12 Pound Combat Robot
ButterBot

Senior Design Proposal submitted to the
Department of Mechanical and Materials Engineering
College of Engineering and Applied Science
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in partial fulfillment of the
requirements for the degree of

Bachelor of Science

in Mechanical Engineering Technology

by

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ABSTRACT

This documents our design of a hobby weight, 12-pound BattleBot that can compete in the NHRL Combat Robotics Competition. The energy transferal device must be able to deliver a large amount of force efficiently and reliably, the frame and armor of the robot must be able to withstand the offensive strikes of the opposing robot, the wheels must be able to effectively maneuver the robot about the ring, and the internal components must be able to operate and run the components while being able to withstand the jostling and blows during the match. We have designed a BattleBot with a horizontal spinner made of AR500 alloy steel. The frame and armor of the robot will be made of 7075 Aluminum and TPU, respectively, and the robot will have a two-wheel direct drive system. The frame, spinner, and armor materials were chosen based off their mechanical and physical properties, to withstand large amount force and be lightweight to remain under the 12-pound weight limit for the competition. There will be individual containment cells for each of the internal components to reduce the risk of short-circuiting wires or having a potential fire render the internals unable to function. In addition, the wheels have been designed to have a TPU wheel hub and a urethane “tread” for traction. Many of the internal components have been standardized by the UC BattleBots club and the other components have been designed around the specifications of standardized components to be able to reach desired values and performance.

PROBLEM DEFINITION

PROBLEM STATEMENT

To design a combat robot that will maneuver around the arena and deliver damage to the opposing robots. The team will design, assemble, test, and fight with the robot. The project will optimize weight distribution between the frame, weapon, and drive systems to stay within the 12-pound weight limit. The drive system will be designed to be reliable, the frame will be able to sustain damage from other robots, as well as forces exerted by the weapon, and the weapon will be designed to balance weight and functionality. This robot will be completed in time to compete in the BattleBots competition in March 2024 to refine the design for the following competitions.

BACKGROUND

The NHRL (National Havoc Robot League) is the largest robot combat league in the world. Based in Norwalk, Connecticut, the NHRL hosts several tournaments that cater to different weight classes of combat robots, all for the chance to win cash prizes. Robot combat is defined by the NHRL as a “safe, friendly, and slightly chaotic iSport where builders control robots equipped with innovative weapons and ingenious defenses” (1). There are three weight classes that compete in the NHRL, 3lbs, 12lbs, and 30 lbs. Each fight goes for an allotted amount of time or until one robot is eliminated by knockout or tap out. If the fight goes for the full time, three judges rate the competitor’s performance based on three categories: Aggression, Control, and Damage. These categories are defined as follows:

Aggression: Aggression is the intensity and frequency of intentional attacks, preferably with an active weapon. To score points here, you need to make attacks that could affect your opponent. (2)

Control: Control is how well you dictate the flow of the match. To score points here, you want to put your opponent in a bad spot, like pinning them or getting them stuck. (2)

Damage: Damage is the condition of your opponent's bot at the end of a match compared to how it started. To score points here, you need to hurt your opponent's critical systems. (2)

Teams must design a robot with three components: the weapon, the frame/body/armor, and the drivetrain. By utilizing new concepts and innovative ideas, teams will manufacture a robot to compete against another team's robot in a head-to-head match. The robot that is still operable at the end or accumulates the most points from the criteria above is declared the winner.

RESEARCH

RULES, REGULATIONS, AND APPLICABLE STANDARDS

The applicable standards for this project are outlined in the robot design rules section set by NHRL in the *NHRL Full Rulebook.* The rule book covers the rules and restrictions for the different weight classes that compete- 3lb, 12lb, and 30lb. Each weight class has the opportunity for a multibot weight bonus, as well as a non-traditional locomotion weight bonus. The rules provide guidelines for the battery type, size requirements, weapon type, and different design restrictions. Refer to Appendix A for applicable rules and regulations from the NHRL Full Rulebook: Robot Design Rules (3).

There are industry quality standards applied to the hardware of the robot as well. The various screws used meet the following standards: ASME B18.2.1, ASME B18.3, ASTM A574, ASTM B117, ASTM F835, DIN 912, ISO 4762, and SAE J429. The nuts meet the following standard: ASME B18.21.1. Finally, the bearings meet the following standards: DIN 281, and ISO 76. These called out standards can all be found at the point of purchase for the hardware.

CURRENT STATE OF THE ART

UC (University of Cincinnati) (University of Cincinnati) Combat Robotics has been a member of the XtremeBOTS Collegiate league since 2017. Since then, several senior design teams have designed, built, and competed combat robots. These teams have all taken unique approaches to solving various design challenges of the combat robot concept. The design and implementation strategies employed by these teams were analyzed to determine effectiveness and to identify any potential areas for improvement. In addition to previous club designs, robots have appeared in the National Havoc Robot League (NHRL) as well as the BattleBots club program. Reviewing these robots provided additional design context and a better understanding of how certain design principles evolved through iterative testing. This analysis provided a basis for implementing design concepts that would be both effective and practical. As part of this research, a few main design categories were identified- weapons, armor, and drivetrain.

Weapon

The most critical decision in designing a combat robot is choosing what is referred to as the robot's "weapon." Simply put, this is the device the robot will use to attack and dominate the opponent. Because the weapon is the primary means by which the robot can influence the competition, robots are generally designed around it. This leads to a few basic robot design types, categorized by their weapon styles.

Spinners

These are robots that use the inertia of a rapidly spinning mass to damage the opponent. The most common implementations of this are horizontal or vertical beams, discs, or barrels. These robots are currently the most popular designs. This is likely due to their effectiveness and general simplicity. One of the most important elements in spinner design is the spinner orientation. For this reason, horizontal and vertical spinners will be discussed separately.

Vertical Spinners

This is by far the most popular and most successful category of robot; 13 out of the top 15 NHRL robots are vertical spinners (4). Vertical spinners typically involve a spinning disc, bar, or drum orientated so that the axis of rotation is horizontal and parallel to the wheel axes. These devices can be mounted with relatively low ground clearance, enabling them to fling opponents into the air. Due to Newton's 3rd law, the force that is transferred into the opponent is reactively transferred into the attacking bot (5). Because of the configurations of verticals, this force can be channeled into the ground, improving handling and control during a hit. Something that must be considered with verticals is gyroscopic precession. Because the steering axis of rotation is not aligned with the axis of rotation of the spinner, sharp maneuvers can lead to the robot lifting into the air. This could potentially create attack openings for opponents or even the robot flipping itself over and becoming stranded. A vertical is very stable upon impact because the weapon is typically spinning "up" so the force is transferred into the ground, but a vertical spinner does not typically have a deep reach into an opponent, requiring many hits to damage an opponent. The weapon also must be fairly lined up with an opponent in order to get a successful, powerful hit. The need for precise alignment combined with the gyroscopic effect can make maneuverability extremely difficult to be precise with.

Horizontal Spinners

Another popular robot design, horizontal spinners utilize a disc or bar with a vertical axis of rotation. The most notable benefit of this design is that gyroscopic effects will no longer affect the robot's maneuverability. Additionally, spinners can be designed with greater weight and size. This design, however, does mean that impact reaction will be transferred back into the robot weapon motor. This can lead to both the target and the attacker being erratically flung across the arena. In some cases, this can even lead to weapon drive failure. Because the weapons are relatively thin, they can be mounted at different heights on the robot. These configurations are referred to as "uppercut," "mid-cut," and "undercut." UC's 2021 Beetleweight robot, "Hash-Slinging Slasher," utilized a midcutter horizontal disc (6). It should be noted that uppercut configurations become undercut when the bot is flipped over. Undercut configurations are particularly popular due to their ability to reach underneath robot armor, while midcutter robots have the highest likelihood of hitting another robot. A final benefit of horizontal robots is that they can be easily designed to drive both right-side-up and upside down, eliminating any threats of being stranded by a flip. Major adjantages of horizontal robots is the ability to have a larger “bite” into the opponent as well as a large hitting area extending from the robot compared to a vertical spinner and does not need to be as precise in the line-up of a hit. Based on the reach, design of the blade, and the angle of the blade upon impact, a horizontal can severely damage the armor of an opponent.

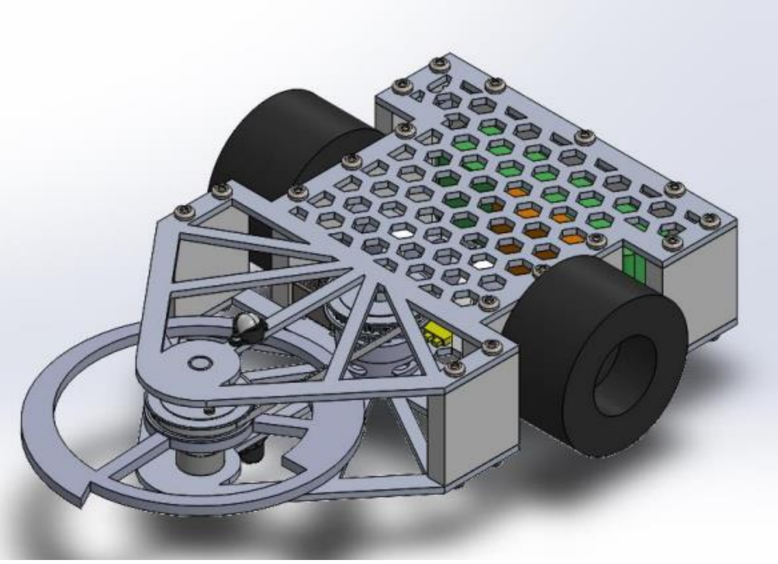


Figure 1: "Hash-Slinging Slasher" with a horizontal disc.

Hammers

Hammer, or “dead-blow” robots are a less popular and uncommon configuration. These robots use a powered hammer to damage the opponent. The hammer is typically powered by a motor and gear chain, though pneumatic and hydraulic systems have also been used. A major drawback of this style of attack is that the impact area is very small; the attacker must be carefully aligned with the opponent. Additionally, the reaction force is not transferred into the ground, but rather causes the attacker to flip over, lessening the impact on the opponent.

Wedges

Wedges on a robot are simply an implement designed to push the opponent or scoop it off the ground. While commonly used in addition to other attack devices, lone wedges have been seen in tournaments. The biggest draw of a wedge is its simplicity. Because there are no moving parts, there are virtually no systems that can break down. The wedge is designed to have low floor clearance, allowing them to lift and carry the opponents. Additionally, the wedge itself doubles as thick armor, resulting in robots that are very difficult to destroy. This allows the robot to be maneuvered in an extremely aggressive manner, much akin to sumo wrestling. Due to the lack of an active weapon, matches frequently come down to judge rulings, which are influenced by several factors such as aggression, hits (if applicable), and control. One major drawback of wedges is that the wedge becomes functionally useless when inverted.

Armor

Armor is a critical part of the design of a combat robot. It is the component that allows the robot to withstand high-force impacts without any loss of functionality. The different armor materials that are commonly used are TPU, UHMW, aluminum, and steel. Characteristics for these materials are as follows:

Table 1: Material Properties Chart

Material	Notes	Material Properties
TPU	Able to be 3D printed, elastic, good for unconventional and complex geometry	Yield Strength: 7600-11500 kpsi Elongation breaks at 86%

UHMW	Rigid, better for frames and structural components	Yield Strength: 5000 psi Elongation breaks at 500%
Aluminum 6061	Plastic deformation when hit, “smears”	Tensile Strength: ~ 35 kpsi
Aluminum 7075	Harder material, more brittle. “Shatters” when hit	Tensile Strength ~ 65 kpsi
Aluminum 5052	Easier to bend	Tensile Strength ~ 33 kpsi
S7 Steel	Shatters when over-hardened, good for 3D components	Hardness, Rockwell C: 59-61
Hardox	Thinner material, pre-hardened, lower hardness, higher impact resistance. 2D parts only	Hardness (HBW): 425-475
4140	General purpose material for shafts, gears, etc.	Hardness, Brinell: 197

Previous UC BattleBots teams have used simple sheet metal or plastic casing for armor. Some more recent designs have implemented a shell that is designed to absorb impacts. Doomba, for example, used a molded, spring-loaded UHMW ring to absorb impact force (7). Another consideration is ensuring that the armor is thick enough that the opponent’s attack device cannot “bite” too far into the robot and damage the electronics or other internal components.

Drivetrain

Combat robots typically use wheels to provide mobility. Other designs have been seen, but do not usually make it far in competitions. Two- and four-wheeled designs are the most popular configurations by far. One of the benefits of two wheels is simplicity. The wheels can be directly mounted on the motor driveshafts, reducing potential points of failure. However, there is a greater risk of a wheel being damaged and severely hampering maneuverability. UC's 2018 60lb robot used a two-wheel system protected by a metal shell to help alleviate this risk (8). Four-wheel robots typically require pulleys or belts to move. This increases complexity, which in turn increases points of failure. The benefit to this configuration is that there is redundancy in the wheels and the robot is well balanced, improving maneuverability.

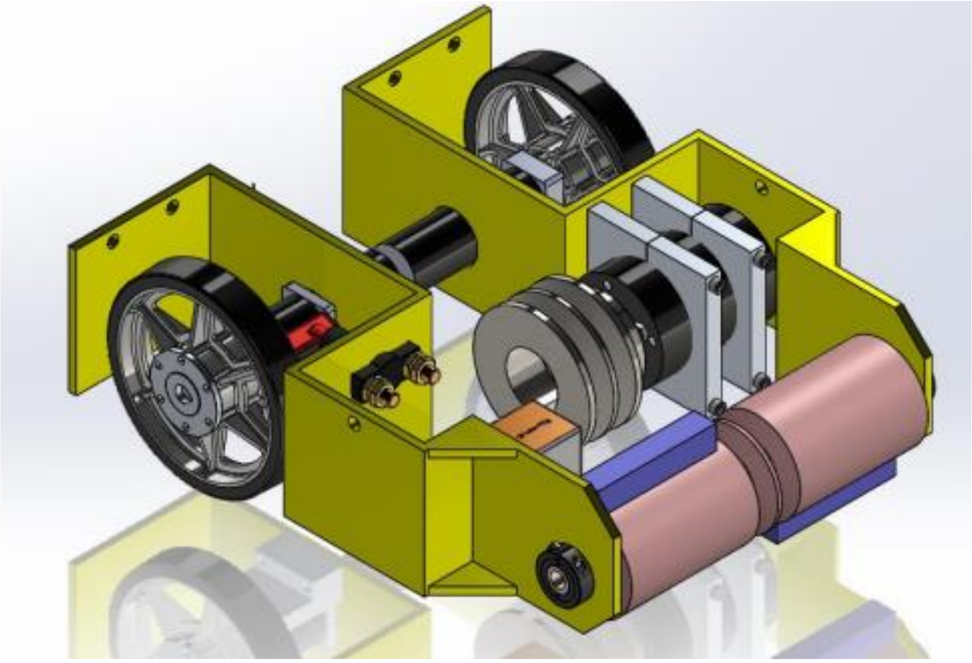


Figure 2: UC's 2018 60lb robot exhibiting two-wheel drive functionality.

Electronics

The University of Cincinnati Combat Robotics club has a standardized internal electronics system which includes a battery pack, a remote-control receiver, an ESC transmitter for the spinner and one for each wheel, and wires that connect to each component that needs controlled- the motors for the wheels and the motor for the weapon. Electronics design for the ButterBot will be based on the power drawn from the three motors and will determine how large the battery will need to be. There are several other options for the batteries, electronics, and control components, but through trial and error done by previous groups within the club, they have made the recommended components standard for the club. This is due to the components' reliability and cost effectiveness.

END USER

The end user of our robot is going to be the members of Team ButterBot. The robot will need to be simple enough to operate so that each member of the team can drive the robot if needed. One member of the team will be the designated driver, so that member will need to be more familiar with the handling of the robot to successfully maneuver it in combat. Independent components and assemblies will need to be modular in design so that each member can replace and/or repair them quickly between rounds of the competition. This applies to external attachments and alternative components that can be employed with different strategies. In addition to the components and assemblies being modular, they must also be cost effective. The cost of the robot must be within the allotted budget given to the team. All components and functions of the robot must be compliant with NHRL rules and regulations to ensure the safety of the team and competitors and protect them from disqualification from the competition.

CONCLUSIONS AND SUMMARY OF RESEARCH

The weapon type is the most influential factor for the design of combat robots. The different types of weapons include horizontal and vertical spinners, hammers, and wedge designs. The most effective weapons are the spinners which dominate the field. Vertical spinners are effective at delivering force but can be difficult to maneuver. The horizontal spinners are easier to maneuver and have a large weapon delivery area, but the reactive forces can send the robot across the arena. With that being said, there has only been one horizontal spinner to win the championship in 250lb weight-class since 2015. The rest have been some form of vertical spinner with the exception of Sawblaze which was a hammer saw. Armor to protect the robot during competition can range from hard to soft materials, and can be used just to protect internal components, or also to make oncoming attacks less effective by absorbing the impact. The drivetrain of the robot can be two-wheel drive or four-wheel drive. Two-wheel drive robots are more robust but can become unbalanced if damaged. Four-wheel drive robots have more failure points but are better balanced.

The design for ButterBot will be a midcutter horizontal robot with two-wheel-drive. Due to the stability of the robot with respect to maneuverability, a two-wheel-drive horizontal robot is preferred. The robot will be a midcutter because it will ensure the greatest likelihood of making impact with an opposing robot in a right-side-up orientation and an upside-down orientation, as well as the ease of assembly.

QUALITY FUNCTION DEPLOYMENT

CUSTOMER FEATURES

By surveying builders in the combat robotics community, many good suggestions were made about different criteria we should target to include in the design of our robot. There were 10 customer requirements, listed here:

1. Weapon type
2. Weapon strength
3. Armor/frame material
4. Armor/frame strength
5. Maneuverability
6. Speed
7. Invertibility
8. Weight
9. Cost
10. Part modularity

These criteria are the most important to other builders, so we will take these criteria into heavy consideration upon design.

PRODUCT OBJECTIVES

The customer features will be addressed by several measurable criteria. The weapon type and orientation will be a horizontal spinner. It will also need to have a good hardness on the Brinell scale. The hardness will be balanced with the yield strength of the weapon. This is because the weapon needs to be hard enough to withstand high energy impacts but needs to have a high yield strength so that the material yields rather than cracks. The torque of the wheels on the robot will affect its maneuverability and will be measured in N/m. The weapon's angular velocity is also related to the maneuverability and will be measured in RPM. The wheel diameter has an impact on whether the robot will be able to be used in an inverted state. The wheel diameter will be measured in meters. The armor durability will be measured by whether it is made of TPU or not. Speed will measure both the weapon and the wheels of the robot. The robot must be able to drive upside down and will be measured in m/s. The robot must stay within the weight limit of 12 pounds that is set by the competition rules. The cost of the robot is to be balanced among all aspects of the robot and will be measured in USD. This robot must also be designed with minimal part replacement time, measured in minutes.

PRODUCT CONSTRAINTS

The project must remain within the proposed budget. Due to the sensitivity of Lithium Polymer batteries and the control electronics, the robot must remain dry and within the temperature range of -4°F and 140°F. In consideration of sustainability and cost reduction, the electronics and batteries will be reused from previous BattleBots. Once the robot has been retired the remaining components will be preserved as a trophy and then eventually recycled, reused, or thrown away. The parts must all be manufacturable using CNC, laser cutting, waterjet, or 3D printing processes. The robot must follow the NHRL rules and regulations to ensure that the robot is a fair competitor, is safe to operate under the prescribed conditions, and complies with industry standards. This includes features such as an accessible emergency shutdown and a locking mechanism for the weapon.

ENGINEERING CHARACTERISTICS

The weapon will be made from AR500 steel. This is because it has a high yield strength and hardness which will maximize the effectiveness of the impact it has during a hit.

AR500 Steel Properties

Table 2: AR500 Steel Properties

Hardness	477-534 BHN	ASTM E10
Yield Strength	215 Ksi	1480 MPa
Ultimate Tensile Strength	240 Ksi	1655 MPa
Elongation	8% (50.8 mm gage)	

The body will be encased in TPU because it absorbs impacts extremely well due to the Izod Impact, Unnotched value being 52-95 kJ/m^2.

TPU (Thermoplastic Polyurethane) Properties

Table 3: Thermoplastic Polyurethane Properties

Density	1.28-1.66 g/cc
Hardness, Shore D	55.0-83.0
Yield Strength	52,4-79.3 MPa
Tensile Strength	28.0-96.0 MPa
Elongation	10-86%
Izod Impact, Unnotched (ISO)	52.0-95.0 kJ/m^2

The body will have two plates of Aluminum 7075 in order to ensure that the impacts the robot takes from opponents will not impact maneuverability because the material will “chip off” instead of smear like other alloys.

Aluminum 7075

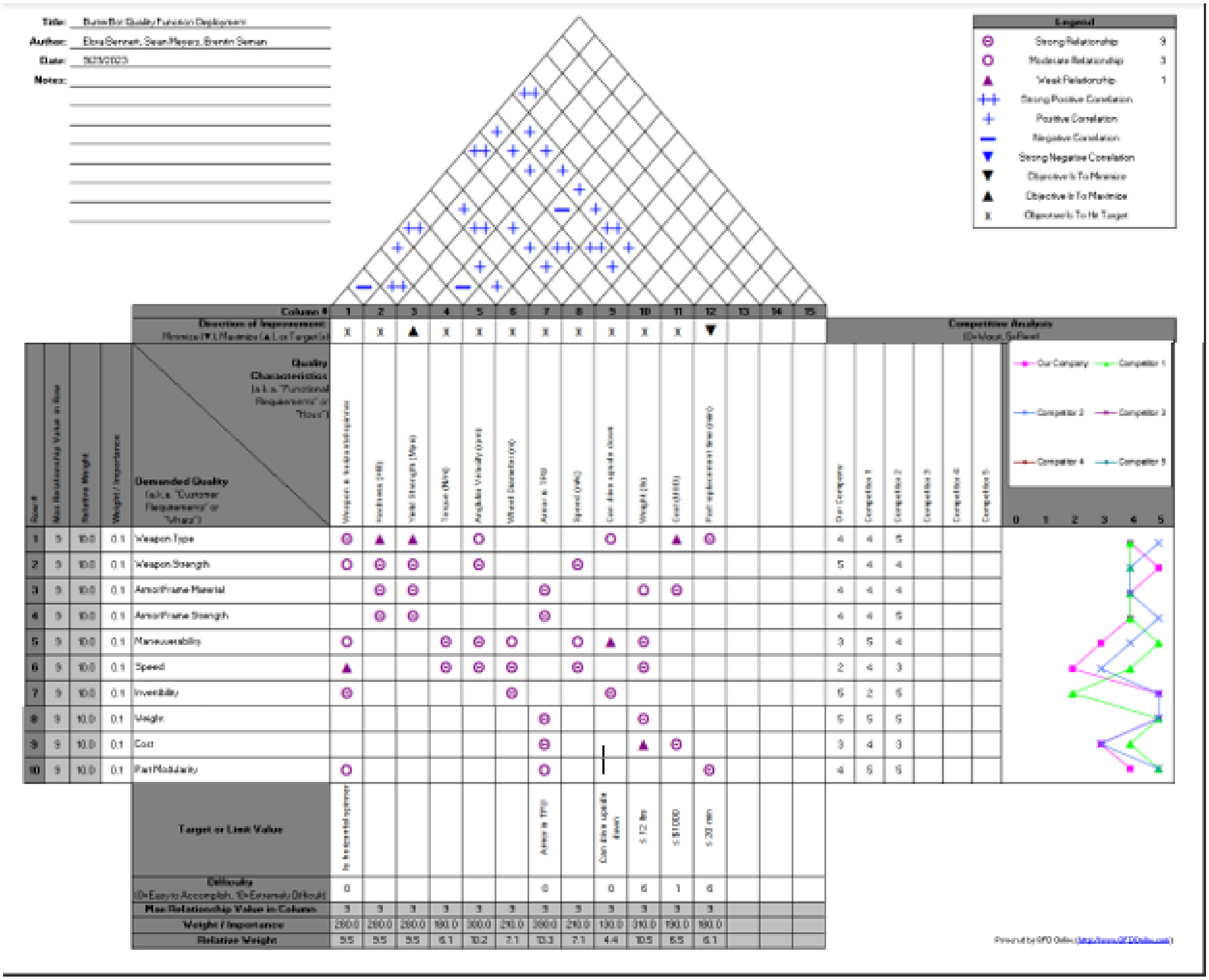
Table 4: Aluminum 7075 Properties

	-O	-T6	-T73
Hardness	B17 | 60	B87 | 150	B82 | 135
Yield Strength	21 Ksi	73 Ksi	63.1 Ksi
Ultimate Tensile Strength	40 Ksi	83 Ksi	72.2 Ksi
Elongation	10%	11%	7.1%
Shear Strength	22 Ksi	48 Ksi	42.5 Ksi

The weapon will be a horizontal midcutter and will have 2-wheel-drive. The tip speed of the weapon will be 220 RPM, and the speed of the wheels will be roughly 700 RPM, depending on the wheel diameter, to achieve a 25 MPH speed across the arena. The wheel diameter will be 3 inches which allows the robot to have 8.5mm of clearance between the top and bottom plates and the ground depending on which side is up. The wheels will also extend above the height of the robot in order for the robot to be able to drive upside down. The weight will stay within the 12-pound weight limit set by the NHRL competition. The design of the robot will need to facilitate easy component replacement in order that the robot can have easy part replacement within 10-30 minutes.

HOUSE OF QUALITY

Above is the House of Quality that was created based on customer requirements.



Title: Battle Bot Quality Function Deployment
Author: Elora Bennett, Sean Meyers, Brendin Seman
Date: 9/21/2023
Notes:

				Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Competitive Analysis (0=Worst, 5=Best)					
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	x	x	▲	x	x	x	x	x	x	x	x	▼									
Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Weapon is horizontal spinner	Hardness (HB)	Yield Strength (Mpa)	Torque (N/m)	Angular Velocity (rpm)	Wheel Diameter (in)	Armor is TPU	Speed (m/s)	Can drive upside down	Weight (lb)	Cost ($)	Part replacement time (min)				Our Company	Competitor 1	Competitor 2	Competitor 3	Competitor 4	Competitor 5
1	9	10.0	0.1	Weapon Type	⊙	▲	▲		○				○		▲	⊙				4	4	5			
2	9	10.0	0.1	Weapon Strength	○	⊙	⊙		⊙			⊙								5	4	4			
3	9	10.0	0.1	Armor/Frame Material		⊙	⊙				⊙			○	⊙					4	4	4			
4	9	10.0	0.1	Armor/Frame Strength		⊙	⊙				⊙									4	4	5			
5	9	10.0	0.1	Maneuverability	○			⊙	⊙	○		○	▲	⊙						3	5	4			
6	9	10.0	0.1	Speed	▲			⊙	⊙	⊙		⊙		⊙						2	4	3			
7	9	10.0	0.1	Invertibility	⊙					⊙			⊙							5	2	5			
8	9	10.0	0.1	Weight							⊙			⊙						5	5	5			
9	9	10.0	0.1	Cost							⊙			▲	⊙					3	4	3			
10	9	10.0	0.1	Part Modularity	○						○					⊙				4	5	5			
				Target or Limit Value	Is horizontal spinner						Armor is TPU		Can drive upside down	≤ 12 lbs	≤ $1000	≤ 20 min									
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	0						6		0	6	1	6									
				Max Relationship Value in Column	9	9	9	9	9	9	9	9	9	9	9	9									
				Weight / Importance	280.0	280.0	280.0	180.0	300.0	210.0	390.0	210.0	130.0	310.0	190.0	180.0									
				Relative Weight	9.5	9.5	9.5	6.1	10.2	7.1	13.3	7.1	4.4	10.5	6.5	6.1									

Legend	
⊙ Strong Relationship	9
○ Moderate Relationship	3
▲ Weak Relationship	1
++ Strong Positive Correlation	
+ Positive Correlation	
− Negative Correlation	
▼ Strong Negative Correlation	
▼ Objective Is To Minimize	
▲ Objective Is To Maximize	
x Objective Is To Hit Target	

Powered by QFD Online (http://www.QFDOnline.com)

Figure 3: House of Quality

QFD Ranking

Based upon the survey results and the HOQ, we ranked our top deliverables as follows:

1. Robot is a horizontal spinner
2. Ability to drive inverted
3. Stay within 12-lb weight limit

4. Lightweight Armor (TPU)
5. Robot speed for maneuverability
6. Spinner speed for high-energy impact
7. Strong frame for quick repairs and withstand enemy blows
8. Compartmentalized internals for easy replacement of damaged parts

TEAM MEMBERS AND RESPONSIBILITIES

The team members of ButterBot are as follows: Brentin Seman, Elora Bennett, and Sean Myers. Brentin and Elora are studying Mechanical Engineering Technology, and Sean is studying Mechanical Engineering.

Elora is responsible for coordination of team meetings, communication, and organization of documentation. All members are responsible for maintaining the shared document folders in the CAD (Computer Aided Design) software Fusion360. Each team member has been working simultaneously on different design aspects of the robot. The distribution of designing the frame, drive, weapon, and electronics is equal among members and every member is working on each aspect together to optimize the design. This is a strategic plan to ensure that all team members are familiar with the whole design, and that each member understands how any design decisions affect the rest of the design.

EVOLUTION OF DESIGN

DESIGN ALTERNATIVES AND SELECTION

The original design concept was to have a horizontal fly wheel with two identical aluminum plates to create a "sandwiched" assembly design. The armor for the internal components was to be made of UHMW with an integrated plow on the back in case our weapon was to be disabled. This would allow the robot to maintain a method of influencing the opponent to still earn points and win the match, even without the primary form of attack. The flywheel was designed using the golden ratio as inspiration and the robot was designed to be a two-wheel direct drive.

Figure 4: Early CAD Concept

Our next design incorporated a cutout of the top and bottom plates where the motor was set to be mounted as seen below. After configuring the layout of the internal components, the motor needed to be mounted vertically for the weapon and was too big to fit within the frame of the body. The cutout allows the motor to mount securely and to be aligned properly with the energy deliverance system. The flywheel was also changed to a bar spinner because the initial design was too big and negatively impacted the location of the center of gravity which would make maneuvering difficult. By changing the flywheel to a bar spinner, the robot would be able to deliver a stronger impact on opponents. Lastly, the integrated plow on the back of the robot was removed.

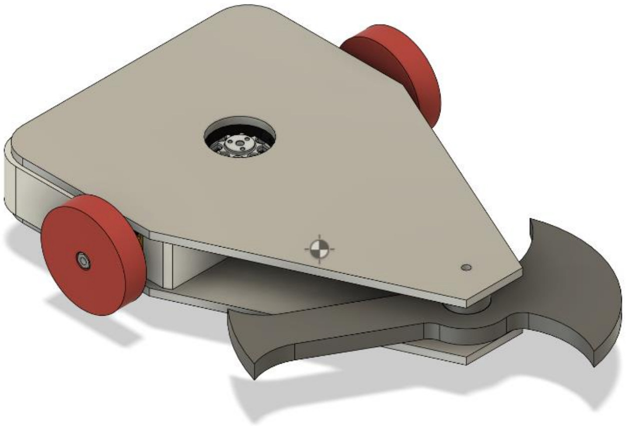


Figure 5: Bar Spinner Design

The original design concept was to have a horizontal fly wheel with two identical aluminum plates to create a “sandwiched” assembly design. The armor for the internal components was to be made of UHMW with an integrated plow on the back in case our weapon was to be disabled. This would allow the robot to maintain a method of influencing the opponent to still earn points and win the match, even without the primary form of attack. The flywheel was designed using the golden ratio as inspiration and the robot was designed to be a two-wheel direct drive.

At this point, the weight of the robot exceeded the 12-pound weight limit, so cutouts were added to the bottom and top plates to reduce weight. We also needed a way to fasten the top and bottom plates to “sandwich” the armor and internal components, so two .25in diameter bolts at a length of 2.25in were added. A small jut out had to be added on both sides of the robot to accommodate the space needed for internal components. This was also effective in creating a “toast” look to the body of the robot and keeping the theme of ButterBot. These bolts would also act as a mounting point for a plow like the one shown to the right to go on the back of the robot for more defense and controlling aspects. Other mounting points were added on the UHMW armor on the back of the robot to mount forks if desired. The weapon design was also changed to decrease the weight further while maintaining a similar moment of inertia.

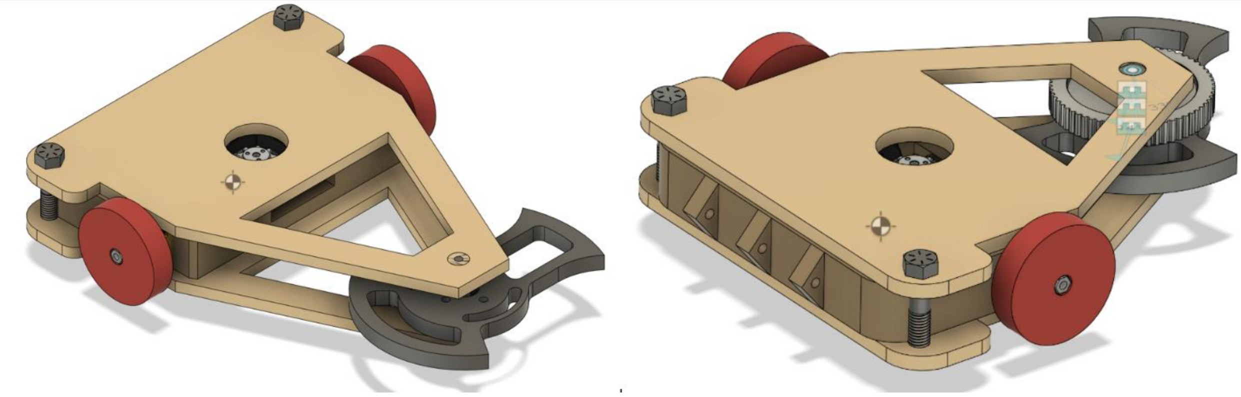


Figure 6: Center of Mass and Spinner Weight

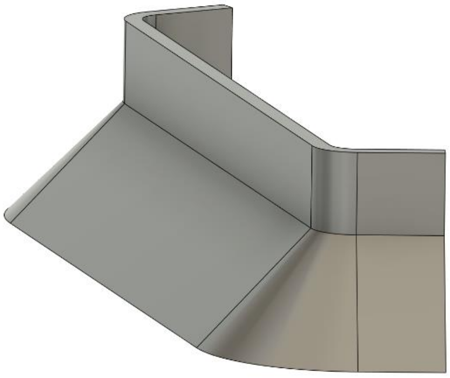


Figure 7: Plow Concept

To further reduce the weight of the robot, a large cutout was taken out of the top plate to allow for easy access to the internal components for maintenance and repairs. The cover plate material was chosen to be carbon fiber because it is lightweight and would protect the internals from any debris or possibly absorb a fair amount of energy if the opponent were to hit this part of the robot. Two more bolts from above were added to the front side of the body to increase security of the top and bottom plates. Holes were also drilled in the energy deliverance system pulley for weight reduction. The pulley belt was also added for further completion of the assembly and more accurate weight calculations.

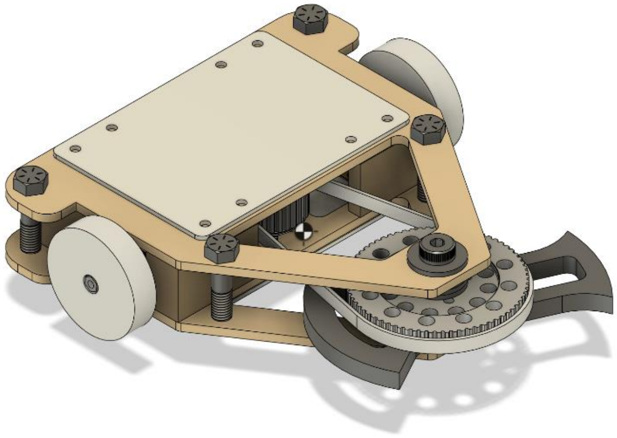


Figure 8: Final Spinner Design and Center of Mass

Another component that went through a couple design iterations would be the tires. In the previous models, there were cylindrical placeholders to assist in getting the clearance of the robot as well as spacing and configurations. The first design for the tires as seen below and to the left was a custom designed TPU core and a cast urethane tire tread. The 1313 Hyper Hub clamp was going to be mounted on the back of the TPU core and then clamped onto the drive shaft. Although this design was more aesthetic, having the clamp externally mounted increased the needed length for the drive shaft as well as increased the stresses acting on the shaft. The new tire design as seen below to the right was available through the club and incorporates and integrated clamp within the TPU core. This shortens the distance between the tire and body as well as helps disperse the forces applied to the tire within the tire itself.

Figure 9: Early Wheel and Drive System Assembly

The current state of the design as shown below incorporates all of the previous design decisions but refined to make the robot more aesthetic. The cutouts on the top and bottom plates between the spinner and body have smoother curves and are less blocky. One additional feature added to the final design is slots on the top and bottom plates next to where the motor is mounted to allow tension of the pulley belt. The carbon fiber cover plate is fastened with small screws and the energy deliverance system pulley no longer is riddled with holes. Through design modification and optimization of parts, less weight reduction cuts were needed. The new design for the tires has been implemented and all of the proper fasteners, spacers, and bearings have been added. An internal TPU shell for the individual component compartments has also been implemented but is not shown in the figure.

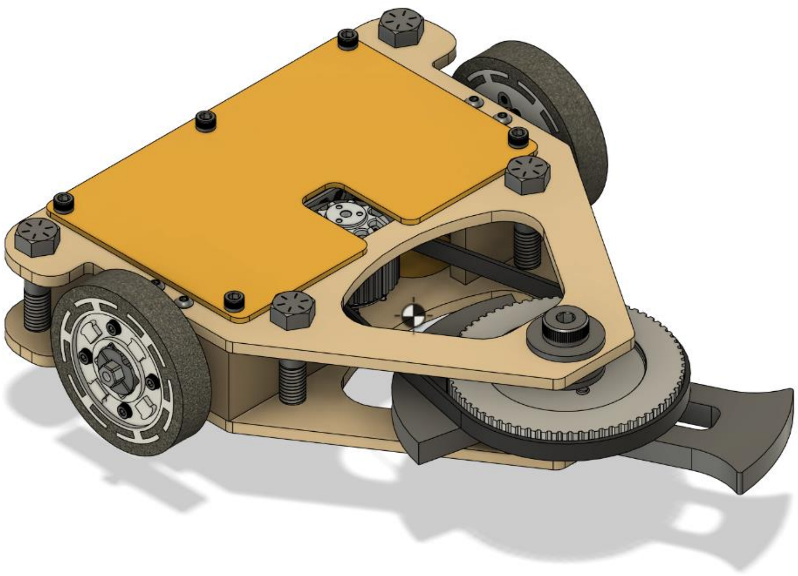


Figure 10: Final Assembly Model

ORIGINAL CONCEPT DRAWINGS

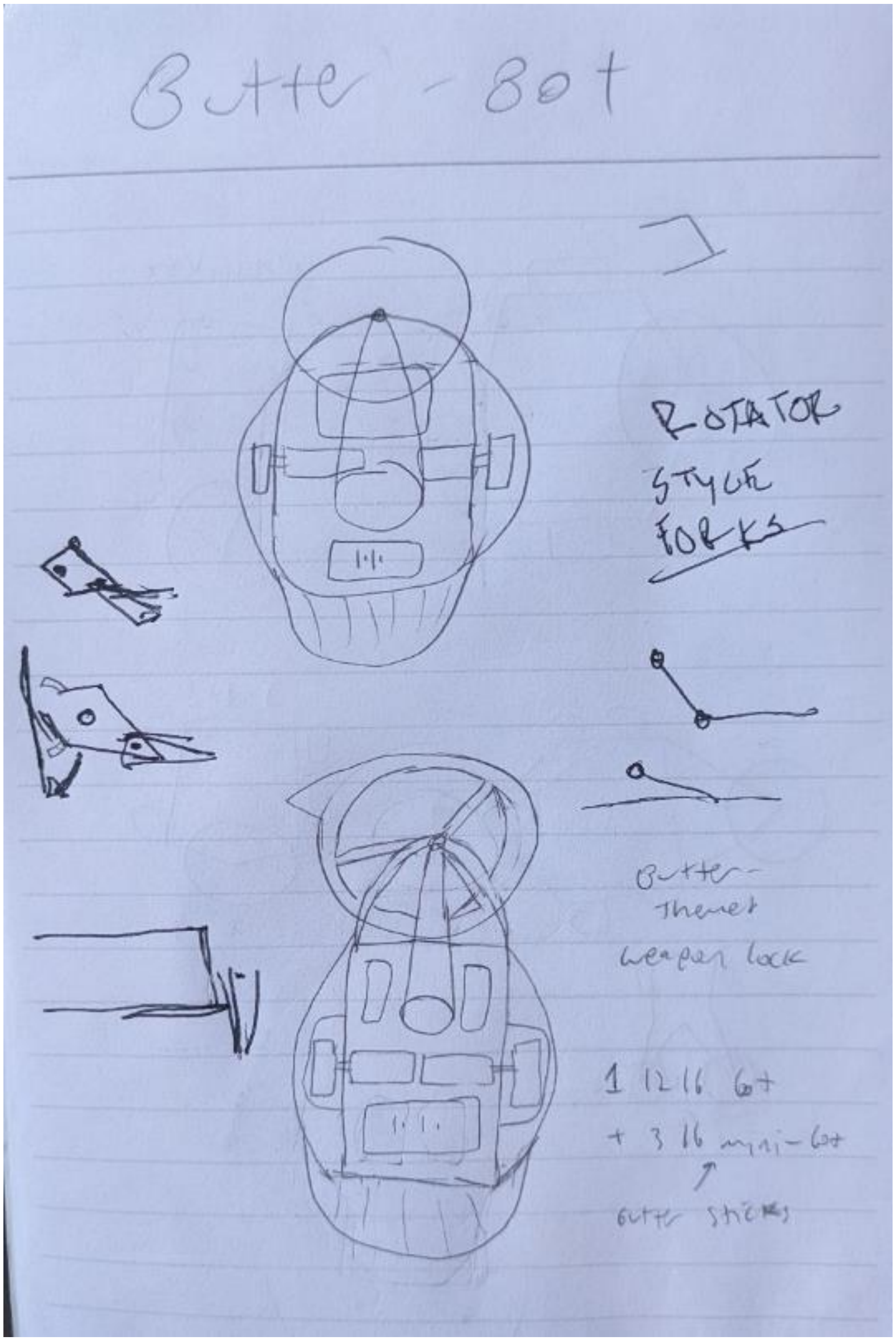


Figure 11: Initial Design Concepts

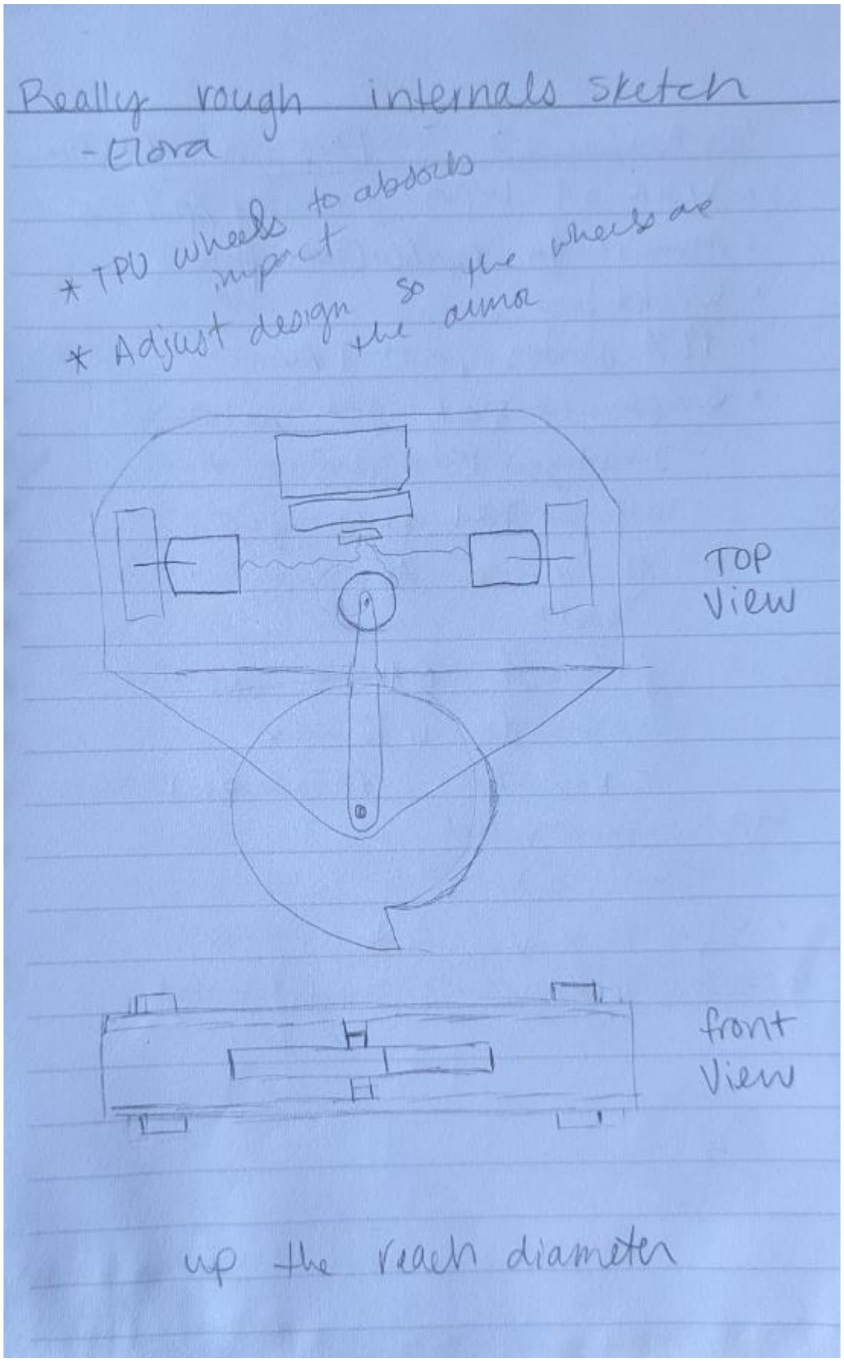


Figure 12: Internal Component Location Sketch-Up

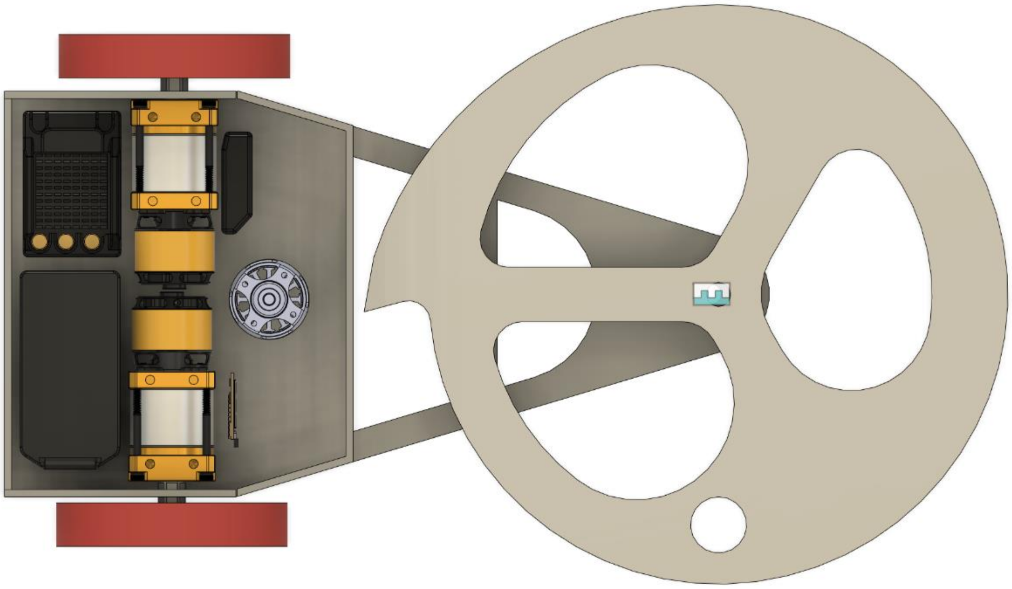


Figure 13: Early Internal Component CAD Layout

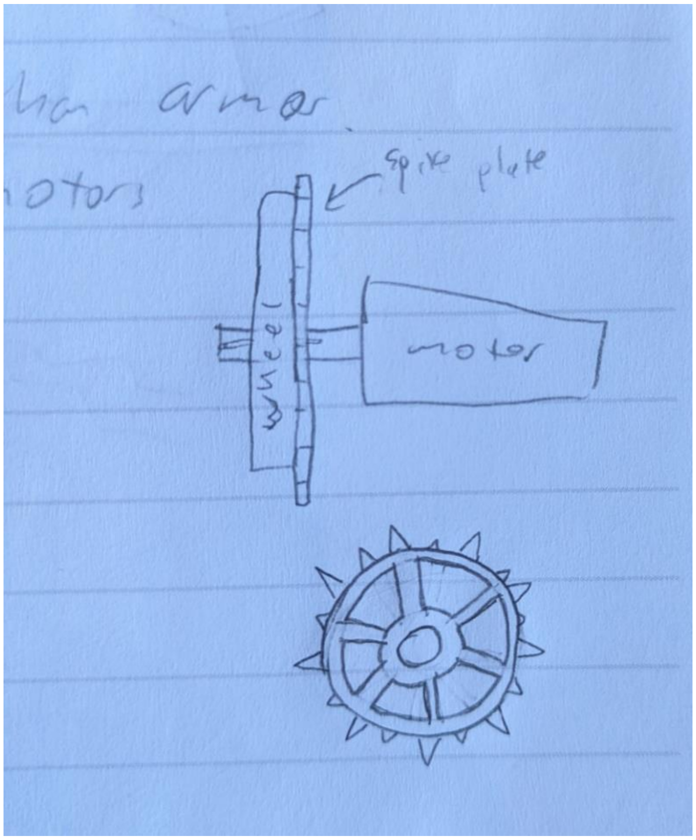


Figure 14: High Grip Wheel Spike Plate

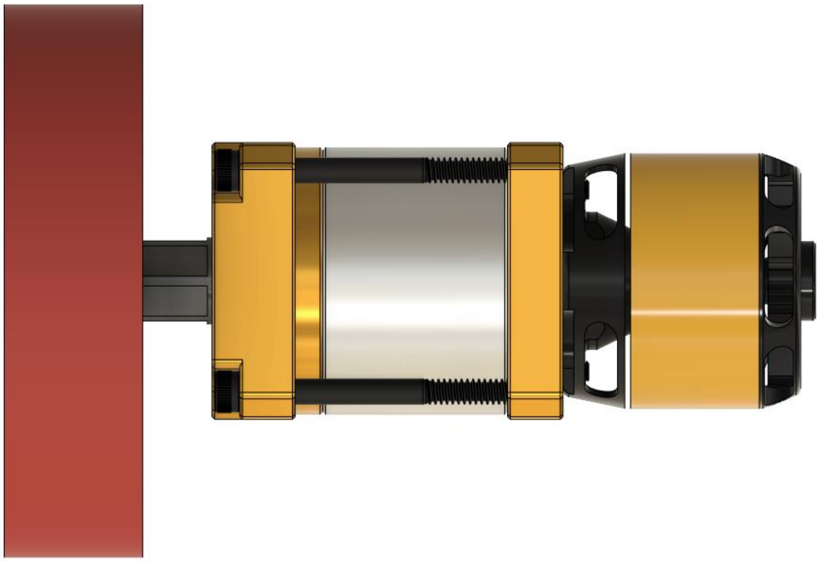


Figure 15: Direct Drive Wheel and Motor assembly

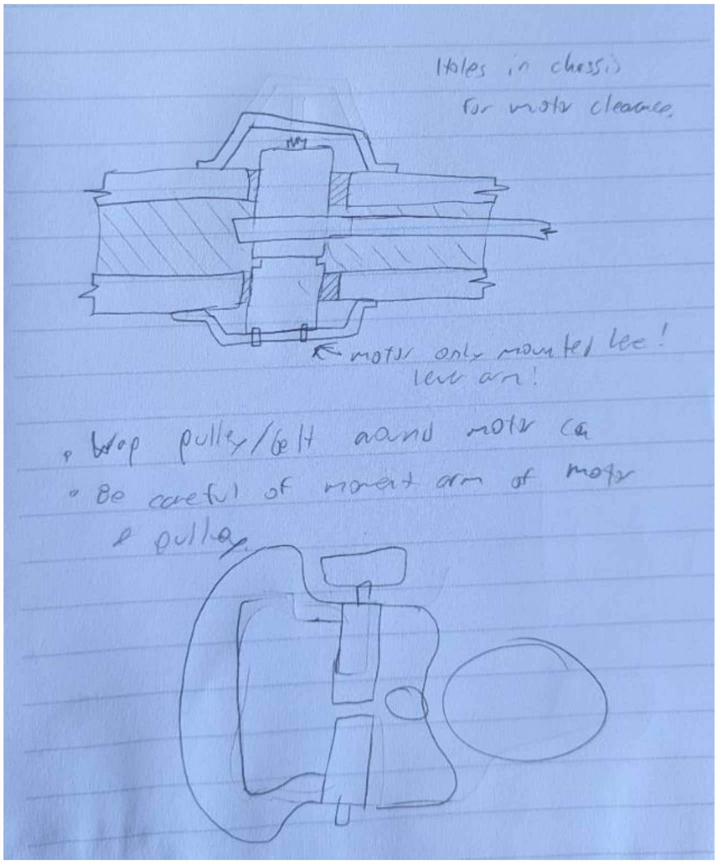


Figure 16: Top: Motor installation Concept. Bottom: Buffer Zone Design

LOADING CONDITIONS

Because the purpose of the spinner is to impact other robots at high speed, an analysis was performed to determine the reactive forces on the spinner as well as to generate an estimate of the maximum possible output force under typical conditions. An aluminum cube was chosen as the impact target. This was chosen because the vast majority of opponents faced in the 12lb weight class will be made of aluminum or softer materials. The spinner was given an initial angular velocity of 1030 rad/s; our maximum velocity based on the gear ratios, spinner diameter, and motor power. It was found that a maximum stress of 19,558 MPa occurred at the tip of the spinner. This exceeds the ultimate yield strength of the spinner by a factor of twelve, however this is not a concern as the tip is expected to become damaged with use. If the tip becomes sufficiently blunted to have a noticeable effect on performance, the spinner may be run in reverse, taking advantage of the fresh tip on the mirror axis.

One of the risk factors for the design is the reactive forces from spinner impact being transferred into the frame and potentially damaging it. To ensure that risk is mitigated, a dynamic stress test was set up to measure the maximum stress in the component. To represent the force being transferred through the spinner shaft into the frame, a bearing load into the frame was set up. A load of 3000 N was used as this is the maximum possible output force that the spinner can produce. It was found that the maximum stress and displacement occurred in the frame truss with a magnitude of 29.469 MPa. Since the yield strength of 7075 Aluminum is 503 MPa, this gives us a safety factor of 17. This exceeds our safety factor goal of 8, indicating that the design will work in these conditions.

DESIGN ANALYSIS

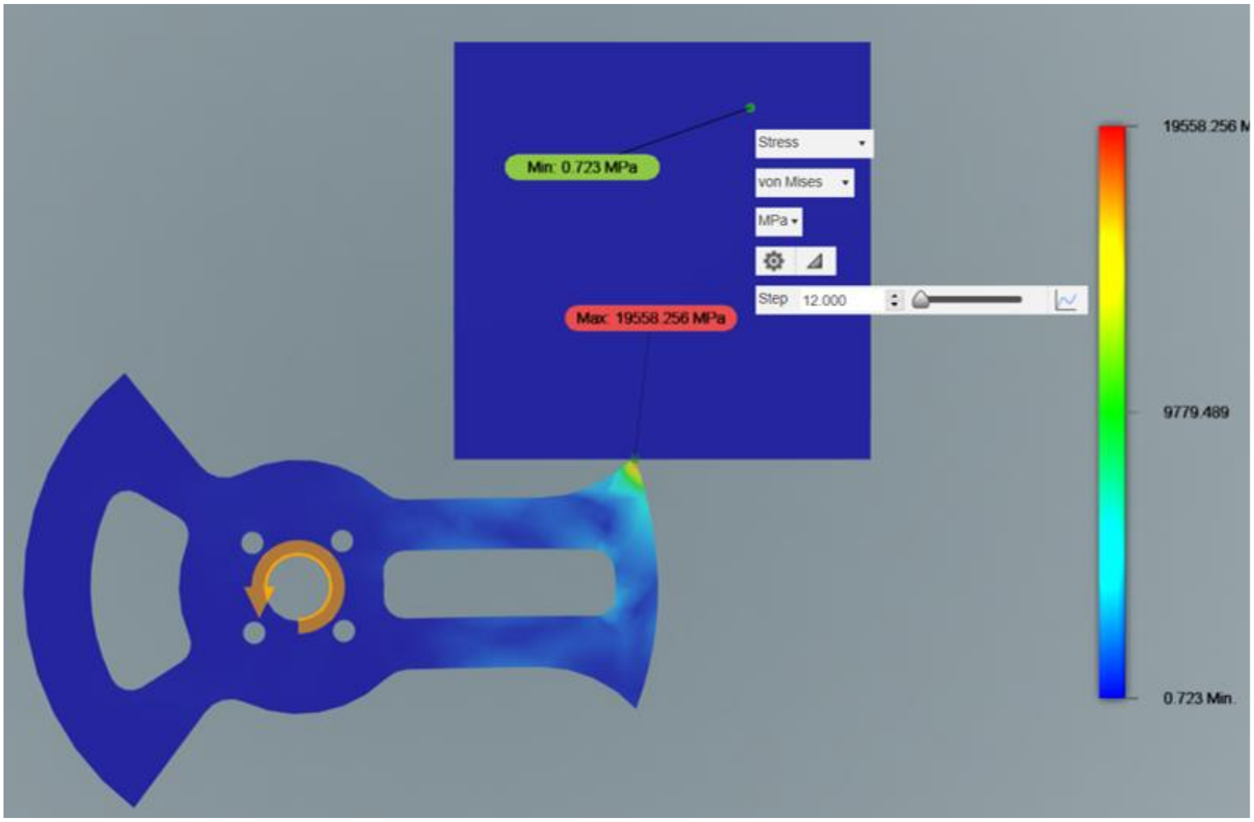


Figure 17: Spinner Dynamic FEA

Theoretical Maximum Force Calculations

Table 5: Maximum Force Parameters

Parameter	Value
m	5.4 kg
g	9.81 m/s^2
h	3 m
I	0.003764 kg m^2
t	2.6 x 10^-4 s

$$PE = mgh = I\omega^2$$

$$\Delta L = I\Delta\omega$$

$$F = \frac{\Delta L}{t}$$

$$PE = (5.4\ kg)\left(9.81\ \frac{m}{s^2}\right)(3\ m) = 159\ J$$

$$\omega = \sqrt{\frac{PE}{I}} = \sqrt{\frac{159\ J}{3.76 \times 10^{-3}\ kg \cdot m^2}} = 206.17\ \frac{rad}{s}$$

$$\Delta L = (3.76 \times 10^{-3}\ kg \cdot m^2)\left(206.2\ \frac{rad}{s}\right) = 0.776\ N \cdot s$$

$$F = \frac{0.776\ N \cdot s}{2.6 \times 10^{-4}\ s} = 2985\ N$$

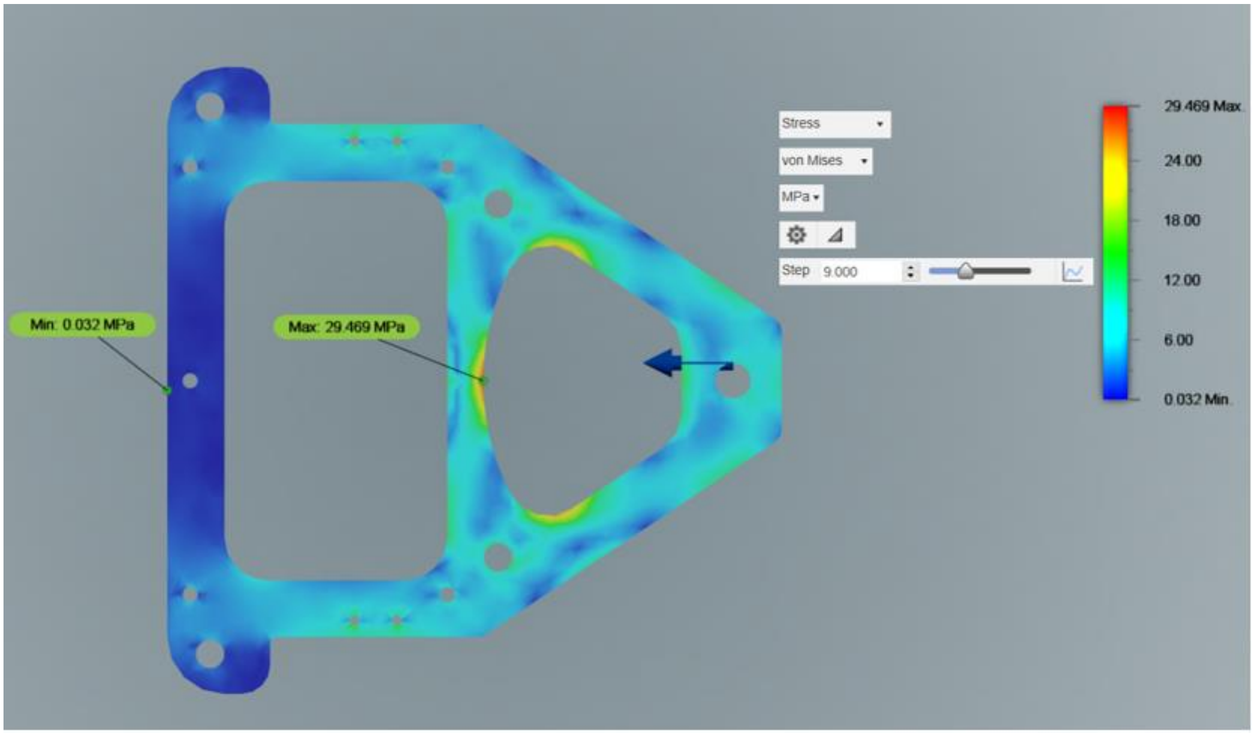


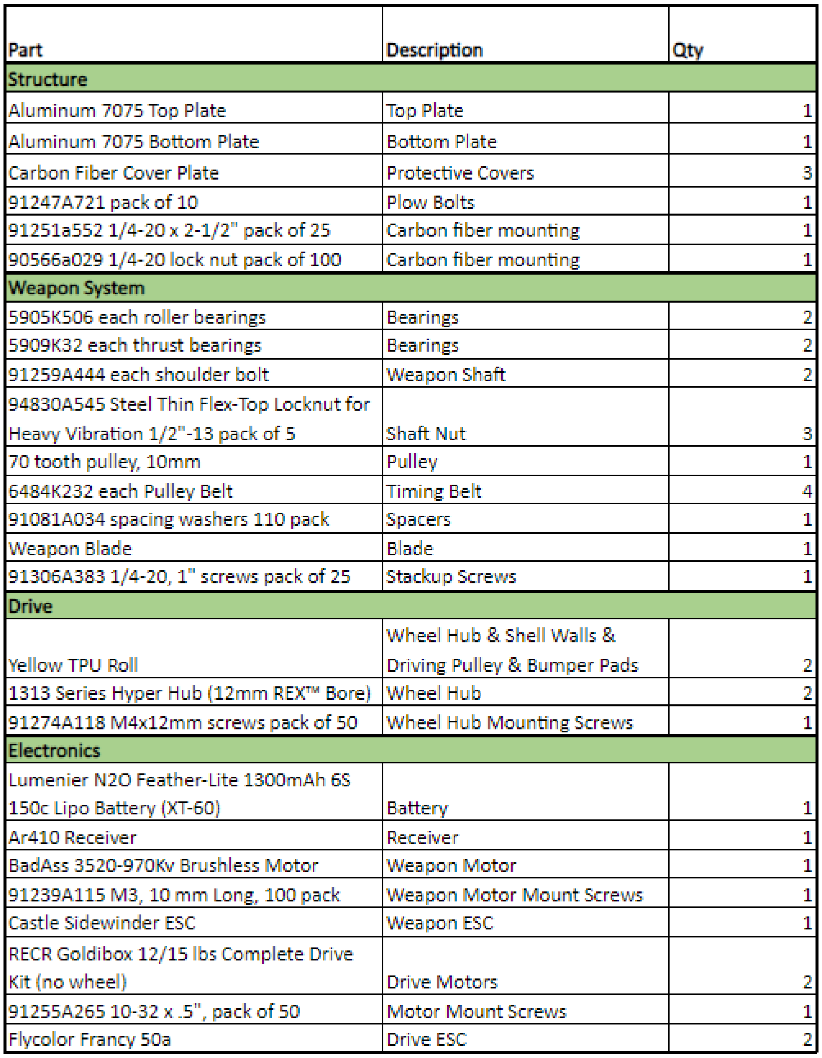
Figure 18: Frame FEA

COMPONENT SELECTION

The frame is made of 7075 Aluminum for its high strength (503 MPa) and relatively high modulus of elasticity (71.7 GPa) (9). This means that the frame will chip when struck, rather than deforming, which is preferred for a part that is designed to support the overall shape of the robot. The core housing structure of the robot will be made of 3D-printed thermoplastic urethane (TPU). This polymer has very high tensile strength which allows it to absorb impact energy by deforming without failing (10). This will allow the part to be made with internal air pockets, thereby reducing the weight of the part, and improving the energy absorption characteristics. To provide access to the robot internals as well as reduce weight, the aluminum frame plates have large port cut outs. The cover plates needed to have a high strength to weight ratio. Carbon fiber has a density of 1440 kg/m^3 and 4205 MPa (11), making it ideal for this application. The spinner will be made of AR500 steel, an alloy steel with very high hardness (450 BHN) and very high strength (1379 MPa) (12) (13), making it ideal for high impact applications.

BILL OF MATERIALS

Table 6: Bill of Materials



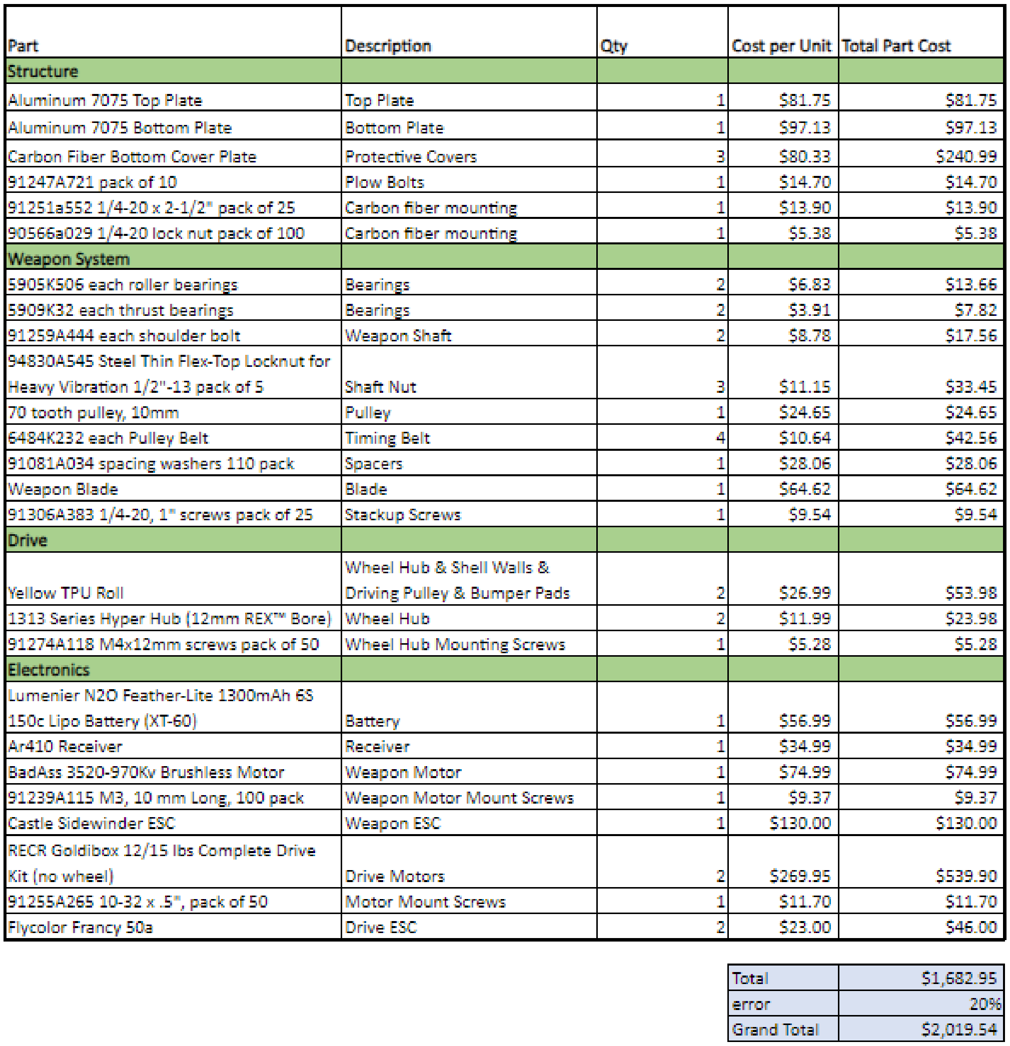
Part	Description	Qty
Structure		
Aluminum 7075 Top Plate	Top Plate	1
Aluminum 7075 Bottom Plate	Bottom Plate	1
Carbon Fiber Cover Plate	Protective Covers	3
91247A721 pack of 10	Plow Bolts	1
91251a552 1/4-20 x 2-1/2" pack of 25	Carbon fiber mounting	1
90566a029 1/4-20 lock nut pack of 100	Carbon fiber mounting	1
Weapon System		
5905K506 each roller bearings	Bearings	2
5909K32 each thrust bearings	Bearings	2
91259A444 each shoulder bolt	Weapon Shaft	2
94830A545 Steel Thin Flex-Top Locknut for Heavy Vibration 1/2"-13 pack of 5	Shaft Nut	3
70 tooth pulley, 10mm	Pulley	1
6484K232 each Pulley Belt	Timing Belt	4
91081A034 spacing washers 110 pack	Spacers	1
Weapon Blade	Blade	1
91306A383 1/4-20, 1" screws pack of 25	Stackup Screws	1
Drive		
Yellow TPU Roll	Wheel Hub & Shell Walls & Driving Pulley & Bumper Pads	2
1313 Series Hyper Hub (12mm REX™ Bore)	Wheel Hub	2
91274A118 M4x12mm screws pack of 50	Wheel Hub Mounting Screws	1
Electronics		
Lumenier N2O Feather-Lite 1300mAh 6S 150c Lipo Battery (XT-60)	Battery	1
Ar410 Receiver	Receiver	1
BadAss 3520-970Kv Brushless Motor	Weapon Motor	1
91239A115 M3, 10 mm Long, 100 pack	Weapon Motor Mount Screws	1
Castle Sidewinder ESC	Weapon ESC	1
RECR Goldibox 12/15 lbs Complete Drive Kit (no wheel)	Drive Motors	2
91255A265 10-32 x .5", pack of 50	Motor Mount Screws	1
Flycolor Francy 50a	Drive ESC	2

PROJECT MANAGEMENT

BUDGET

An adjusted BOM below shows the cost and quantity of each package of the parts in the ButterBot assembly, showing the cost of each part. This is the cost of the raw materials and the cost of subassemblies. The raw materials that are needed are the TPU plastic used for the wheels, TPU material for the armor/frame of the robot, and AR500 steel, aluminum, and carbon fiber sheets and carbon fiber for the armor and spinner of the robot, as well as the different hardware like screws, nuts, washers, and bearings. The purchased subassemblies include the motors for the wheels and the weapon, the battery, the two ESCs, and the receiver. The weapon blade will be outsourced and arrive as a cut part. The budget for the base materials is $1682.95, so with a 20% buffer for errors and re-orders, our final budget is $2000. In addition to the $2000 for the robot assembly, Team ButterBot has received a generous donation of $300 from Bob's Backyard Barbeque that will be used to cover travel costs for the NHRL competition in March.

Table 7: Adjusted BOM



Part	Description	Qty	Cost per Unit	Total Part Cost
Structure				
Aluminum 7075 Top Plate	Top Plate	1	$81.75	$81.75
Aluminum 7075 Bottom Plate	Bottom Plate	1	$97.13	$97.13
Carbon Fiber Bottom Cover Plate	Protective Covers	3	$80.33	$240.99
91247A721 pack of 10	Plow Bolts	1	$14.70	$14.70
91251a552 1/4-20 x 2-1/2" pack of 25	Carbon fiber mounting	1	$13.90	$13.90
90566a029 1/4-20 lock nut pack of 100	Carbon fiber mounting	1	$5.38	$5.38
Weapon System				
5905K506 each roller bearings	Bearings	2	$6.83	$13.66
5909K32 each thrust bearings	Bearings	2	$3.91	$7.82
91259A444 each shoulder bolt	Weapon Shaft	2	$8.78	$17.56
94830A545 Steel Thin Flex-Top Locknut for Heavy Vibration 1/2"-13 pack of 5	Shaft Nut	3	$11.15	$33.45
70 tooth pulley, 10mm	Pulley	1	$24.65	$24.65
6484K232 each Pulley Belt	Timing Belt	4	$10.64	$42.56
91081A034 spacing washers 110 pack	Spacers	1	$28.06	$28.06
Weapon Blade	Blade	1	$64.62	$64.62
91306A383 1/4-20, 1" screws pack of 25	Stackup Screws	1	$9.54	$9.54
Drive				
Yellow TPU Roll	Wheel Hub & Shell Walls & Driving Pulley & Bumper Pads	2	$26.99	$53.98
1313 Series Hyper Hub (12mm REX™ Bore)	Wheel Hub	2	$11.99	$23.98
91274A118 M4x12mm screws pack of 50	Wheel Hub Mounting Screws	1	$5.28	$5.28
Electronics				
Lumenier N2O Feather-Lite 1300mAh 6S 150c Lipo Battery (XT-60)	Battery	1	$56.99	$56.99
Ar410 Receiver	Receiver	1	$34.99	$34.99
BadAss 3520-970Kv Brushless Motor	Weapon Motor	1	$74.99	$74.99
91239A115 M3, 10 mm Long, 100 pack	Weapon Motor Mount Screws	1	$9.37	$9.37
Castle Sidewinder ESC	Weapon ESC	1	$130.00	$130.00
RECR Goldibox 12/15 lbs Complete Drive Kit (no wheel)	Drive Motors	2	$269.95	$539.90
91255A265 10-32 x .5", pack of 50	Motor Mount Screws	1	$11.70	$11.70
Flycolor Francy 50a	Drive ESC	2	$23.00	$46.00

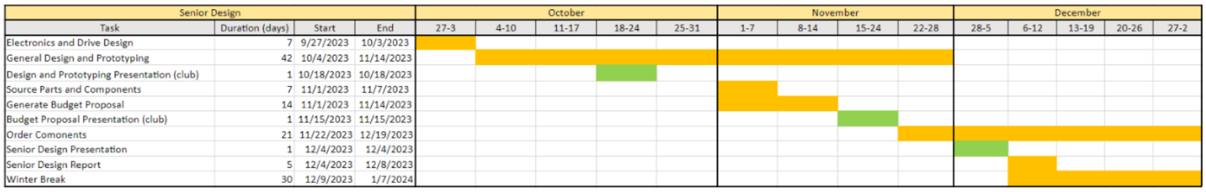
Total	$1,682.95
error	20%
Grand Total	$2,019.54

SCHEDULE

The expected schedule for Senior Design I and Senior Design II is illustrated in the first GANTT Chart below. The green highlighted boxes were the major presentations we had during the Fall semester. It included two design presentations with UC Combat Robotics Club, and one presentation to faculty for Senior Design II. This was the proposed schedule, but because it was structured around the club meetings for UC Combat Robotics, we were able to complete all objectives on time.

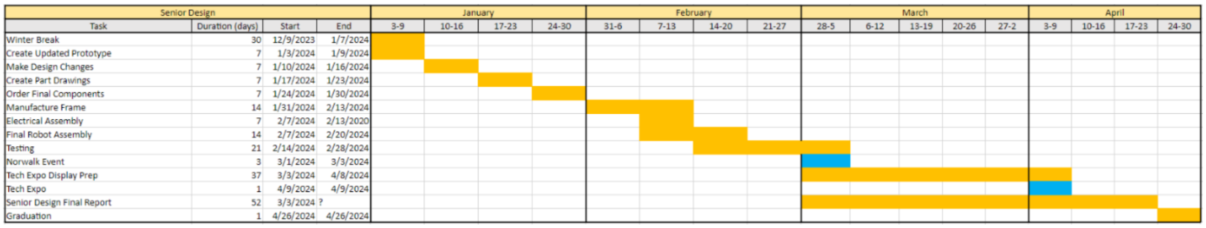
Senior Design III is outlined in the second GANTT Chart. Major dates are highlighted in blue. The first is the NHRL Competition in Norwalk, Connecticut on March 1-3, and the second is the Tech Expo on April 9. Other major features of this proposed schedule are creating a design prototype, and making any necessary design changes, as well as manufacturing major components.

Table 8: Senior Design I & II Gantt Chart



Senior Design				October					November				December				
Task	Duration (days)	Start	End	27-3	4-10	11-17	18-24	25-31	1-7	8-14	15-24	22-28	28-5	6-12	13-19	20-26	27-2
Electronics and Drive Design	7	9/27/2023	10/3/2023	🟨													
General Design and Prototyping	42	10/4/2023	11/14/2023		🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨					
Design and Prototyping Presentation (club)	1	10/18/2023	10/18/2023				🟩										
Source Parts and Components	7	11/1/2023	11/7/2023						🟨								
Generate Budget Proposal	14	11/1/2023	11/14/2023						🟨	🟨							
Budget Proposal Presentation (club)	1	11/15/2023	11/15/2023								🟩						
Order Comonents	21	11/22/2023	12/19/2023									🟨	🟨	🟨	🟨	🟨	🟨
Senior Design Presentation	1	12/4/2023	12/4/2023										🟩				
Senior Design Report	5	12/4/2023	12/8/2023											🟨			
Winter Break	30	12/9/2023	1/7/2024											🟨	🟨	🟨	🟨

Table 9: Senior Design III Gantt Chart



Senior Design				January				February				March					April			
Task	Duration (days)	Start	End	3-9	10-16	17-23	24-30	31-6	7-13	14-20	21-27	28-5	6-12	13-19	20-26	27-2	3-9	10-16	17-23	24-30
Winter Break	30	12/9/2023	1/7/2024	🟨																
Create Updated Prototype	7	1/3/2024	1/9/2024	🟨																
Make Design Changes	7	1/10/2024	1/16/2024		🟨															
Create Part Drawings	7	1/17/2024	1/23/2024			🟨														
Order Final Components	7	1/24/2024	1/30/2024				🟨													
Manufacture Frame	14	1/31/2024	2/13/2024					🟨	🟨											
Electrical Assembly	7	2/7/2024	2/13/2020						🟨											
Final Robot Assembly	14	2/7/2024	2/20/2024						🟨	🟨										
Testing	21	2/14/2024	2/28/2024							🟨	🟨	🟨								
Norwalk Event	3	3/1/2024	3/3/2024									🟦								
Tech Expo Display Prep	37	3/3/2024	4/8/2024									🟨	🟨	🟨	🟨	🟨	🟨			
Tech Expo	1	4/9/2024	4/9/2024														🟦			
Senior Design Final Report	52	3/3/2024	?									🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	
Graduation	1	4/26/2024	4/26/2024																	🟨

The key milestones of this project are based on the UC Combat Robotics club semester schedules and Senior Design I, II, and III major milestones. The tasks are the expected major design and manufacturing milestones. The goal of the schedule is to keep the ButterBot team on-task each week.

Table 10: Significant Milestones

Milestone	Date
Design and Prototyping Presentation (club)	10/18/2023
Budget Proposal Presentation (club)	11/15/2023
Senior Design II Presentation	12/4/2023
Create Updated Prototype	1/9/2024
Testing	2/14/2024 - 2/281024
Norwalk Event	3/1/2024 - 3/3/2024
CEAS Tech Expo	4/9/2024

COMPETITION RESULTS

On March 2nd, 2024, ButterBot competed in the National Havoc Robot League. The competition is divided into two parts: qualifiers and tournament. The qualifiers are run as a double elimination bracket. That means competitors must win two out of three matches to be entered into the single-elimination tournament bracket.

Before the competition, it was discovered that the spinner drive pulley had a serious design flaw related to the material selection. This flaw is further detailed in areas of improvement. To prepare for competition the next day, the spinner drive speed was capped at 50%, the pulley was glued to the motor, and tape was used to create a temporary flange. This was effective at returning the spinner to operation.

ButterBot competed against three opponents: Ambiguously Dynamic Duo, Tough Love, and Creature. Ambiguously Dynamic Duo (ADD) was a team comprised of two identical flamethrower bots. Upon beginning the match, we discovered that our left drive and spinner were both non-functional. Due to this, ADD was able to flank and begin to melt ButterBot until tap out. After the match ButterBot was disassembled to perform repairs and inspect for damage. Fortunately, the only damage sustained was cosmetic. It was found that the bot was fastened too tightly, preventing the spinner from moving. The drive issue was determined to be due to a fault in the left drive ESC but there was not enough time to repair it.

The second match was against Tough Love, a four-wheel horizontal undercutter. The left drive was still non-functional but the spinner was in working condition. ButterBot was able to move by “crab-walking,” a method of locomotion that involves using the bot’s own momentum to throw itself in a controlled direction. In the beginning of the match, Tough Love’s spinner shaft sheared and the spinner was disabled for the rest of the match. ButterBot was able to pursue Tough Love and attack with its own spinner, securing a win by judge’s decision. After the match the faulty drive ESC was replaced and ButterBot was restored to full functionality. It was found that the source of the fault was a solder joint that had broken.

In the third match, ButterBot faced another multibot team. Creature was comprised of a small horizontal spinner and a lifter bot, designed to gain control points by pinning and flipping its opponent. ButterBot was fully functional in all regards and was able to temporarily demobilize the spinner as well as attack the lifter with several large hits. Due to ButterBot’s invertible design, the lifter was unable to effectively impact its maneuverability. Unfortunately, about two minutes into the match the spinner drive pulley ceased functioning and the judges gave the win to Creature. It was found that the tape used as a flange on the weapon motor pulley had rubbed against the top frame, generating fibers that became caught in the motor and stopped it. Because ButterBot lost two of its three matches it did not qualify for tournament competition.

AREAS OF IMPROVEMENT

There are three main areas team ButterBot could improve the design. These areas are the spinner pulley system, electronics, and assembly.

SPINNER PULLEY SYSTEM

The drive pulley had several design flaws. It was designed to be made of 3d-printed TPU and to press-fit onto the spinner motor. The friction of the press-fit was the only thing holding the pulley to the motor, although the outrunner of the motor does have mounting holes. The pulley was designed for simplicity of assembly, so we thought that the friction fit would be enough to hold the pulley to the motor. This was not the case once the spinner motor was tested at full speed with the pulley on it. When the motor was tested with the friction fit pulley, it resulted in the pulley expanding and losing connection with the motor because of the stress put onto the TPU from the rotational forces of the motor spinning. When the motor was spinning, the pulley also would “float” up and down along the axis of rotation because it had expanded enough not to have connection with the motor anymore. There are a couple ways to fix this issue with the spinner pulley. The pulley could be made out of nylon instead of TPU, or it could be made out of aluminum. Benefits of making the pulley out of nylon would be that it keeps the weight of the pulley low like the TPU while providing more rigidity in the pulley than the TPU did. It is unknown, however, if the nylon would behave the same way by expanding and “floating” on the motor at high speeds, or if it would stay press fit to the motor. The nylon pulley would need to be both press-fit and mounted to the motor using the mounting holes mentioned above as well to prevent the “floating” effect. Alternatively, the pulley could be made from aluminum. An aluminum pulley would need to be mounted to the motor by the mounting screws. This would ensure that there is enough rigidity in the pulley that would not expand or "float" along the motor. The main downside to an aluminum pulley that would mount to the spinner motor is that it would take up a greater percentage of the total robot weight than a nylon pulley. Between the two options, the aluminum pulley would be more reliable and would ensure a working pulley.

Another major flaw of the pulley system is that there were no flanges that would keep the timing belt aligned on the pulley attached to the spinner and the pulley attached to the motor. The timing belt started to travel up and down both pulleys when it was not perfectly aligned. The pulley attached to the spinner did not have flanges because the one that was ordered did not get delivered before the competition, so we had to waterjet the pulley instead so that we could have a working spinner. The temporary fix was to 3d print flanges, but when competing against the flamethrowers the printed flanges melted, and when competing against other spinners the impacts between robots broke the flanges. The 3d printed pulley attached to the motor was not designed with flanges, which led to problems during spin-up as mentioned before- the timing belt was traveling up and down the pulley. Designing the pulley to have flanges would have prevented the travel of the timing belt around the motor and kept it aligned better with the pulley attached to the spinner.

Finally, the last major flaw of the spinner pulley assembly was that we had made slots in the bottom frame where the spinner motor mounted so that the timing belt was able to be tensioned. The slots were made so that the motor could be completely loosened so that the timing belt is no longer meshed with the pulley on the motor. This seemed to be a good idea, but the mounting screws are only four M4 screws and were unable to hold the motor in place on large impacts with opponents. In the future, there would not be a tensioning system and the mounting holes would be fixed instead.

ELECTRONICS

One of the major errors that occurred during the competition was faulty electronics. The left-side drive motor was having trouble spinning up to full speed to match the right-side drive motor. At first, we thought that the motor itself was bad, so we replaced it, but the same problem occurred. After further investigation on the wiring harness, we found a broken solder joint where the drive ESC connected to the motor. This could have had many reasons, but two main issues were identified. First, the solder joint was clearly not done well and was not adhered correctly between the wire and the ESC. Second, the volume inside the robot where all of the wires and electronics were housed was too small, causing joints like this one to be bent at extreme angles in order to shut the robot. Between the poor connection and the extreme angle, it could have been bent at, the connection broke and caused the drive motor to be unreliable.

ASSEMBLY

The assembly of the robot is a “sandwich” design, where the armor is placed between the frame pieces. This was a good design in general because it made for easy and straight-forward assembly and disassembly. However, it was still a very time-consuming process to disassemble the robot during repairs. If something like the timing belt needed replaced, then the entire robot needed disassembled. This meant that 14 screws needed to be removed just to replace that one part. The frame was held together with five major bolts, to keep the aluminum frame stable, which included the spinner shaft at the front of the robot. The carbon fiber cover plates were also held together with 5 screws that went through the robot to keep them on. Finally, the drive motors were mounted directly to the top and bottom aluminum frame pieces. Having so many fasteners was good to provide structure to the robot, but it did make repairing the robot between matches difficult. The frame could have easily been held together using only the 5 major bolts holding the aluminum frame, and the carbon fiber covers could have been designed to mount to those instead of using 5 separate screws to mount them. Designing it this way would have drastically reduced repair time and made reassembly easier between the rounds of competition, as well as saved on weight because the extra carbon fiber to reach those bolts weighs less than the hardware used to mount the carbon fiber.

SUGGESTIONS FOR CONTINUOUS IMPROVEMENT

If there had been time to better prepare for making the robot, it would have been easier to identify the issues like the assembly taking too long because of how many fasteners there were, as well as there not being enough room inside the robot for all the electronics to fit easily without being bent too much.

There could be several ways to improve the design process of a combat robot. The first recommendation is to make a cardboard mock-up of the robot, or a fully 3d printed version to see how everything fits together. This would provide insight into complications like what we ran into, mentioned above. The second improvement is to ensure that there are flanges on any pulleys. This will ensure that the belt will not slip off or start traveling to undesired places within the assembly. The third suggestion is to order any outside-manufactured parts needed well ahead of time, and through a reliable source. The fourth suggestion is to test any 3d printed parts, especially those that are used on any moving parts like any motors or the “weapon” subassembly. Finally, any electronic connections need to be checked for quality and durability. If the connection is fragile, it should be re-done to strengthen it and make sure that it can handle the use and abuse it will endure during competition.

CONCLUSION/SUMMARY

Over the span of about 5 months, our team has come up with concept ideas, drawings, CAD models, a functioning prototype, and competed in a competition against other robots, many of which had far more experience than what we possessed. For each member of Team ButterBot, this was our first combat robot building experience, and we are proud to have accomplished having a functional robot and finding victory in our first competition. Building Butterbot from an idea to a physical prototype that worked (for the most part) within five months was an accelerated schedule that visibly impacted our final product. Even with working at a rapid pace and having no experience with robot building, we are proud of our progress and had a blast while doing it.

Having an accelerated schedule and building a robot from the ground up required our team to actively practice time management. To accomplish our goals that were set by both our team and the UC Combat Robotics Club, we met every Wednesday to discuss overall goals and milestones with the club as well as progress updates to make sure we were on track to completing the robot before competition. In addition to the club meeting, our team decided to meet every Tuesday to work collaboratively on the robot and have rapid feedback from each other on ideas and steps moving forward within the project. During these individual team meetings, we set our specific goals and allocated work to group members, so if the work was not completed within our meeting time, each member would know what was expected of them for the week. Setting weekly goals allowed our members to stay on task and facilitated greater progress for the group. It also made the whole project of making a combat robot less daunting by breaking up the major milestones into manageable tasks. Throughout the course of our project, our team was able to maintain a high level of punctuality and quality of work; what was completed for each milestone was thought out and developed through trial and error, not just a placeholder idea. Because our schedule set by the club and the competition was at a faster pace than the senior design classes of the college, the stress of these deadlines was non-existent and made finishing these assignments as simple as submitting what we already had or adding a little more detail.

Since we had little stress during the design phase, our stress had to come during our fabrication, assembly, and testing phases. Unfortunately, just because concepts work within the CAD model, they do not always translate directly to the actual product. When creating our schedule for milestones, we learned from previous teams that the fabrication and assembly stages were going to need more critical time management. Due to long lead times on our ordered parts and our fabricated components, we took every bit of the time allotted for fabrication and assembly. ButterBot was designed to implement “sandwich” assembly methods and to begin our assembly, we needed our top and bottom body plates. We did not receive these until well into our assembly phase, so we did not have much to do for much of this phase. When we did receive our parts, it was a mad dash to assemble everything. Thankfully, we were generous with our planning for this phase and we were still able to assemble everything before our competition date. Our success as a group was greatly in part to having a structured schedule and adhering to critical time management practices.

Another key to our success was our division of powers, allowing members to “specialize” in certain areas of the robot. We still had members participate in discussion and share ideas when faced with a problem, but there was still a member that was an expert for that field. Our designated leader of the group, Elora Lopane, was great at communicating expectations of members and required tasks to meet and maintain deadlines as well as the design of the energy transferal system. Sean Myers was the expert on the internal components and electronics, programming the controllers, and the force analysis of the robot during testing. Brentin Seman was the expert on the assembly of the robot, drive system, and the driver of the group. Having people specialize in a field was pivotal in allowing quick repairs and adjustments during our breaks between matches. Decisions could also be made quicker by having a leader for the problem and input from other members. Having structure within the group and designating leaders for the group or specific tasks is integral to being successful within a team environment.

In addition to time management and team structure contributing to our success, implementing practical engineering practices helped alleviate stresses of assembly and repairs. For example, we designed for manufacture by having simple geometry for components; things that could have a flat drawing and be manufactured on a water jet table. This reduced the price of these parts if they were ordered, and the simple geometry made fabricating these parts ourselves by utilizing the resources provided by the university far easier. Another example of practical engineering would be designing for assembly and repair. Our “sandwich” design allowed for the robot to be assembled quickly and have easy access for repairs. This was pivotal in allowing our team to troubleshoot, fix, and adjust the robot in the short breaks between matches.

Throughout the course of this project, our team worked to maintain effective time management, establish structure and leaders within the group, and utilize practical engineering practices. By adhering to these principles, we were able to build a robot that was able to compete in a highly competitive environment and find victory at least once. Looking back on our experiences with this project, we can say that we actually had fun and enjoyed the process, the fruits of our labors. Going forward, combat robotics is something that our members have considered continuing, building upon our experiences and the knowledge that we gained.

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APPENDIX A

WEIGHT CLASSES

NHRL offers 3 different weight classes to compete in: 3lb, 12lb and 30lb. All robots must be at or below the maximum weight listed for their respective weight class at the start of the fight. In any given class, additional weight allowances may be allotted to entrants that meet certain criteria.

MULTIBOT BONUS

- Any competitor with multiple independent robots fighting under a single name qualifies for the Multibot Bonus. Each bot in a Multibot must have independent active control and be capable of influencing the fight. Only the heaviest bot in a multibot must have an active weapon. Additionally, for a multibot to benefit from the Non-Traditional Locomotion Bonus, only the heaviest segment of the bot needs to meet the criterion to qualify for the weight bonus.
- The weight of any segment of a multibot may not exceed 110% of the ‘base weight’ for its respective weight class, except in the beetleweight class. If the bot also qualifies for the Non-Traditional Locomotion Bonus, the additional weight may also be factored into the base weight.
- For example, the heaviest segment of a 12-pound multibot may not exceed 13.2 lbs. However, if the robot also qualifies for the shuffler weight bonus, the maximum weight of the heaviest segment increases to 19.8 lbs. (18lbs x 110%).
- Competitors may choose to forgo their multibot bonus so long as their robot still meets the base weight for their weight class. If a competitor’s robot requires the

multibot bonus to make weight, but arrives at the cage with a non-functional multibot, the match will be forfeited.

Weight Class	**Non-Traditional Locomotion**	**Multibot**	**Absolute Maximum**
3 pounds	+2 pounds	+1 pounds	6 pounds total
12 pounds	+6 pounds	+3 pounds	21 pounds total
30 pounds	+15 pounds	+8 pounds	53 pounds total

BATTERIES AND POWER

- Bots must have an easily accessible master power cutoff in the form of a switch or removable link. The power cutoff must be accessible without disassembling the robot in any way. The power cutoff must be able to be deactivated in no more than 15 seconds.
- Nominal battery voltage may not exceed 60 volts for 3lb bots, or 75 volts for 12lb and 30lb bots. It is understood that a fully charged battery pack will have an initial voltage above its nominal Voltage.
- Any robot system that produces voltages above the robot's battery voltage limit must be approved by NHRL and may require additional inspection. Email hello@nhrl.io to discuss your design!

Battery charging must be done safely! Batteries may be charged within your robot, except for robots with flame or heat-based weapons. Unsafe charging procedures may result in a penalty via the demerit system.

SAFE CHARGING PRACTICES:

- Inspect batteries for damage or puffiness before charging.
- A team member must be present while the battery is charging.

- Balance charge leads must be used for any OTS battery that has them.
- Keep a sand bucket or liposafe bag nearby.
- Set an appropriate charge rate based on your battery.
- While not a requirement, it is good practice to make sure your robot has enough power to be idle for up to 3 minutes prior to the start of your fight.

ROBOT CONTROL SYSTEMS

- Robot controls and communication systems must pass a failsafe test. In the event of signal loss or transmitter power-down, the bot's drive system must stop within 30 seconds and weapons must come to a complete stop within 60 seconds.
- All robots and multibots must have a dedicated receiver(s).
- Autonomously controlled robots are allowed, but they must still retain a radio control module that can remotely activate and deactivate the robot.

SIZE REQUIREMENTS

- 3-pound robots must be able to fit into a 30x 30 x 24-inch box.
- 12- and 30-pound robots must be able to fit into a 36 x 36 x 36-inch box.
- In the case of a multibot, all segments of the robot must fit within the box size together.
- Once the match begins, robots are allowed to expand or contract to any size.

WEAPONS

- All entrants must have an active weapon. An active weapon is defined as a weapon or mechanism that operates independently from the robot's drivetrain or means of locomotion.

- “Meltybrains” (bots that can show controlled movement while spinning at rapid speeds), and “Gyro Walkers” (bots that use spinning masses or weapons to generate inertia to induce translational motion) are exempt from this rule. “Thwackbots,” (robots which use momentum created by the robot’s drivetrain to ‘actuate’ an otherwise unpowered weapon) do not qualify as having an active weapon.
- In a multibot, only the heaviest bot is required to have an active weapon.

WEAPON LOCKS

- All weapon systems must have a lock that stops their actuation, extension, expansion, rotation, ignition, etc. Weapons that move or rotate must have a lock or be constrained such that movement is restricted in all directions. Weapons that shoot a projectile or gas must have physical means to prevent firing AND block the expulsion of a projectile. Additionally, all means of fuel storage must be designed to default to the closed position if damaged or removed from the robot.

ADDENDUM ON SPECIFIC WEAPON CLASSIFICATIONS

- Flame and heat-based weapons are allowed. This includes but is not necessarily limited to flamethrowers and low or medium-power rocket motors. Robots with flame and heat-based weapons must be able to self-light and self-extinguish. In the case of signal/communication loss with the transmitter, flame and heat-based weapons must self-extinguish in 30 seconds.
- 3lb robots are allowed up to 8 ounces of fuel. 12lb and 30lb robots are allowed 16 ounces of fuel. Consumable fuel and gases do count towards your overall robot weight.

- NHRL allows the use of propane, butane and other fuel sources that are gaseous at STP (Standard Temperature and Pressure) (standard temperature and pressure). Fuels cannot be self-oxidizing and flame systems must not include additional oxidizing systems (e.g., oxy acetylene torches and similar).
- Matches may be stopped and your robot disqualified if cage equipment, cameras or safety gear, is being damaged by fire.
- Rocket motors (also referred to as rocket engines) and fireworks are not allowed as of May 2023. This may change in the future.
- Drive systems and weapons powered by internal-combustion engines are allowed. Combustion engines may be manually or electrically started during load in, provided they do not cause the weapon to move. Consumable fuel and gases do count towards your overall robot weight.
- Projectile weapons, both tethered and untethered, are allowed. A fired projectile's maximum speed may not exceed 150 miles per hour. Additionally, a tethered projectile must not be designed in a way that is likely to become entangled with the opposing robot.
- Modular weapon systems are allowed. Modular weapon systems are defined as mechanisms, subsystems, or subassemblies that are interchangeable between fights. For example, a modular weapon system may allow a competitor to choose between a horizontal spinner and a vertical spinner configuration between fights.
- No more than 50% of a robot's weight may change between configurations. Additionally, all configurations of the robot must qualify for the same weight bonuses.

- Designs that utilize pneumatics, hydraulics and subsystems using airbags are allowed, but must be approved by NHRL staff through the Design Approval Process.

DESIGN RESTRICTIONS

- Fabric, foam, and other ablative armor are allowed. However, ablative armor must not be designed in such a way that it presents a likely entanglement risk. The decision of what is a likely entanglement risk is up to the discretion of NHRL.
- Entanglement devices are not permitted. An entanglement device is defined as a component, subsystem or armor configuration that is designed to be entangled in the rotational or moving parts of an opponent.
- Liquids expelled from the robot are not permitted; However, liquids expelled from a robot that become gaseous shortly after leaving the robot and/or before hitting the opponent are permitted. Expelled liquids must be gaseous at STP conditions.
- Electrical and shock weapons such as tasers and cattle prods are not permitted.
- Weapons that primarily act by obstructing visibility are not permitted; However, weapons that produce smoke or fog as a by-product of their attack (i.e., rocket motors) are allowed.
- Signal jamming devices or systems which interfere with communication between a robot and its controller are not allowed.