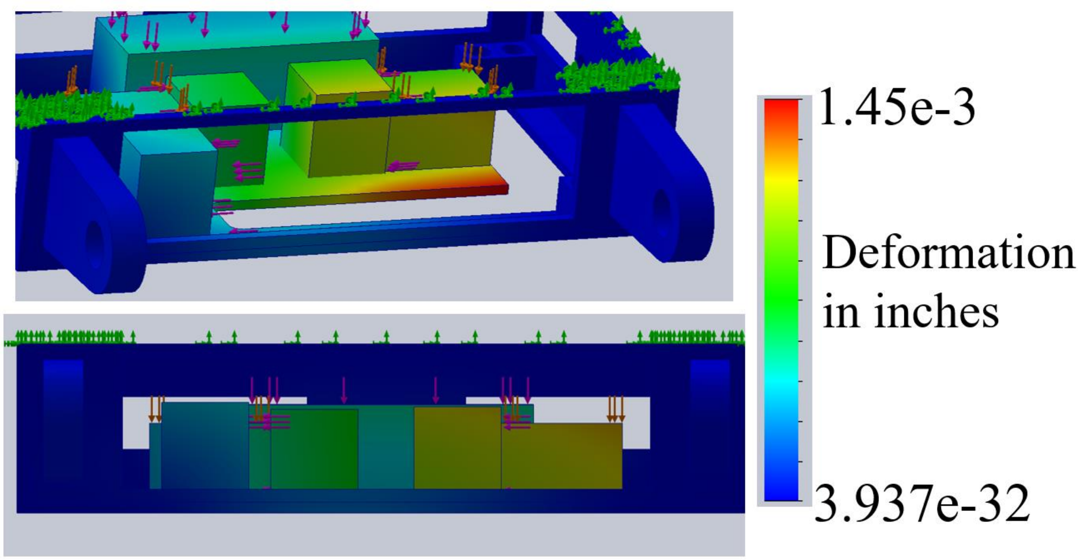

Figure 5: Solidworks Gravity Deformation by Electronic Components Study in Inches

5.2 Weapon

The weapon of a BattleBot is the part that is used to inflict damage to the opponent. In the sport, most competitors use a weapon that falls into one of several commonly used categories of weapon. These categories, which are flipper, horizontal spinner, vertical spinner, hammer, and full-body horizontal spinner, are named for the functionality of the weapon. While there is nothing in the competition rules that requires the weapon to be one of these styles, it was decided to stay within the styles that are most often run by professional teams. It was determined after a review of each styles' pros and cons, that a vertical drum spinner, which is a variation of a vertical spinner, was the most advantageous style. Other style weapons such as those intended to flip opponents over (flipper) or larger hammers that come down and strike opponents (hammer) require experienced drivers and good control in order to be effective. The horizontal spinner style weapons, which has a larger blade that spins parallel to the ground were avoided as they have a tendency to result in the robot getting flung around when it strikes the opponent. This could result in self-inflicted damage. After deciding on the style of weapon that was believed to be the most beginner friendly, a critical design was created and validated. The critical weapon design, for which the requirements can be seen in Appendix D, with dimensions and highlighted components can be seen in Figures 6-8 below. This design is made of 1018 cold-drawn steel for the shaft and ½-inch 1018 cold-rolled steel plate for the components. This was due to the material's low cost, good machinability and weldability, and higher toughness than that of materials like aluminum. The weapon is spun using two v-belts turned by a motor inside the frame. V-belts were used as opposed to other methods, like a chain, to allow for slippage if the weapon shaft was to bind up, as to not burn out the motor. Two belts were used in order to have a backup in the event one of the belts was cut or damaged. This current design weighs 6.01 pounds, which meets the weapon system weight requirement as the final robot weighed 27.1 pounds. Additionally, this weapon design has a rotational diameter of 4.5 inches and a weapon lockout mechanism. The diameter of 4.5 inches means that the blades will rotate out further than the frame holding the shaft extends, which stratifies the requirement of rotating outside the front envelope. The lockout pin, when in place, prevents the weapon from spinning, which satisfies the lockout requirement.

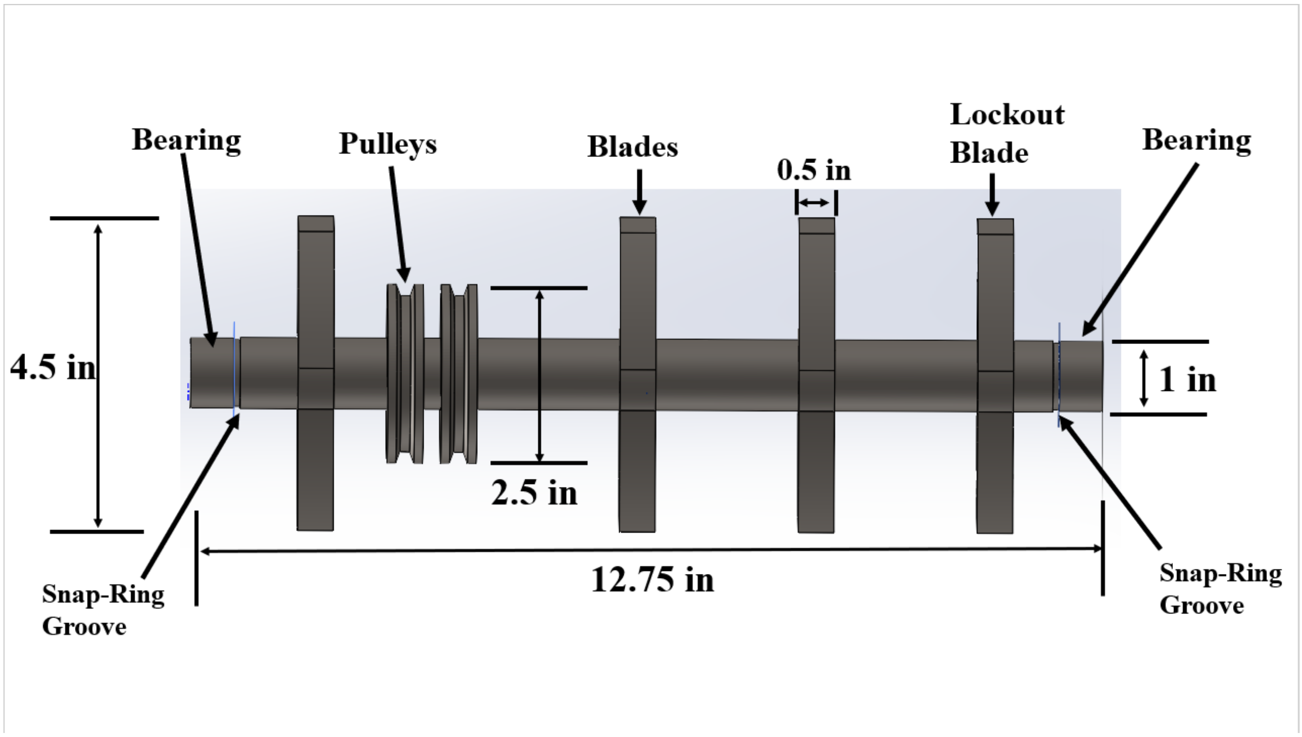

Figure 6: An image of the critical design for the weapon

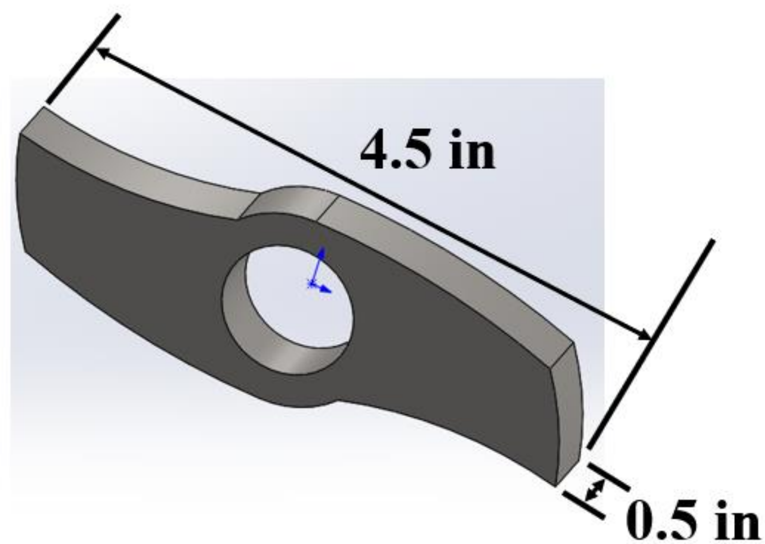

Figure 7: An image the critical design of the weapon blades

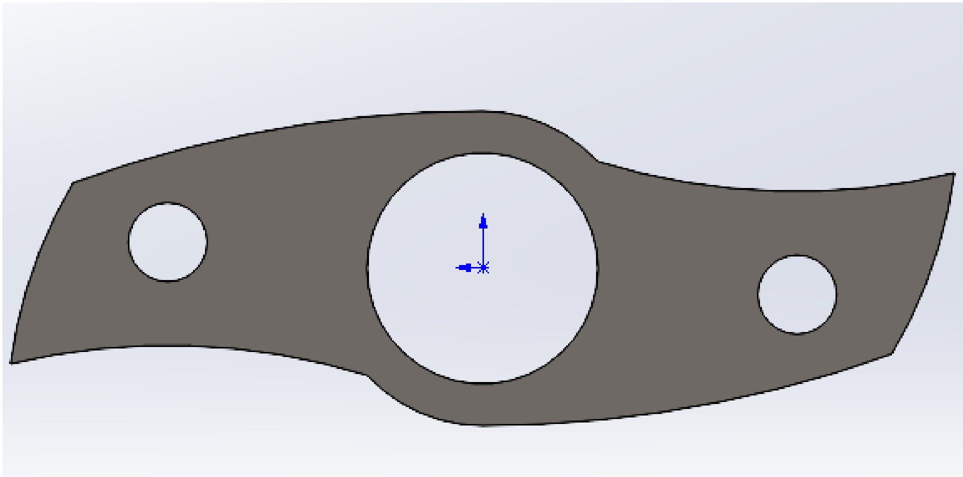

Figure 8: An image of the critical design for the weapon lockout blade

5.2.1 Critical Weapon Interfaces

The weapon subsystem interfaces with two other subsystems, the frame and the electrical system. The interface with the frame occurs through two bearings located in the front of the frame that allow for the rotation of the weapon. Additionally, the frame and weapon interface through the weapon lockout, which is located at the far right in Figure 6 above, allowing a pin to be inserted through the frame and weapon lockout to prevent weapon rotation. The interface with the electrical system occurs through the pulleys on the shaft that will be powered by one of the robot's motors to provide weapon rotation. These interfaces are highlighted in Figure 6 above.

5.2.2 Weapon Critical Speed Calculations

The critical speed of the weapon was calculated to avoid rotating the weapon at an rpm to close to the first natural frequency of the geometry. The was done because at the critical rotational speed the weapon will begin to resonate and could damage itself or other parts in the robot. To calculate the weapon critical speed, the critical speed of the shaft alone was first calculated using equation 1 shown in Appendix E [7]. The shaft was treated as a uniform 1 inch diameter shaft, as the effect of the diameter changes at the snap-ring and bearing locations is negligible. The result of this calculation was a shaft critical speed of 2908.0 rads/s. Next, the critical speeds of the components on the shaft was calculated, the calculation for which can be seen in equation 2 in Appendix E, and the result was determined to be 998.6 rads/s [7]. Combing these critical speeds, which can be found in equation 3 in Appendix E, resulted in an overall critical speed of 944.48 rads/s or 9019.2 RPM. This is well above the intended weapon rotational speed.

5.3 Armor

It was decided to have a sacrificial armor layer instead of making the frame thicker and more durable to direct impact loads. High-Density Polyethylene, or HDPE, was chosen due to lower density than metals like steel and aluminum and its impact resistance. HDPE being a thermoplastic meant it could be heated and reformed into a new shape without burning. The outer armor started as a flat ½-inch thick, 39-inch long, and 4-inch wide plate which was heated past the material's glass transition temperature, the temperature at which a material becomes malleable, in a kiln. After heating the HDPE it was placed in a plywood mold, pictured below in Figure 9, that was cut to the desired shape and left to air cool overnight. After cooling mounting holes for the compliant mechanisms and weapon lockout pin were cut from the HDPE. The armor was mounted with non-permanent nuts and bolts to the frame in order to ease repair and allow parts to be swapped out. A backup outer armor HDPE sheet was brought to competition in case enough damage was sustained to the first sheet to break it. Compliant mechanisms were used to connect the HDPE sheet and the aluminum frame because the mechanisms are designed to deform and absorb energy, which will reduce the amount of energy transmitted to the frame and outer armor during an impact load from an opposing robot.

Figure 9: Plywood mold for HDPE armor

To mount the armor to the frame compliant mechanisms were designed. These mechanisms are designed to be compressed horizontally with the armor and function as springs, absorbing energy from a blow from an opponent through their deformation so less energy is transferred to the armor and frame. The compliant mechanism shown in Figure 10 was used on the backside of the frame. Unlike a common coil spring, the chosen mechanism design only compresses parallel to the armor and frame allowing the compliant mechanism to hold the armor off the ground. To further increase the mounting strength of the armor, bolts were run through the armor, the compliant mechanisms, and the frame on either side of the robot. There were four bolts used in total, two per side, and bolts were not used on the rear of the robot as that was a longer distance and would require custom-made bolts.

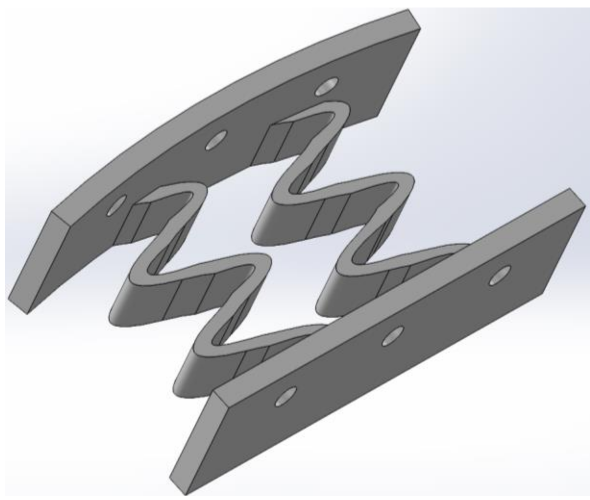

Figure 10: A Solidworks drawing of the rear compliant mounting bracket

5.4 Electrical System

In order to power the electrical system, a 15.2-volt, 8000 milli amp hour lithium polymer battery was chosen. Lithium polymer batteries were chosen over other types because of their high energy density, which allows for the battery to be smaller and therefore weigh less than other types of batteries with similar voltages and discharge capacity. The battery provides power to two 80 Amp bi-directional electronic speed controllers (ESC) that control rotation of the wheel motors, which allowed the robot to go forward and backwards at varying speeds. The battery also supplies power to one-directional ESC for weapon rotation. Three alternating current (AC) outrunner motors were used to power the wheels and weapon. The system also contained two push/pull switches for breaking the circuit between the battery and the ESCs. These switches were strategically placed in a visible area where an operator can disable the power while avoiding the weapon and wheels of the robot. One of the switches was designated for the drive system and the other one for the weapon system. To identify if each system was powered on or off, 5-volt LED lights were connected to the circuit and function to alert the public and drivers that the weapon and the motors are powered on or off. A full electrical diagram can be seen in Figure 11 below.

To control the robot from a safe distance, a model airplane RC transmitter was used to transmit signals to a receiver that was powered by one of the ESCs. The positive power from the battery eliminator circuits on two of the ESCs was used to power the LED lights. Here, the transmitter was in charge of controlling every movement of the robot using three different channels on the controller, one for each of the motors and one for the weapon. Once the receiver gets the information from the transmitter, it sends it to the ESC allowing the motors and weapon to spin in the wanted direction. This radio control system also allows to safely turn the robot on and off. In order to be complainant with the competition rules, the control system could not violate any FCC rules. According to FCC Standard Title 47, Chapter 1, Subchapter A, Part 15, Subpart C, Section 15.205, which lists restricted bands of operation for radio frequency devices, the chosen 2.4 gHz controller was an allowed frequency. Lastly, the model airplane controller had built-in failsafes that allowed for failsafe positions, which resulted in no motion of the wheels or weapon, to be set for each individual motor.

As part of a safety electrical plan control, a 10-gauge fuse holder with a 60-amp fuse was connected to the battery protecting the electrical equipment from an immoderate amount of current, as well as to prevent short circuits. A 10-gauge wire of Copper Clad Aluminum (CCA) was used to make every connection from the fuse to the ESC possible.

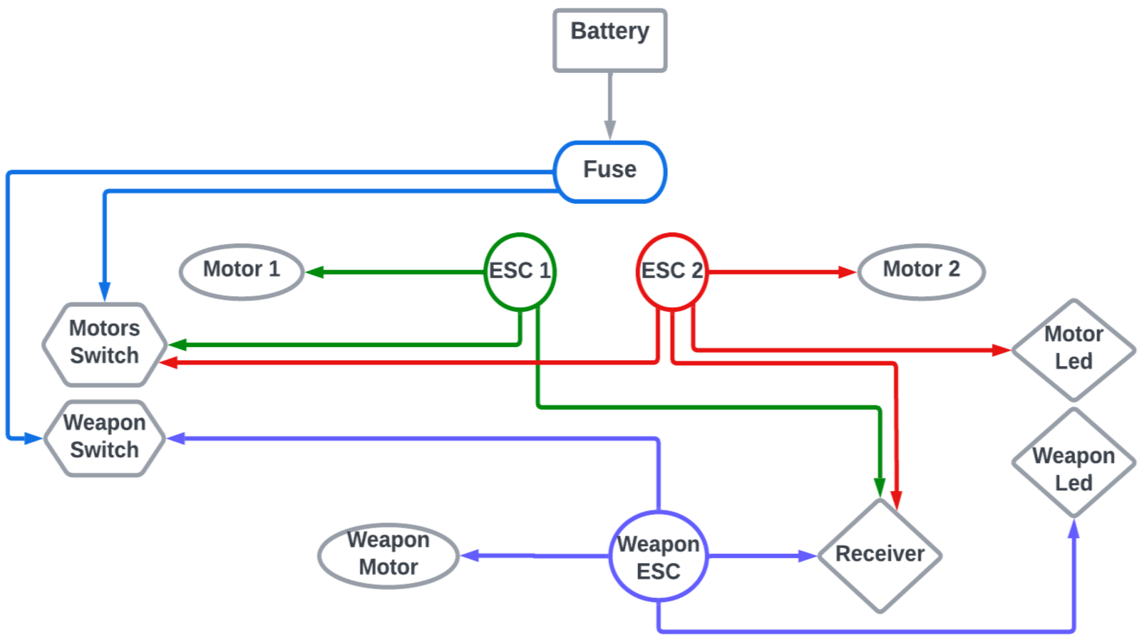

Figure 11: Full Electrical Diagram

5.5 Drive System

The drive system of the robot consisted of two motors each attached to a 38:1 gearbox and each gearbox had a 3D-printed black PETG wheel hub with a rubber outer ring. Gearboxes were chosen to efficiently control the speed of the robot, as they stepped down the motor's RPM and increased the torque to usable levels. Two wheels were made for zero-point turn capability and reduced weight. The wheels, pictured in Figure 12, were placed in 5-inch diameter molds and had a two-part rubber compound poured around the 3D-printed wheel to improve traction on the steel arena floor. Using 5-inch diameter wheels also allowed the robot to be driven even when flipped over, as the wheels protruded out both sides of the frame equally.

The wheels were kept from sliding on the gearbox output shaft by a keyway in the gearbox output shaft and a key printed into the 3D-printed wheel. To prevent the wheel from falling off the gearbox output shaft the wheel was bolted through a central hole into a threaded hole in the gearbox output shaft. To mount the entire drive system to the frame 3D-printed blocks with bolt holes placed strategically in them were made to space the gearbox and motor consistently in the frame. On one wheel, gearbox, and motor section, eight bolts mounted the gearbox to the top and bottom frame plates and four shorter bolts mounted the drive motor to a 3D-printed gearbox block.

Figure 12: An image of the robot wheel casting

6.0 Manufacturing and Assembly

The manufacturing process of the robot was separated into different subsystems, full breakdown seen in Appendix F, due to each subsystem requiring different tools and methodologies for construction.

6.1 Frame Manufacturing

The frame was manufactured by cutting the top, bottom, and 4 side plates out of ¼-inch 6061 aluminum plate at the Applied Engineering Center. The side plates were welded together, and ½-inch aluminum nuts were welded into the corners of the side plates. The top and bottom plates were attached to the side plates by running ½-inch aluminum bolts through the top and bottom plates into the nuts welded onto the side plates. The length of the frame mounting bolts was reduced until about two bolt threads were sticking out past the mounting nut. For aesthetic reasons, the frame was painted red and blue.

6.2 Weapon Manufacturing

As previously mentioned, the weapon was made from 1018 steel. The shaft of the weapon was made of 1-inch diameter round bar. Both ends are the shaft were machined down slightly in diameter in a lathe in order to have an interference fit with the bore of the bearings. Additionally, during the machine process the lathe was also used to add grooves on either side that allow for snap-rings to be placed on the shaft. The purpose of this was that the snap-rings would contact the inner ring of the bearings on either side of the weapon and prevent the weapon from sliding side-to-side. The blades of the weapon were cut to shape on a waterjet from a 1018 steel plate. In order to make the pulleys that went on the weapon, a 2.5-inch diameter steel round bar was turned on a lathe to form the slots for the v-belts and to bore the centers out for them to slide onto the shaft. To make the finished shape of the weapon, the mounting locations of each of the components was marked on the shaft. The components were then placed onto the shaft at their proper locations and welded into place. An image of the features done to manufacture the weapon can be seen in Figure 13.

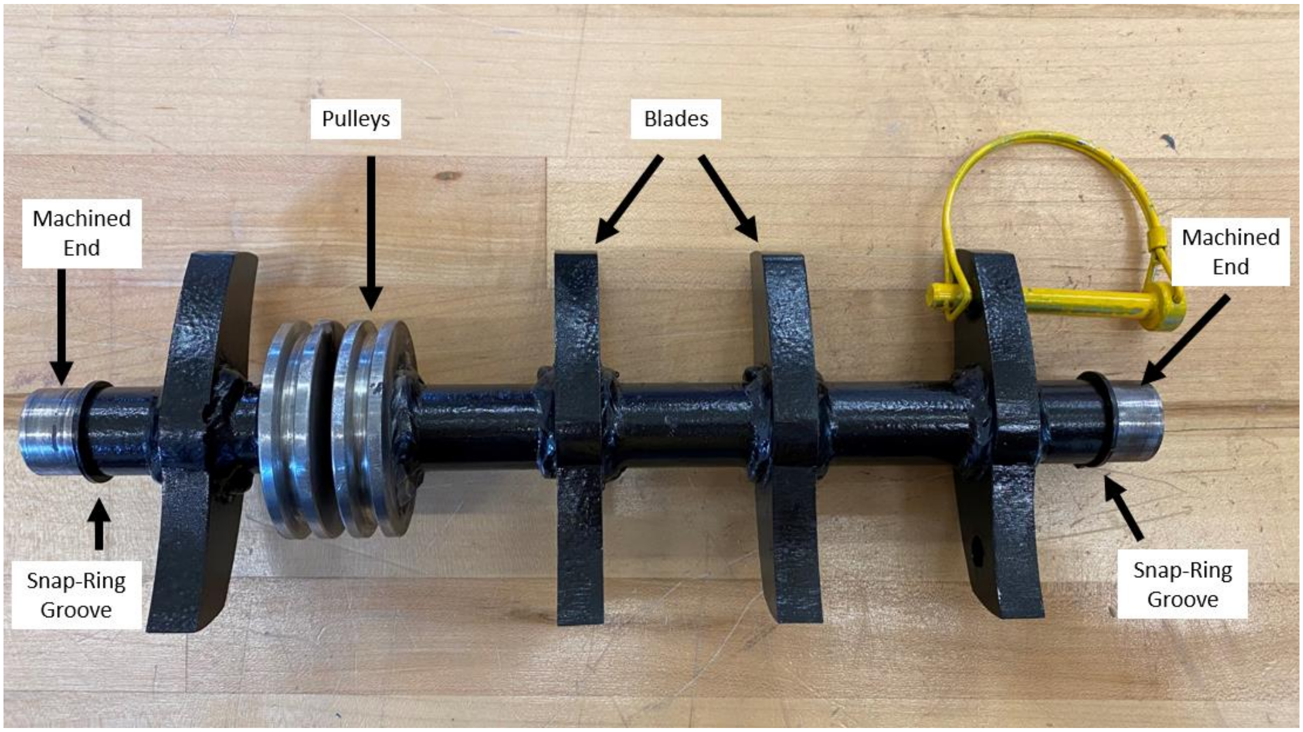

Figure 13: The features done to manufacture the weapon

To manufacture the components of the weapon system that provided the weapon with its rotation, two parts were made. The first was a set of 3D-printed mounts for which to house a bearing and to mount the motor. These parts were made by drawing the desired part shape and dimensions in SolidWorks and printing them out on a Prusa 3D-printer. The second part was a machined piece of 1018 steel used to connect the v-belts, which was called the internal weapon shaft. This piece was machined on a lathe such that one end was 5mm in diameter, the other end was the appropriate diameter to fit in the weapon housing bearing, and in between were two slots for the v-belts that aligned with the those on the weapon. An image highlighting these components can been seen in Figure 14. The two 3D-printed components were mounted to the bottom plate via bolt holes printed into them and drilled into the plate. The internal weapon bearing was press-fit into the 3D-printed weapon bearing mount using a hydraulic press. Bolts that went through the motor mounting bracket as well as through intentionally placed holes in the other 3D-printed motor mounting bracket were used to hold the motor brackets in place. Lastly, the 5mm portion of the internal weapon shaft was connected to the 5mm motor output shaft using a shaft coupling connector.

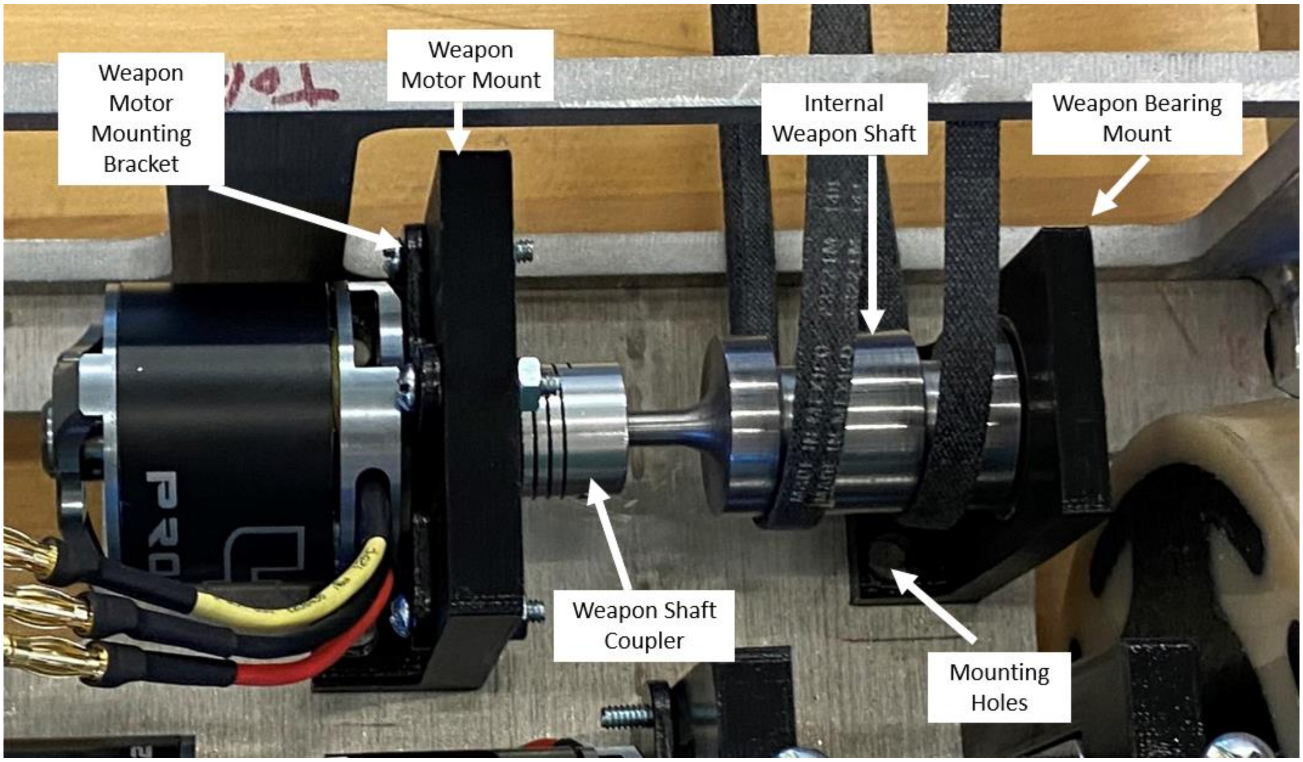

Figure 14: Internal weapon drive components

6.3 Armor Manufacturing

To build the outer armor, the high-density polyethylene was put into a gas kiln to heat it to the glass transition temperature, where at the HDPE would be formable. To mold the outer armor, a plywood mold was built using two separate sheets of plywood that had the armors shape cut out of them. The shape of the mold was created as a draw on SolidWorks with precise and accurate measurements that align perfectly with the frame of the robot, printed on the large format printer, traced onto the plywood, and cut out with a jig saw. Once the polyethylene was bent into the mold, (Figures 15 and 16,) it was allowed to cool at room temperature. Lastly, the armor was fitted up to the frame and had the mounting holes drilled out in their respective locations.

Figure 15: Side view of the double plywood sheets

Figure 16: Jigsaw cut of the outer armor

6.4 Electrical System Assembly

To assemble a strong electrical system, every wire that did not need to be detachable was soldered together. For this process, the wires were cut and stripped out to apply the solder using a soldering iron. Once they were soldered, heat-shrink tubing was applied using a heat gun. The process can be seen in Figure 17. This was done to avoid any electrical contact with another component of the robot. As the robot was assembled, electrical tape was used to keep the wires in their corresponding position and avoid a shortage between wires. To reinforce the electrical system of the robot, zip ties were used between the wires and the frame to hold the wires in place during the competition and prevent disconnection in the event of a large impact to the robot.

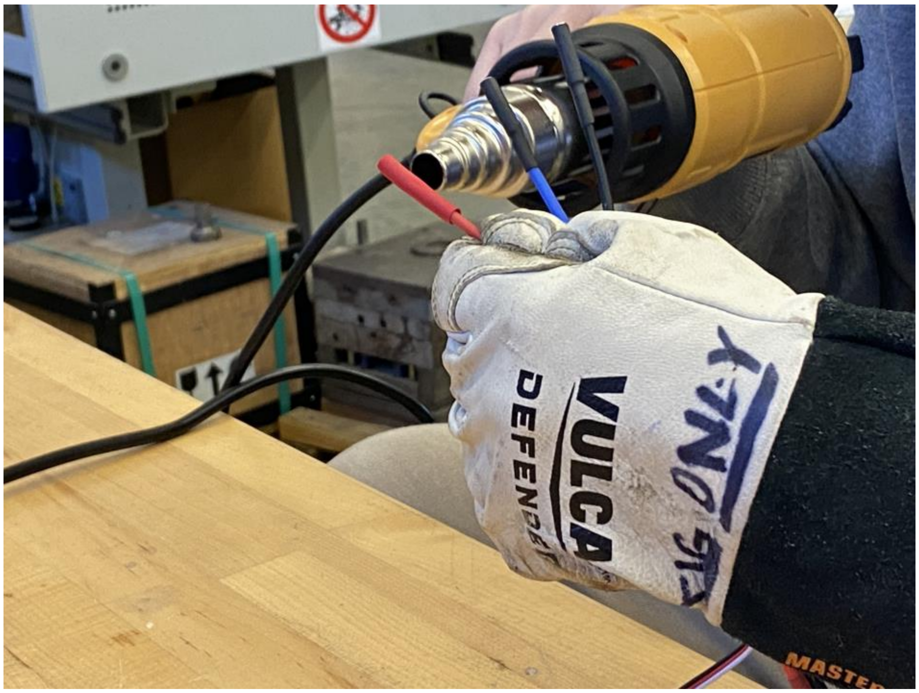

Figure 17: Heat-Shrinking tubing over the motor's wires

6.5 Drive System Assembly

To make and assemble the drive system, several components were either purchased or made. The motors and gearboxes were purchased each fully assembled. To connect the motor output shaft to the input of the gearboxes, a pinion that came with the gearboxes was pressed onto the motor shaft using a hydraulic press. While the motor simply slides into the gearbox with the pinion, a way was needed to hold the motor and gearbox in place inside the robot. For this, 3D-printed mounts were made using PETG, an image of which can be seen in Figure 18. Figure 19 illustrates how these mounts were used in the robot’s drive system. These brackets had a space in them that would fit on the front and back of the gearboxes and hold them at the exact centerline of the robot’s height, which put our wheel at the center as intended for the invertible design. Additionally, the mounts had holes through them that allowed for bolts to go through the top and bottom frame plates and into thread holes that came in the gearboxes from the factory. This method held the gearboxes securely in place. The motors were attached to the mounts via holes that were printed into the sides of the mounts that match up with those from the factory motor mounting plates and allowed for bolts to be placed through the mount and factory motor mount to securely hold the motors to the gearboxes.

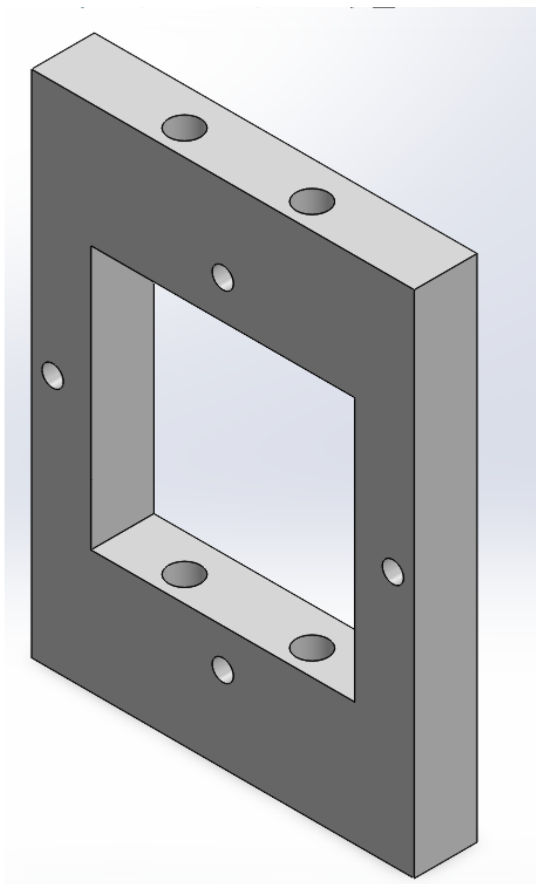

Figure 18: The gearbox mounting brackets

While only two of these brackets needed holes to hold the motors in place at the ends of the gearbox, it was decided that only one bracket design would be used in order to minimize the chance the robot got put together incorrectly and to reduce the different types of spare parts needed at the competition. Lastly, the wheel was put onto the gearbox output shaft by lining up the printed key in the wheels with the keyway on the output shaft. A bolt and washer were then put through the wheel hub and into a threaded hole at the end of the output shaft, which kept the wheels from working loose.

To assemble all the components into the robot, the left and right drive assemblies, which consisted of a wheel, gearbox, motor, and two gearbox mounts, were put together by inserting the wheel on the gearbox and the motor into the mounting bracket. The red box in Figure 19 below highlights the components that comprised one of the drive assemblies. The bolts that went through the top plate were inserted, with the top plate off, and screwed into the gearbox. This held the whole assembly together. Next, the assemblies were put into place and the bolts that went through the bottom bolt were inserted. At this stage, the drive system was ready to be connected to the electrical system. The very last step was to put the top plate on and put the bolts that went into the gearbox in from the top.

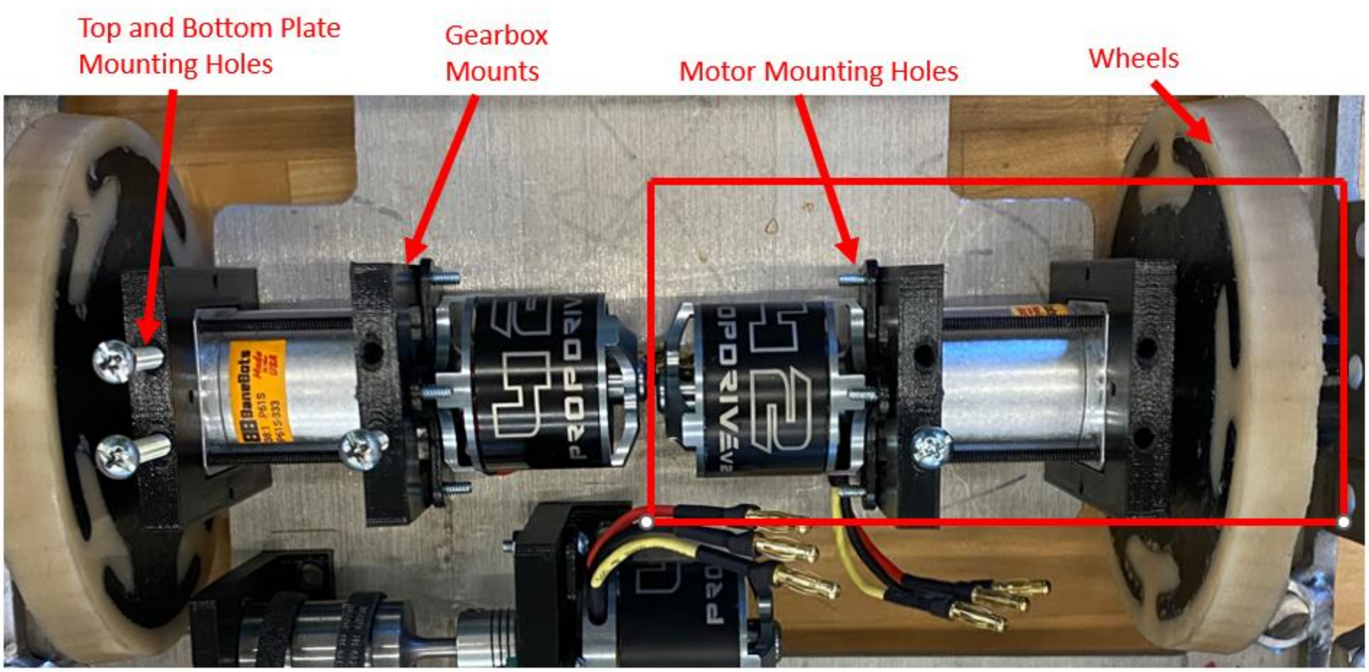

Figure 19: The robot’s drive system

7.0 Testing

During the design phase, several failure modes were considered, a full list considered can be found in Appendix G. To ensure various failures would not occur at the competition, failure testing was conducted in addition to benchmark testing to gain quantitative data on project performance.

7.1 Wheel Speed Testing

A tachometer, an instrument that measures revolutions per second, was used to measure the speed of each wheel when the drive system was fully powered. The measured rpm of the wheels was 157 rpm and 160 rpm. The difference in speed is explained by small manufacturing differences in the gearboxes and motors.

7.2 Compliant Mechanism Strength Testing

The compliant mechanisms were tested by first fully compressing the compliant mechanism by hand to ensure deflection forces would not break the part. Then, impact loads of increasing magnitude were applied to the compliant mechanism. If the part did not break in either test, it was considered a success. Three iterations of part design were required before a final part was selected and mass-produced.

7.3 Weapon Testing

To test the effectiveness of the weapon for inflicting damage and surviving the impact, the robot was taken outside and placed on a large aluminum plate, to mimic real world conditions of the steel plate Robobrawl arena, and a scrap piece of wood was placed a short distance in front of the robot. The robot was powered on and the weapon was activated. The robot was then slowly driven toward the scrap wood until contact was made, then the weapon was stopped, and the robot was turned off. Figures 20 and 21, which are of the test setup and damage caused to the wood, illustrate that the weapon is capable of inflicting damage. Additionally, an inspection of the weapon after the test revealed no damage to any areas of the weapons system, which meets the requirement of being able to withstand impact.

Figure 20: Weapon testing setup

Figure 21: Resulting damage to the wood from the weapons test

7.4 Agility Testing

To test the agility of the robot, three traffic cones were placed in a line, shown in Figure 22, and the robot was driven in a serpentine fashion around them. The weapon was powered off during the test for safety purposes. The driver was capable of completing a full loop around the cones without hitting them. Although it was competition capable, a delay in the signal transmitted to the receiver was detected. Due to the zero-point rotation of the robot, each wheel was connected to a different input on the transmitter requiring a skillful driver.

Figure 22: Robot agility test setup

7.5 Electrical Testing

A match in competition lasts for 3 minutes. In this time, the electrical components must not overheat or deplete the battery. In order to verify that the battery could provide sufficient power to all systems for a full 3 minutes, no components would overheat, and no wires would short, both the wheels and the weapon were turned on at full power for 3 minutes in a Plexiglas box for safety (figure 23). The robot ran in this state for a full three minutes without overheating, shorting, depleting the battery, or any other indication of any electrical system issue.

Figure 23: Robot electrical system endurance test setup

7.6 Weight Verification

To ensure the robot would weigh no more than 30 pounds, all the components of each of the subsystems were weighed to get the weight of each subsystem, which can be seen in Table 1. Once it was known that the entire robot should not exceed the weight limit based on each subsystem, the robot was assembled and weighed as a whole. Using a scale at the AEC, the completed weight came out to 27.4 pounds, which is less than the 30-pound limit at the competition. This turned out to be 0.3 pounds more than the official weight of our robot at competition, which was 27.1 pounds. The discrepancies between the completed weight when measured in the AEC, the official weight at the competition, and the weight based on the individual component breakdown (found in Appendix H) is attributed to differences in scale calibration and rounding on the individual component weights.

Table 1: Subsystem weight breakdown

Subsystem	**Weight (lbs.)**
Frame	6.73
Weapon	7.63
Armor	3.97
Electrical System	4.03
Drive System	4.75
Total Weight	**27.11**

8.0 Budget

The total cost of the robot was $ 1417.66, a full parts list and their respective cost are in Appendix K. Money was saved by using existing scrap metal in the AEC and using a used controller and receiver instead of purchasing new ones.

9.0 Disposal Plan

The robot will be stored with the local chapter of the American Society of Mechanical Engineers as a reference and learning tool for any future teams that may choose to design a BattleBot. Additionally, the motors and gearboxes used for the project are in good condition and could be repurposed for future projects. Spare steel and aluminum plates have been donated to the Applied Engineering Center for use in other projects.

10.0 Lessons Learned

Background Knowledge

- Keep in mind that online orders take time to deliver that could potentially decide the future of the project;
- Teamwork is necessary in order to overcome challenging tasks and ensure that the best designs move forward to critical design;
- Past projects could offer good ideas through the design and build phases;
- Keep in contact with advisors for professional opinions;
- Split the job between the team members so no one is overworked;

Building Phase

- Construct a schedule of important dates in order to keep track of the project;
- Find experts in the field to guide you through the building phase to obtain better results;
- Keep in mind that order pieces sometimes will not be in the desired condition, therefore; have a backup plan;
- Extra material will be necessary to replace damage during the building phase;
- Allow extra time for 3D-printing complications;

Competition Phase

- Spare parts, such as 3D printed pieces, can help through the competition;
- The HDPE outer armor proved to be an effective design as it was able to withstand many direct hits and prevent opponents' weapons from damaging the frame;
- The 3D-printed compliant mechanisms, while good in theory, proved to break upon impact too easily;
- The decision to use v-belts to spin the weapon proved to be an ineffective design as the belts would slip off on impact and render the weapon useless;
- The invertible design proved extremely effective as the robot was flipped over several times and was able to continue in the fight;

11.0 Future Work

For future work, going off the Damage Gallery in Appendix J, a more damage resistant or fully replaceable weapon mounting system would be desirable, as this project saw a complete loss in offensive capability after fight 3. The usage of compliant mechanisms in armor mounting should be designed with methods that prevent the compliant members being loaded in torsion or perpendicularly to the floor. The method of torque transfer from the weapon motor shaft to the weapon shaft should be changed, as during competition all belts were stretched to the point, they were no longer taut on the pulleys. More consideration into how parts will be replaced when working with a fully assembled robot should be done, as during competition replacing a single part requires partial disassembly of working subsystems and multiple people to complete. For example, the bolts that run through the armor and frame are unable to be replaced without removing the wheels, and the wheels cannot be removed without disassembling the electrical system. Also bolt placement should be considered for insertion and removal as multiple times in multiple subsystems inserting and removing a single bolt took multiple people multiple tries and multiple tools being used for not their intended purpose. To use a simile, it was like playing a 3D *Operation* game with a ¼-inch diameter, ¾-inch long bolt.

One of the main problems when building the robot was the placement of the wires and motors. The motors chosen were outrunners motors which complicated the electrical system. Although the electrical system worked perfectly, there was a risk of cutting or damaging the wires of the electrical system due to the movement of the motors. To solve this problem, inrunner motors should be picked.

The ability of the robot to move while flipped-over was a strength of the design. For future work, consider the rotation of the weapon and include a method for the controller to realize the robot has been flipped over to automatically invert the controls and make driving easier.

12.0 Conclusion

The objective of this project was to design and build a functional BattleBot-style robot that complies with the University of Illinois Urbana-Champaign's 30 lbs. combat robotics division rules and regulations to compete in the annual Robobrawl held in April of 2023. Design considerations and decisions were made using the requirements of the competition, research into BattbleBots, and design factors given by the University of Southern Indiana, as seen in Appendix L. The primary requirements governing the project that the total weight of the robot cannot exceed 30 pounds, it must have an active weapon consisting of at least 20% of the robot's final weight, it must have a manual disconnect for each power supply, it must have an operational indication light, and lastly the communications systems must failsafe in a manner that does not allow the robot to move. All the competition requirements were met, and the robot was taken to the competition and allowed to compete.

At the competition, the robot proved to have aspects of the design that were both effective and ineffective. The competition served as an educational experience for the team and as an excellent reference for any teams that may wish to tackle a similar project. Overall, the robot demonstrated to be a successful project due to its capability to fight against its opponent without receiving major damage during the three first battles. Even after complete weapon failure the robot was able to compete and win two rounds. The robot went 4 wins - 2 losses finishing in the top 6 out of 31 teams in competition.

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[4] Murphy, Joseph, et al. University of Cincinnati, 2022, *2021-22 UC CEAS 15lb BattleBot Team*, file:///C:/Users/rjmey/Downloads/MET2022_Murphy_Joseph.pdf.

[5] Bakenhaster, Braden and Nick Newton, directors. *BattleBot*. *Kaltura*, Miami University Department of Engineering Technology, 2021, https://www.kaltura.com/index.php/extwidget/preview/partner_id/886232/uiconf_id/27510051/entry_id/1_c4u8oe8e/embed/dynamic.

[6] Bernstein, James, et al. "Spring Semester Final Report." *BattleBot Senior Design Home,* Florida State University College of Engineering, 2003, https://web1.eng.famu.fsu.edu/me/senior_design/2003/team9/Documents.htm.

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Appendices

Appendix A: Concept of Operations

Concept of Operation

Competition Goals:

- Survive 3 minutes
- Destroy opponent

Method:

- Attack with weapon
- Avoid enemy weapon

How:

- Control the robot

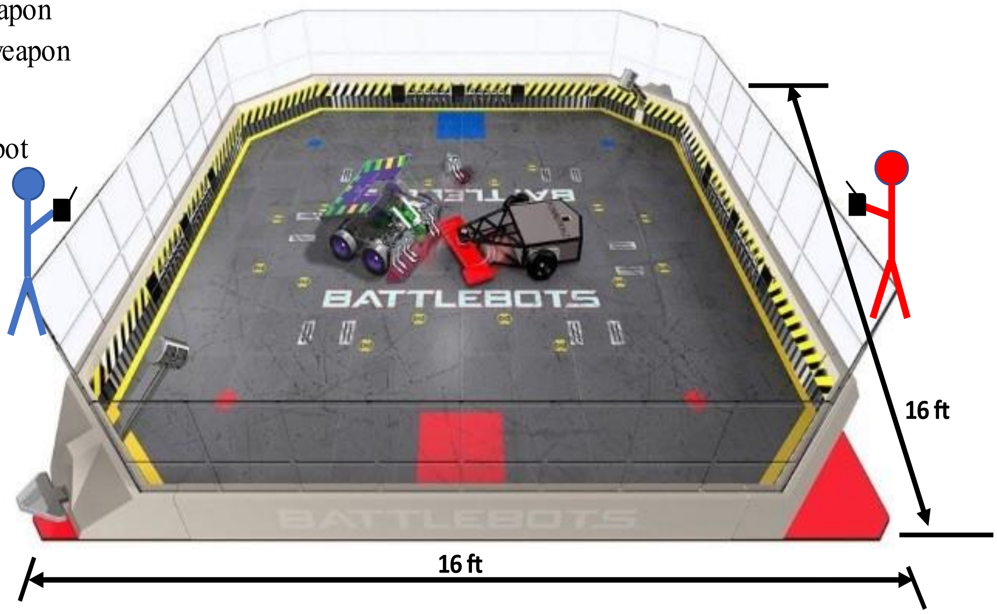

Figure 24: Concept of Operations

Appendix B: Images of similar projects

Figure 25: The 2021-22 UC team's BattleBot [4]

Figure 26*: The MU team's BattleBot [5]*

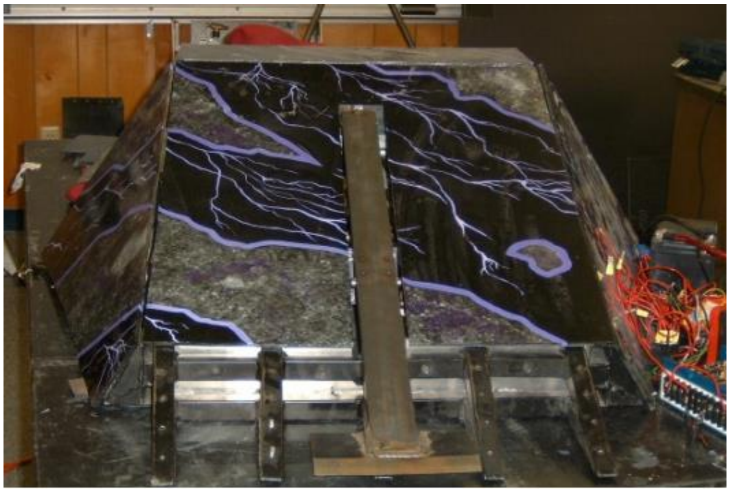

Figure 27: The 2002-03 FSU team's BattleBot [6]

Appendix C: System Hierarchy

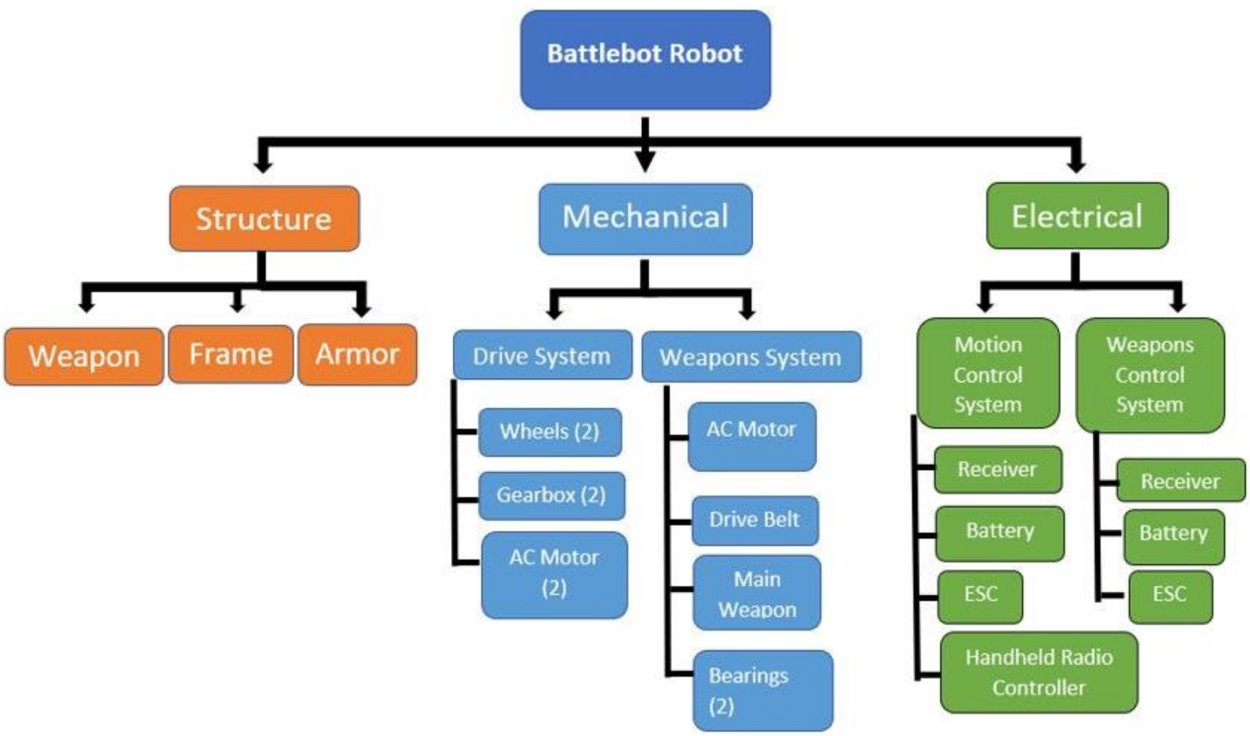

Figure 28: System Hierarchy

Appendix D: Requirements of the Weapon

The weapon shall:

- Spin at 5000 rpm
- Spin below the shaft's critical speed (1st natural frequency of the geometry)
- Withstand expected impacts during competition
- Rotate in an envelope that exceeds the front of the robot
- Comprise at least 20% of the robot's final weight
- Have a lockout devise that prevents unintentional weapon movement+

Appendix E: Weapon Critical Speed Calculations

Equation 1: Critical speed of the shaft alone: $\omega_s = \frac{\pi^2}{l^2} * \sqrt{\frac{gEI}{A\gamma}}$

- l = Length = 12.75 in
- g = Acceleration due to gravity = 386.4 $\frac{in}{s^2}$
- E = Young's modulus = 27$* 10^6$ psi
- I = 2nd moment of area = 0.0491 in^4
- A = Cross sectional area = 0.7854 in^2
- γ = Density = 0.284 $\frac{lb}{in^3}$

Equation 2: Critical speed of the loads on the shaft: $\omega_1 = \sqrt{\frac{g\Sigma w_i y_i}{\Sigma w_i {y_i}^2}}$

- w_i = Weight of the ith location
- y_i = Deflection at the ith body location
- g = Acceleration of gravity

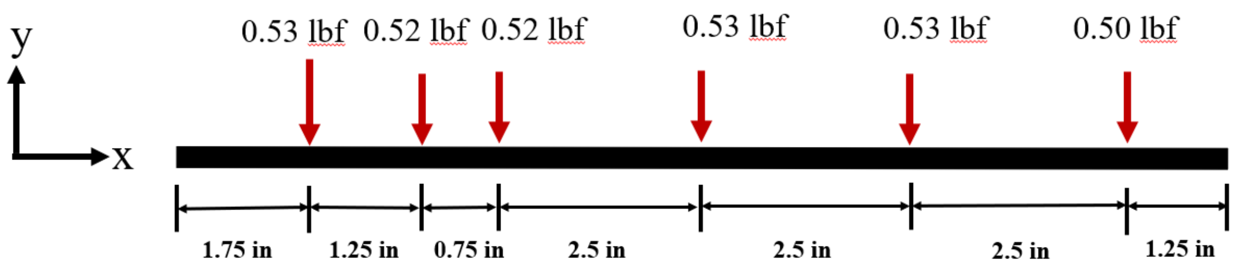

Figure 29: The free body diagram used to determine the deflection of the shaft

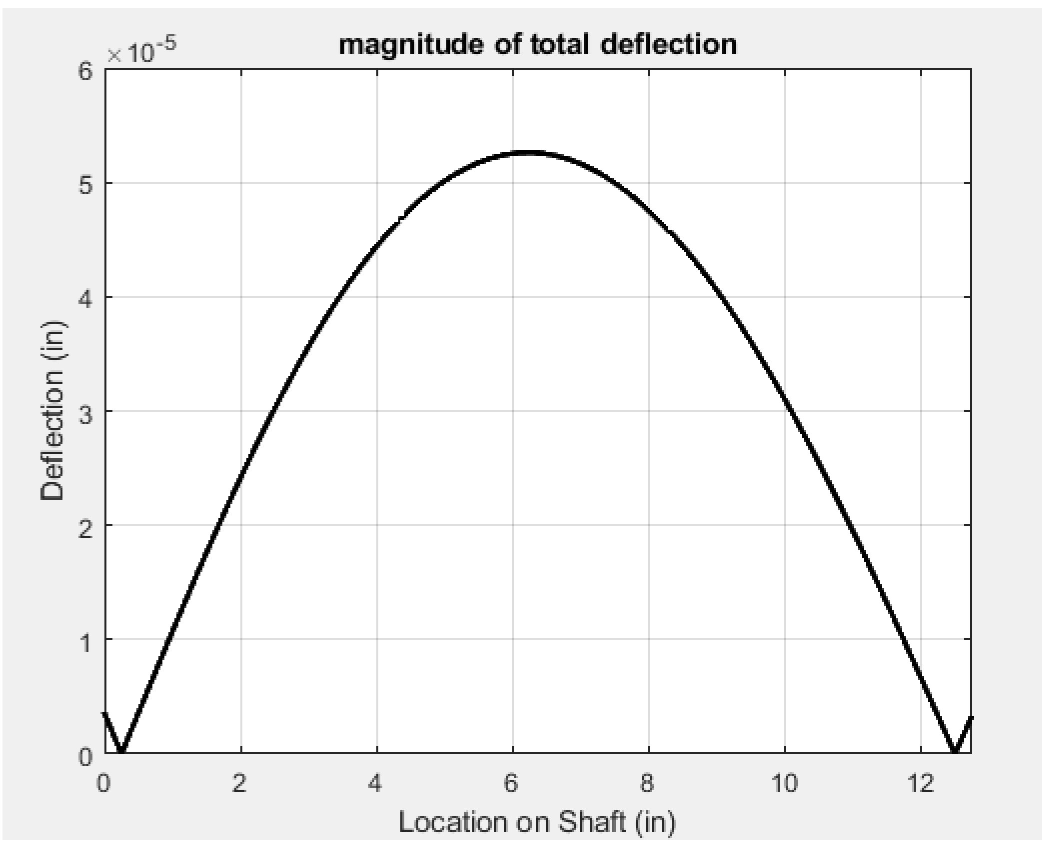

Figure 30: The graph of the defection of the shaft used to determine the deflection at each shaft component location

Equation 3: Dunkerley's Equation: $\frac{1}{{\omega_{tot}}^2} = \frac{1}{{\omega_s}^2} + \frac{1}{{\omega_1}^2}$

Appendix F: Mechanical and Functional Block Diagrams

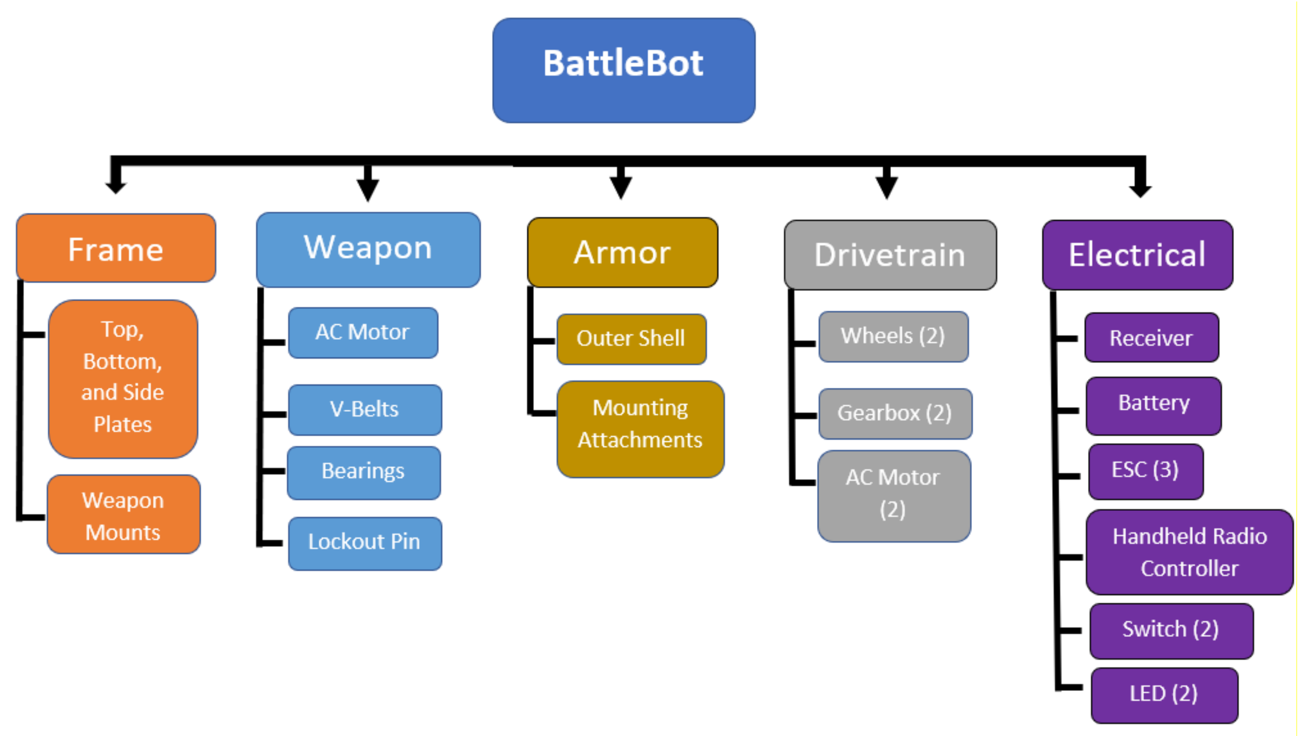

Figure 31: Mechanical Block Diagram

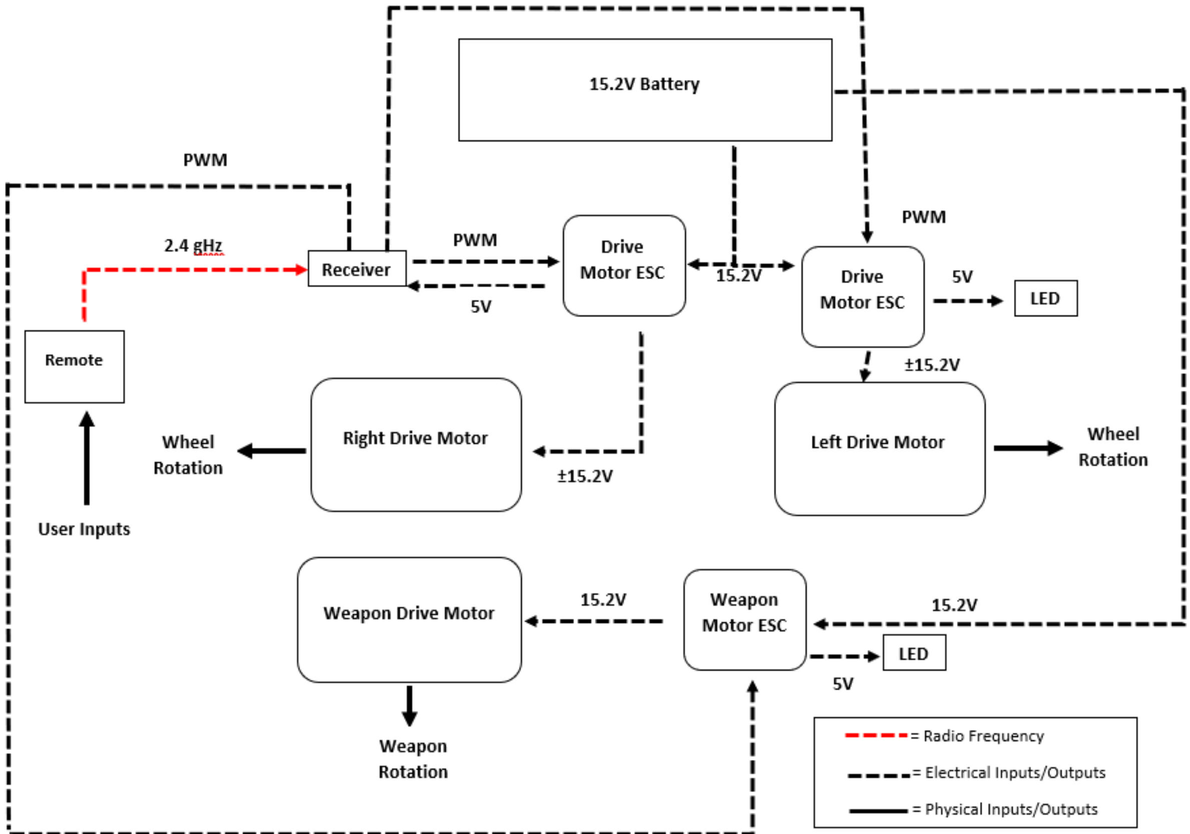

Figure 32: Functional Block Diagram

Appendix G: Failure Modes and Effects Analysis (FMEA)

Appendix G.1: Design FMEA

Table 2: FMEA for during the design and build phase

Item	Failure Mode	Cause of Failure	Possible Effects	Prob	Level	Possible Action to Reduce Failure Rate or Effect
Part Delivery	*Parts are damaged *Parts are late	*Deliveryman error *Parts get misplaced in shipping	*Delay of project	*High	Medium	*Order parts early *Order through reputable seller

Frame	*Static Failure	*Frame cannot hold inner parts	*Redesign *Delay of Project	*Low	Critical	*Proper static analysis *Professional consultation
Motors	*Calculation *Undersized motors	*Motor unable to carry load	*Robot is slow/ inoperable *Delay of project	*Low	Critical	*Oversizing motors *Proper analysis *Professional consultation
Weapon	*Undersized	*Design	*Unable to damage opponent	*Low	Critical	*Weapon testing
3D Printing	*Prints fail	*Print overhang *Incorrect printer settings	*Delay of assembly *Delay of testing	*High	Medium	*Start printing early *Consult individuals with more experience

Appendix G.2: Competition FMEA

Table 3: FMEA for during the competition

Item	Failure Mode	Cause of Failure	Possible Effects	Prob.	Level	Possible Action to Reduce Failure Rate or Effect
Motors	* Burnout * Physical Damage	* Overheating * Overloading * Takes an impact * Poor quality	* Loss of weapon function * Match forfeit	Medium	Critical	*Bring replacement motors

			by loss of movement			
Weapon	* Shear	* Takes an impact	* Loss of weapon * Cannot score attack points	Low	Critical	*Bring an extra weapon *Bring tools capable of reshaping weapon
Frame	* Shear *Compression	* Takes an impact	* Failure of internal components	Low	Medium	*Bring replacement frame *Bring spare parts to patch damage with
Wiring	* Disconnect * Short	* Impact damage * Overload current rating	* Loss of movement * Loss of weapon * Match forfeit	Medium	Critical	*Bring replacement wire *Attach firmly to parts
Weapon Belt	* Tension * Rupture	* Stretches out * Gets cut by opponent	* Loss of weapon	Medium	Medium	* Design adjustable belt tensioner * Bring replacement belts to competition * Redundant weapon drive belt

Appendix H: Mass Breakdown Table

Table 4: The mass breakdown for the entire robot

Part	Quantity	Individual Unit Weight (g)	Total Weight (g)
Weapon	1	2723.82	2,723.82
Motor	3	233.00	699.00
Gearbox	2	839.15	1,678.29
Battery	1	589.00	589.00
LED	2	3.00	6.00
ESC	3	45.36	136.08
Wheel	2	148.00	296.00
Fuses	1	88.00	88.00
Push Pull Switch	2	56.00	112.00
Gearbox Mounts	4	30.00	120.00
Weapon Bearings	2	138.75	277.50
Frame	1	3052.46	3,052.46
Outer Armor Ring	1	1010.52	1,010.52
Gearbox bolts	16	3.78	60.48
Smaller weapon bearing	1	15.01	15.01
Armor attachment bolts	36	11.50	414.00

Rear Compliant Armor Attachments	2	70.00	140.00
Side Compliant Armor Attachments	4	59.00	236.00
Wiring	N/A	35.36	35.36
Weapon Drive Belt	2	222.62	445.24
Controller Receiver	1	6.95	6.95
Misc. Fasteners	N/A	155.62	155.62
		Total (g)	**12,297.33**
		Total (lbs.)	**27.11**

Appendix I: Schedule

Table 5: The schedule for the project

Date	Objective:
11/14/2022	Submit Design Review Presentation
11/18/2022	Finalize individual component designs
11/22/2022	Evaluate total design
11/23/2022	Thanksgiving Break
11/28/2022	Begin writing pre-senior design report
12/7/2022	Pre-senior design report due
1/9/2023	Schedule weekly advisor meeting
1/13/2023	Critical design review
1/16/2023	Order all components
1/16/2023	Print compliant armor attachments
1/23/2023	Begin testing armor attachments
2/13/2023	Fully assemble robot
3/6/2023	Completed testing on robot
3/7/2023	Begin writing senior design report
3/31/2023	First competition day
4/1/2023	Second competition day
4/6/2023	Draft report due to advisor
4/13/2023	Schedule Exit Interview
4/21/2023	Senior Design Presentations
4/27/2023	Poster Session
4/27/2023	Final report due to advisor
4/27/2023	Final report due on SOAR
4/27/2023	Complete CATME survey
4/27/2023	Have completed exist survey and interview

Appendix J: Damage Gallery

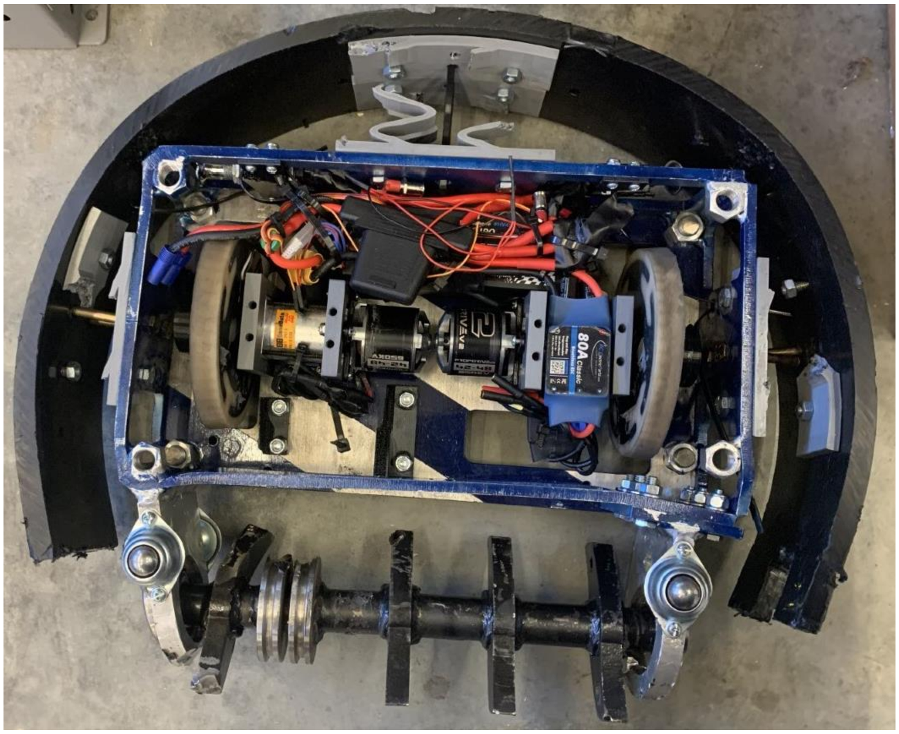

Figure 33: Top-down view of bent weapon blade, broken compliant mechanism armor mounts, broken weapon motor and weapon bearing mounts and inward bent front frame and weapon holders

Figure 34: Right weapon holder after competition

Figure 35: Left weapon holder after competition

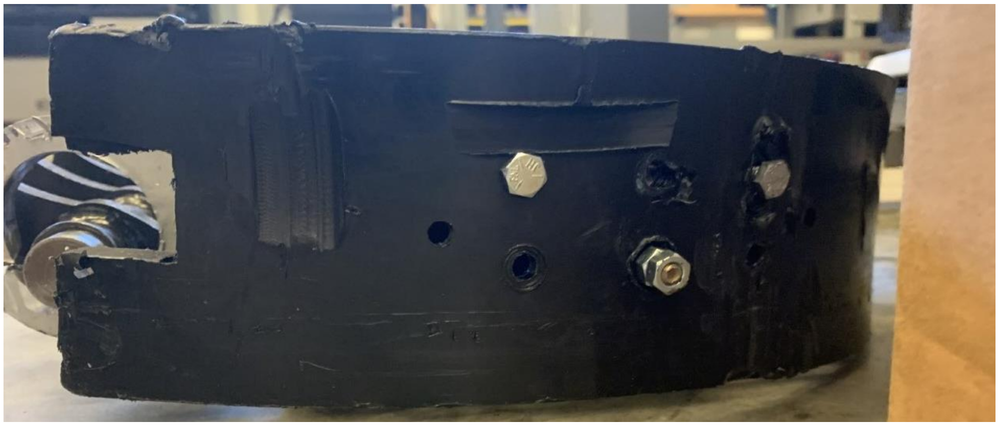

Figure 36: Left side of HDPE armor after competition

Figure 37: Rear side of HDPE armor after competition

Figure 38: Right side of HDPE armor after competition

Figure 39: First PLA weapon bearing mount broken during competition

Figure 40: Interior side of HDPE armor damaged by frame corner impacts after competition

Figure 41: Cracked PLA drive motor mount

Figure 42: Second PLA weapon bearing mount broken and cracked weapon shaft bearing with missing ball bearings

Figure 43: Intact weapon motor pully with absolutely destroyed weapon motor coupler

Appendix K: Budget

Table 6: Budget

Part	Quantity	Individual Unit Price ($)	Total Pric
P6S Gearbox: Standard Duty, 38:1	2	76.4	152.8
80A RC Electric Speed Controller ESC	3	37.49	112.47
PROPDRIVE v2 4248 650KV Brushless Outrunner Motor	3	36.99	110.97
Powerhobby 4s 8000MAH 120C 15.2V Lipo Battery	1	259.95	259.95
OVERTURE PETG Filament 1.75mm, Black, 3D Printer Filament, 2.2lbs	2	19.99	39.98
Smooth-On VytaFlex 30 - Liquid Urethane Rubber	2	27.91	55.82
Universal Mold Release	1	21.69	21.69
Gebildet 5pcs 8mm 3V-4.5V-5V-6V-7.5V-9VDC LED Metal Indicator Light	1	7.99	7.99
10 Gauge Fuse Holder	1	9.99	9.99

Conext Link MAXI60-10 Nickel 60Amp MAXI Fuse 10 Pack	1	5.79	5.79
GearIT 10 Gauge Wire	1	24.99	24.99
Boat Rocker Toggle Switch	1	6.99	6.99
132 PCS Battery Terminal Connectors	1	11.99	11.99
Saiper Flexible Couplings	1	9.99	9.99
1205 Bearing	2	22.5	45
High density polyethalyne sheet (12in x 48in x 0.5in)	1	75.87	75.87
6061 Aluminum Hex Nut, 1/2"-20 Thread	1	10.56	10.56
Heavy Duty External Retaining Ring	1	6.3	6.3
18-8 Stainless Steel Button Head Hex Drive Screw	10	3.11	31.1
WMYCONGCONG 2 PCS Heavy Duty in-line Fuse Holder	2	11.99	23.98
6061 Aluminum Hex Nut, 1/2"-20 Thread Size	1	10.56	10.56
1/2"x12" A36 steel Flat Bar 12" long	1	67	67
1/2"x12" 6061 Alum. Flat Bar 12" long	1	85	85
Push-Pull Switch On/Off 75 AMP	1	17.85	17.85
2-1\2” diameter CR Round Bar 4” long	1	40	40
1” diameter CR Round Bar 16” long	1	25	25

Glarks 2Pcs 5mm x 356mm Aluminum Straight Metal Rods	1	8.96	8.96
Ball Bearing	1	6.75	6.75
Roller Ball Transfer Bearing	1	22.99	22.99
RiToEasysports RC Brushless ESC, Bi Directional 80A Brushless ESC	3	30.43	91.29
V-Belt type	2	9.02	18.04
		Total ($)	1417.66

Appendix L: Design Factor Considerations

Table 7: Design Factors Considered

Design Factor	Page number, or reason not applicable
Public health safety, and welfare	Page 12 - Weapon lockout pin Page 16-17 - Power Switches Page 17 - Operational Indication Lights Page 17 - Communications Failsafe All of these factors of the design were competition requirements put in place for the safety of public viewing the competition and the competitors competing.
Global	This is a robot for a local competition and has no effect globally.
Cultural	There are no cultural design factors for this robot.
Social	This robot shall not impact any society and therefore social design factors do not apply.
Environmental	This robot shall not interact with the environment and therefore environmental design factors do not apply.
Economic	There will be one robot produced and it will not be sold, economic design considerations do not apply.
Ethical & Professional	The robot will be a part of a collegiate tournament not attached to any professional organization and the robot will not be a part of any kind of ethics, so design factors do not apply.

Reference for Standards	Page 17