Senior Design: 12-lb. Combat Robot, Richard

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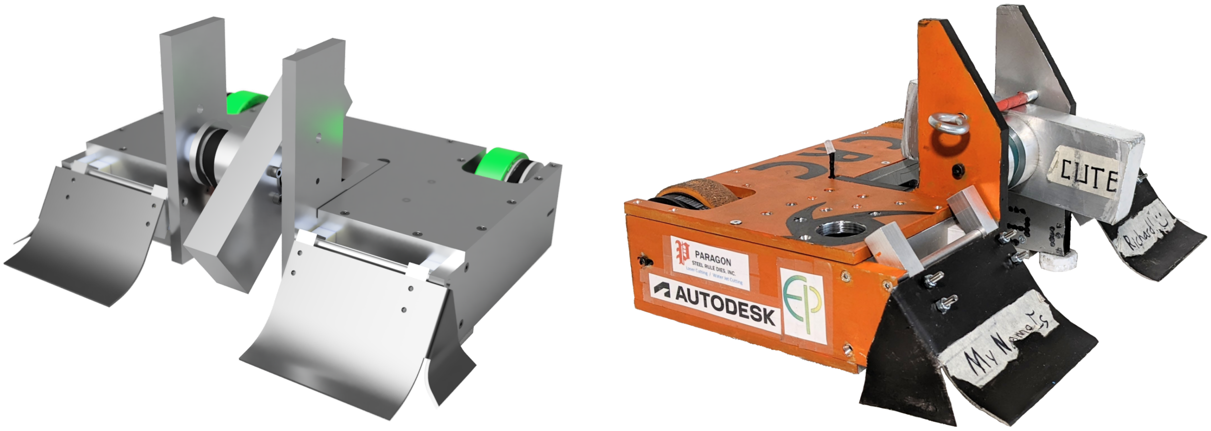
1 Introduction

Our team, Combat Robotics at Cornell (CRC), makes combat robots that participate in the Norwalk Havoc Robot League (NHRL) competition in Norwalk, CT. In this competition, robots fight one another in a series of 3 minute matches in hopes of disabling and destroying the opponent, just like in the show, Battlebots.

This year, CRC completed two competition robots and one autonomous robot (featured at our end of semester showcase). As members of the Kinetic subteam, we designed, manufactured, tested, and competed with our 12-lb. vertical spinner combat robot, Richard (Figure 1). Richard had a record of 3 wins, and 2 losses, and was ranked 4th in the 12-lb. weight class. As a result, Richard was invited to the champions competition held in December 2022.



(a) Final CAD render of Richard on Fusion 360

(b) Image of Richard prior the first fight at NHRL [1]

Figure 1: Images of Richard before/after assembly on the left/right

As a newer project team, the goals of this year revolved around making a working robot, having a clear research-backing for each design choice we made, and maximizing the amount of manual machining and hands on experience that the team could gain.

In this report, we will cover the design changes, testing, verification and analysis, reflection of competition, and proposed design improvements in preparation for Richard's upcoming champions-only competition.

2 Design Overview

Richard's system is divided into three different subsystems: Weapon, Chassis, and Powertrain. This section gives a "big picture" explanation of each subsystem and what they consist of.

2.1 Weapon

The weapon subsystem consists of the attack mechanism, the weapon drive, and mounting to the chassis. Our attack mechanism is a $1 \times 3 \times 6$ in block of aluminum 6061, powered by a brushless outrunner motor and mounted on a stationary shaft bolted to the weapon mounts. The weapon is indirectly driven by the motor via a belt-pulley system.

2.2 Chassis

The chassis subsystems includes the frame of the robot, which protects, holds, and mounts the other two subsystems. The chassis involves a great deal of integration with the weapon and powertrain subsystems, making sure the weapon has full capability and leaving enough room for the electronics, while allowing for an invertible drivetrain. The chassis material is aluminum 6061, machined using a manual Milling machine for the side, front, back, and weapon mounts, and waterjetting for the top and bottom plates (since they have the most amount of holes, compared to the other plates, making it extremely exhausting to machine on the mill).

2.3 Powertrain

The Powertrain subsystem consists of the drivetrain assembly, and the electronic components controlling the acceleration of the weapon and wheels of the robot. Drivetrain components include: brushless outrunner 380 kv motor, 2 – 7/8” × 0.8” wheel, 1/2” Al shaft, 3D-printed Onyx pulley, timing belt, ball bearing, and 3D-printed polylactic acid (PLA) spacers. The electronic components include the electronic speed controllers (ESC), brushless outrunner motors, transmitter, receiver, power switch adaptor (PSA), and power distribution adaptor (PDA).

3 Circuit Improvements Post-Assembly

Upon finalizing the assembly of Richard, changes needed to be made to fit the electronics within the interior of chassis, and distribute power to all motors by using the least amount of wiring possible. Hence, the circuit diagram and wiring of the electronics from the fall semester were reevaluated and developed. The current circuitry of Richard can be seen in Figure 2. This change was mostly due to the necessity of having a power killswitch for the purpose of turning on/off the robot, while still having all connectors engaged within the circuit, and an adaptor for distributing power from the 14.8-volt lithium-polymer battery to the three ESCs (labled as PSA and PDA, respectively in Figure 2).

As seen in Figure 2, starting from the nominal 14.8 V battery, power is distributed from the positive/power (red) and negative/ground (black) leads of the battery on the top and the bottom, respectively. These two lead wires are then wired through PSA, followed by two 1-to-3 Y-connectors – one for ground, one for power – known as PDA in this case, which connects to the three ESCs (2 for drivetrain, 1 for weapon). Through this distribution of power in the PDAs, it was verified that voltage stays the same, however, the current splits into three values, depending on the current draw of the motors at a given time. Each ESC gets one power wire and one ground wire from the two PDAs. The ESCs also have a 3-wire cable specifically for powering, grounding, and communicating with the receiver. The power line, also known as BEC, powers up the receiver by converting the higher voltage received from the battery to a lower voltage of 5 V. To prevent interference of the power lines, only one power line from the 3 ESCs was connected to the receiver (as seen in the bottom drivetrain ESC in Figure 2). However, all ESCs still had their ground and signal connections with the receiver. The receiver also communicated via a radio frequency range of 2.4 GHz with the transmitter to control the robot remotely. Finally, each ESC was connected to the motors via the three neutral wires. The orientation of these wires only affected the direction of the rotation of the motor, hence they were not color-differentiated. If the wrong motor rotation was observed, only the order of two of the wires had to be switched to reverse the direction of rotation.

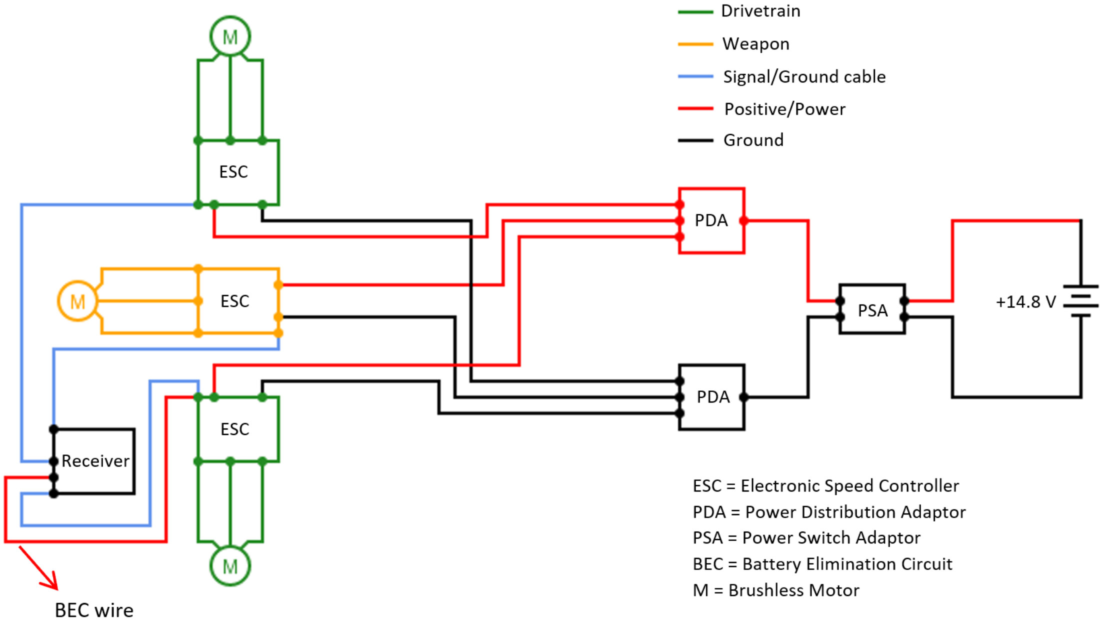


Figure 2: Richard's circuit diagram

4 Test box

In order to test the robot's performance in an environment that mitigates risks to the surroundings, we designed and manufactured a test box. Materials were selected according to the $300 budget (back when CRC did not have a lot of funding yet), and previous designs by NHRL, and SPARC's Arena Construction Best Practices [2, 3]. Hardwood plywood was used for the sides and the floor, with polycarbonate for the ceiling – also known as "bulletproof glass" – offering transparency and high impact resistance. In an ideal design with a higher budge and for the purpose of having more transparency/clear area, one would only use plywood for the floor, with polycarbonate walls and ceiling, and 80/20 aluminum extrusions as joining elements for the polycarbonate walls (to allow for flexibility and alleviate stress concentrations), though in this design a lower budget did not allow for that.

4.1 Original design

The 4 × 4 × 2 ft dimensions of the test box were designed such that they would fit in the storage room the team was given access to in the Engineering Learning Laboratory (ELL), and allow enough room for the robots to test their Drivetrain and Weapon subsystems (Figure 3). Some argue that testing the drivetrain does not necessarily require the "need" for a test box if all components are protected within a chassis. Additionally, testing a Sportsman robot with a low-kinetic energy weapon may also not require a test box. However, having a vertical spinner on Richard leaves no choice but to have an enclosed environment for blocking high-velocity impacts to the surroundings. Since these high-velocity impacts can damage the wood by chipping/denting it, "kickplates" – which are thin metal sheets – were included in the design located inside the test box covering the lower 1-ft height of the walls (Figure 3). According to SPARC, "kickplates should be used to minimize the chances of direct contact between robots and the arena walls. Kickplates often take the form of vertically mounted flat plate, I-beam, or C-channel segments that surround the perimeter of the combat surface and are designed to take direct weapon contact" [2]. The design also consisted of L angle brackets (fixed to the plywood by screws) placed on the exterior of the walls' intercepts to hold the box together. These brackets were also used for "slider guards" as supports for the sliding ceiling.

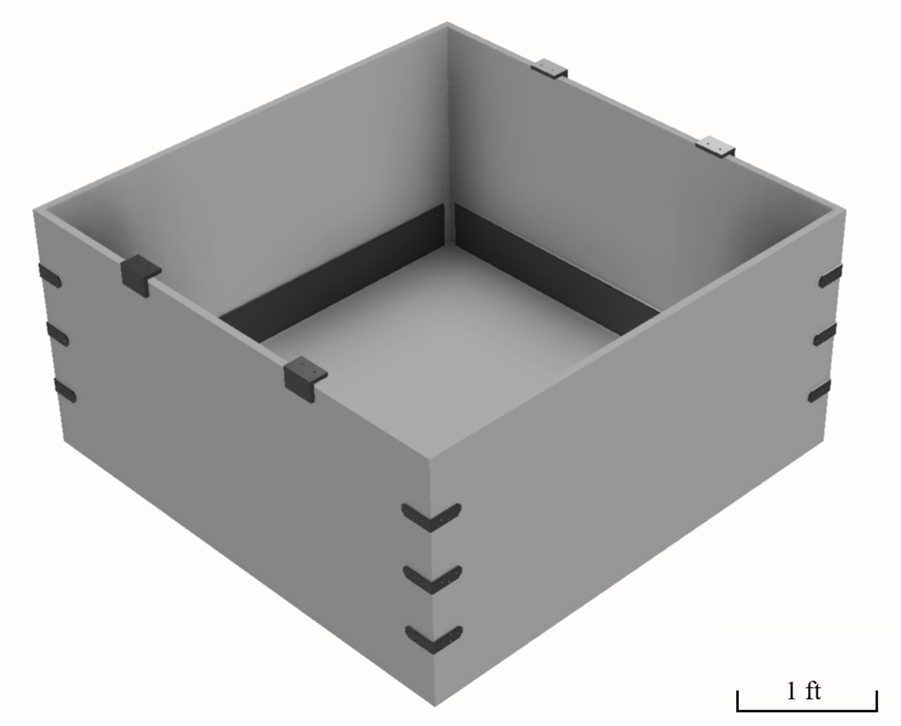


Figure 3: CAD of Test Box

4.2 Changes upon assembly

After purchasing the selected parts from Home Depot, a 6-hour initial team-assembly session was held in the composite room of ELL to put together the walls and the floor of the Test Box. Upon this initial assembly, sanding of the edges had to be done in order to prevent crookedness/uneven results of the Test Box. Unlike the original design, the L angle brackets were placed on the interior side of the walls for ease-of-assembly. In the following assembly sessions, a crossbar (as seen in Figure 4) was placed to have its medium edge align with the top edge of the walls to support the sliding ceiling from warping downward (which is caused due to gravity pulling it down), and complete the preliminary test box. Due to the low budget at the time of assembly, we were not able to purchase kickplates. Hence, impacts to the walls with Richard's weapon were prevented to keep the walls undamaged. To comply with that, weapon testings were performed on objects such as computer cases (with the power supply taken out), routers, and wood sticks. In the future, with additional funding gained through sponsors and Giving Day, we plan to purchase and install kickplates to allow for more flexibility during testing.

Figure 4: Test Box with Richard and test objects inside

5 Post-Competition Performance Analysis

Stall torque of the drivetrain motors were calculated using a theoretical and an experimental method by measuring the current and power drawn by the motors in different load cases. This gives us an idea of how much power/torque (ball park values) was consumed during the competition, and what to expect in the future. The collected data can also be used in the future for thermal design considerations (since a significant amount of the generated power converts into heat and raises the temperature of the electronic components) and lighter battery selections.

5.1 Power and current usage

In order to analyze the power and current usage of the robot – i.e. the current draw at the Powertrain subsystem from the battery – a high precision Watt meter power analyzer (JZCreater 150A) was placed through the circuit, right after the battery (Figure 5 & 6). This Watt meter included a digital LCD screen for voltage (V), current (A), power (W), charge (Ah), and energy (Wh) measurements (Figure 6).

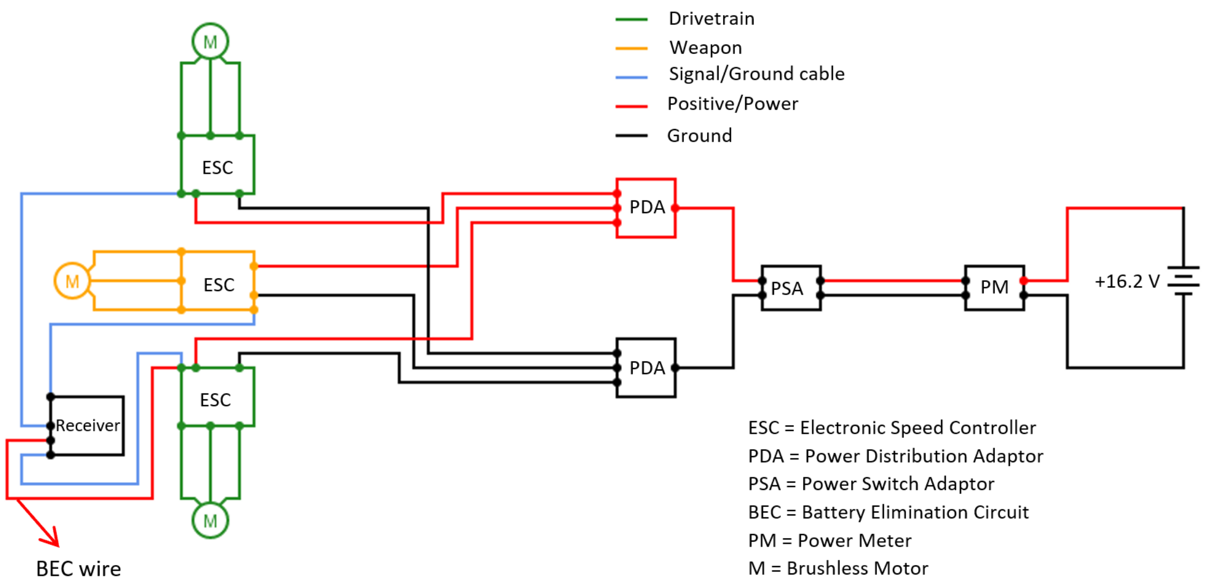


Figure 5: Richard's circuit diagram with the power meter through the circuit

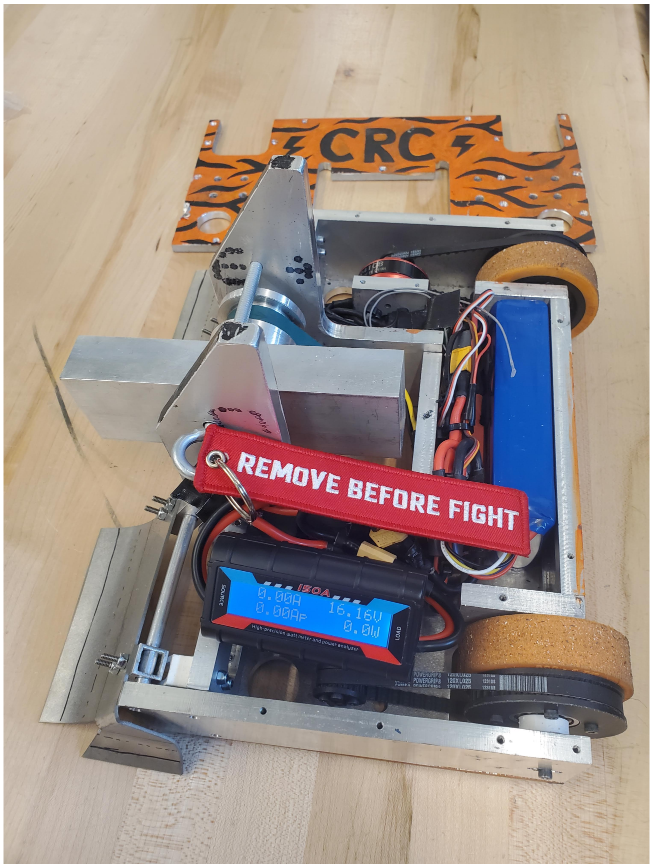


Figure 6: Richard's circuit with the power meter through the circuit. Voltage is measured as 16.16 V across the battery leads, with zero current and power, since PSA is not closed and not current is flowing in the circuit.

Three cases were experimented in order to measure the power and current used by the Powertrain and Weapon subsystems while the motors were accelerating/decelerating (Table 1). Case 1 was having Richard jacked up so the wheels had no contact point with the ground ("No load"). Case 2 was having Richard drive on the floor. Case 3 was ramping up only the weapon with the robot stationary in the test box. As expected for the drivetrain, higher values of power and current were observed when the motors had to handle the 12-lb. weight of Richard and accelerate under load (case 2), resulting in a higher stall torque needed, proportional to the stall current. In both cases 1 & 2, the start-up current upon closing the power switch was $I_n = 0.27A$. Case 3 had the highest values of peak current and peak power, running at an approximate weapon rotational speed of 10,000 RPM.

Table 1: Power meter data from the two case studies

	Minimum Voltage (V)	Peak Voltage (V)	Peak Current (A)	Peak Power (W)
Case 1	16.06	16.15	2.72	43.7
Case 2	15.75	16.07	12.91	204.3
Case 3	15.52	15.99	17.66	275.3

5.2 Stall torque

To verify the stall torque required for the motor, we calculated the following from the measured current:

$$K_t = \frac{60}{2\pi K_v} = 0.0251\frac{N \cdot m}{A}, \tag{1}$$

where K_t is the motor's torque constant, and K_v is the motor's speed constant in $\frac{RPM}{V}$.

$$\tau_{s,experimental} = K_t(I_p - I_n) = 0.2561 N \cdot m. \tag{2}$$

These equations were taken from the RioBotz Combat Robot Turorial [4].

Additionally, the theoretical stall torque was calculated as follows:

$$N = \frac{mg}{4} \tag{3}$$

$$\tau_{s,theoretical} = \frac{\eta \mu N r}{R} = 0.2683 N \cdot m, \tag{4}$$

where η is the efficiency of the motor and the power transmission (85%), μ is the coefficient of friction, N is the normal force applied on each contact point, r is the radius of the wheel (0.073025 meters), and R is the gear ratio of the power transmission pulleys (1:2.78, designed to achieve under 2 seconds of travel-time across the arena). The normal force was calculated using mass $m = 12lb = 5.44311kg$, and the acceleration of gravity $g = 9.81\frac{m}{s^2}$ (Equation 3).

The two values of stall torque agreed with a percent difference of 4.65%.

Although the weight of Richard does not allow for a 4-wheel drive system, the determined values can be used to specc four new drive motors in the future with lower weights to allow for a 4-wheel-drive system, or for spare motors in case the current motor became obsolete (or for future similar robots). Additionally, these values can be used if more weight-cuts were to be considered for the next version of Richard, enough to allow adding two wheels with the transmission system (two more pulleys per drive motor side).

6 Proposed Weapon Subsystem for December 2022 Champions Competition

Based on Richard's performance in competition, we identified some components that require improvement before Richard participates in the championship competition in December. These include the making the weapon blade and shaft stronger, adjusting the weapon blade design so it can cause more impact to the opponent, adding two more wheels to the drivetrain in case one or more wheels breaks in a match, and adjusting the wedge geometry such that Richard's weapon can more easily reach (and hit) the opponent.

This report will focus on improvements in the weapon subsystem, since the weapon requires more urgent changes before the next competition compared to the chassis and powertrain.

6.1 Issues from competition and weak points

In our second competition match, one of Richard's major failure modes was the weapon disconnecting from the weapon frame. Our opponent, Hot Leaf Juice, cut a few chunks out of our weapon blade, decreasing its effectiveness and ability to cause impact. More notably though, the weapon shaft was not strong enough to hold the weapon in place. We are unsure if the opponent made direct impact with the weapon shaft or if their weapon hit Richard's blade hard enough to cause the break, though our broken robot components post-match suggest the latter. This failure mode implies that we should make the weapon mounting more robust before bringing the robot to competition again.

Another weak point of our robot was our attack mechanism itself. During the competition, the commentators made numerous comments and questions regarding our weapon blade. They wondered if it was a block of steel, or layers of aluminum and steel, and consistently called it a ”huge hunk of metal”. Upon first consideration, we did not question why they were talking about our blade so much compared to other competitors' weapons, and assumed it was just ”something for them to talk about” as the competition progresses. Once we talked to other fellow builders at the competition, however, we learned that our weapon design is quite uncommon in combat robotics, and that there was some merit to the commentators' questioning. Usually, builders choose slimmer weapon geometries made out of harder metals, like steel, and opt for more complex blade designs that can cause more impact. In general, it is not worth making engineering design changes based simply on other people's opinions, but combat robotics is a unique area of mechanical engineering that does not have many textbooks and related industry applications to refer to. Therefore, the ”best” resources in combat robotics are Reddit, the builders Facebook groups, and words of advice at competition. Since advice at combat robotics events is one of the few combat robotics resources available to us, we take experienced builders' suggestions seriously, and are choosing to keep it in mind as we develop Richard 2.0, the version of our robot that will attend the December championships competition.

It is important to note that while we are improving the weapon design, we aim to minimize how much this affects the other two subsystems, since we are only adding minor improvements to Richard's design. If we chose to revamp the robot design more dramatically, this would disrupt the design cycle of our subteam's 2023 robots, which would be very problematic to the team's timeline.

6.2 Weapon mounting improvement options

In order to keep the weapon blade securely mounted, we need to make the weapon shaft most robust. We can accomplish this by both improving the mounting of the shaft so it is less prone from being knocked out of place and changing the geometry or material of the shaft to make it stronger.

6.2.1 Improve shaft mounting

We originally designed the weapon shaft and mounting plate to be connected using screws with relatively large bolts. While this mounting design is cost effective and simple, our weak point was choosing to only have the weapon shaft sit half way through each weapon mounting plate, rather than going through the whole thickness of the mounting plates. We can easily solve this by increasing the length of the shafts to be at least the distance from the outer surface of each weapon mounting plate, which is 4 inches. This improvement is demonstrated in the sketch below:

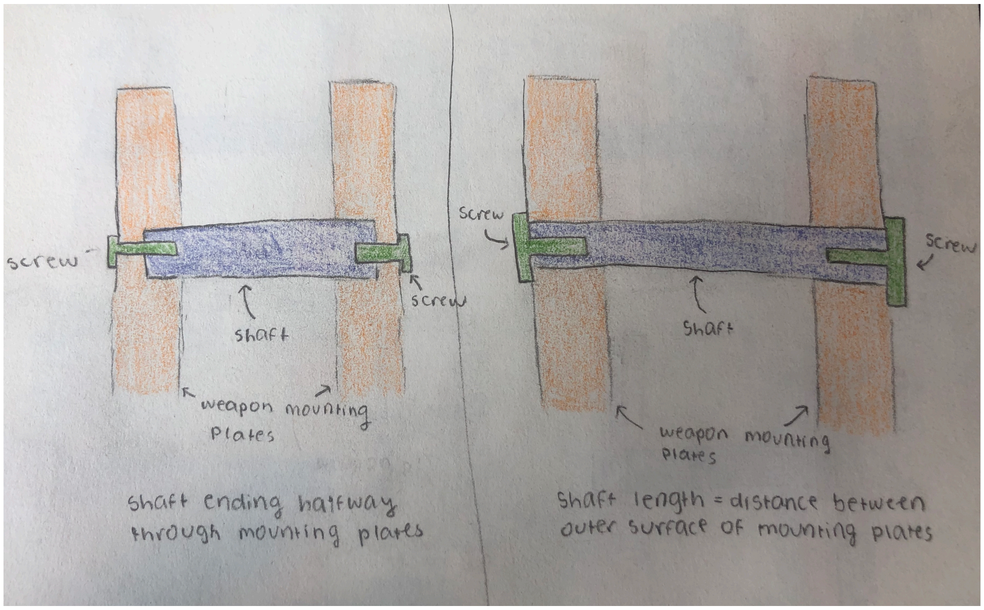


Figure 7: Sketch demonstrating the increased length of the weapon shaft.

We then need to consider how to secure the weapon shaft to the mounting plates. Here are some options:

- Screw the ends of the shaft into each plate (parallel to the shaft)
- Screw the ends of the shaft into each plate (perpendicular to the shaft)
- Insert a rod perpendicular to the shaft that goes through the mounting plate, secured by a screw
- Secure the shaft on the outside of the plates using shaft collar and rubber spacer

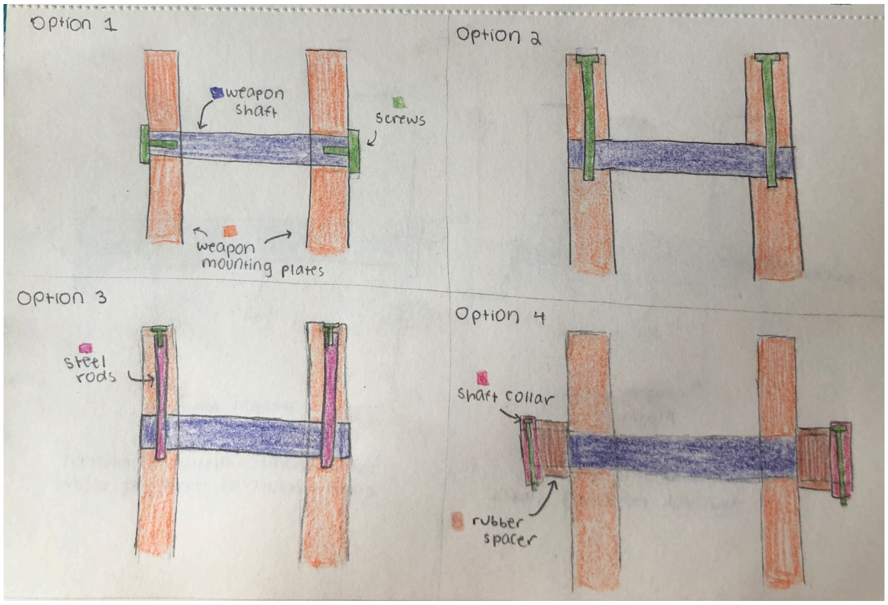


Figure 8: Sketches for four options to secure the weapon shaft to the weapon mounting plates.

Option 1: Screws parallel to shaft

This solution is the one used in Richard V.1, except that the length of the shaft was increased so the ends meet the outer surface of each mounting plate. This solution could work, however our robot would still be prone to the failure mode realized in the match against Hot Leaf Juice, which was when the screw broke (or so it seems). Even if this is not the reason that the weapon shaft failed in the match, it is clear that the small screws that connect the shaft to the plates face a large magnitude of force, which can result in breakage. Therefore, this design should not be used.

Option 2: Screws perpendicular to shaft
In this option, the weapon shaft is secured using a long screw that goes through the top of the weapon plate and intersects with the shaft perpendicularly. While the screw would be less likely to shear, if the screw fails for some other reason (ex: getting hit by a horizontal spinner when the robot is upside down), it could get stuck in the mounting plate and deem the mounting plate unusable for future matches. Since combat robots are expected to break and face damage, it is important to design the robot such that a failure affects the fewest possible components. Therefore, this design solution is worse than the current design because a broken screw in this design would most likely cause 2 other components to fail (mounting plate and weapon shaft), while a broken screw in this original design does not cause the shaft or mounting plates to fail too.

Option 3: Rod perpendicular to shaft
This option adds another component to the weapon mounting assembly: a steel rod on either end of the weapon shaft. The rods secure the weapon shaft using a through hole at the ends of the rod. The rods would then be secured to the mounting plate using small screws. The benefit of adding the rods is to increase the strength of the component holding the weapon shaft in place. However, adding the rod makes this assembly unnecessarily complicated, and it would likely result in the same failure as Option 2. Therefore, it is not an optimal design.

Option 4: Shaft collar + spacer
This fourth option introduces a shaft collar and spacer, instead of just using screws to secure the weapon shaft to the mounting plates. Shaft collars are very useful as mechanical stops, which means that will prevent the shaft from falling out of the mounting plates on either side. Additionally, steel shaft collars are affordable, as one with the required dimensions would cost less than $4.00, and are extremely robust due to the placement of the set screw within the collar. While this option has more components than the other options, it reduces the likelihood of the failure modes Richard saw in the April competition. Therefore, this is the most robust design of the four options, and the one that will be used in the redesign of the weapon subsystem.

6.2.2 Changing the geometry or material of shaft

Aside from mounting, we can consider changing the weapon shaft design to improve its strength. One option is to switch the shaft from Aluminum 6061 to steel. This will increase the weight of the shaft (unless we choose to decrease the diameter), but it makes sense to design the shaft with a high safety factor, since the shaft is a very important component in ensuring the functionality of the weapon. Another option is to switch the aluminum rod out for a screw whose shaft which serve as the weapon shaft. This screw from McMaster would be a suitable option because it is the same diameter as the current aluminum rod and is the appropriate length (0.5” longer than the distance between the mounting plates).

In order to determine whether the steel rod or large steel screw would be a more suitable option, we considered cost, weight and strength. Weight calculations for the rods are in Section 7.1 in the Appendix, and the weight for the steel screw was found by exporting the McMaster item into Fusion 360.

Table 2: Comparing options for weapon shaft

	Aluminum Rod (original choice)	Carbon Steel Rod	Stainless Steel Screw
Unit Cost	$0.59	$1.31	$18.33
Strength	35,000 psi	100,000 psi	70,000 psi
Weight	0.0766 lb	0.223 lb	0.289 lb

While the stainless steel screw would be the most simplistic assembly, it is way more expensive, less strong, and marginally heavier than the steel rod. Therefore, based on the above criteria, **the carbon steel rod is the best option.** Compared to the aluminum rod, the steel rod is more expensive than the aluminum rod, by the strength increases almost 3 fold, so the weapon shaft will be able to withstand hits more effectively.

6.3 Blade improvement options

After seeing Richard's performance at competition and taking advice from more experienced combat robotics builders, we have a few routes to consider to improve the robustness of the weapon design. In considering the design options, we will aim to keep the weight of the subsystem relatively the same, as we cannot decrease the weight of the chassis and powertrain much without significantly changing the robot design. Here are some potential design improvements we considered before landing on our final decision:

- Smaller steel blade of the same weight as the aluminum blade
- Sandwich steel between a layer of aluminum either side
- Sandwich steel with aluminum in the other direction (ends of blade are aluminum)
- Decrease the number of teeth on the blade to one tooth (out of steel)
- Smaller steel blade with steel spikes at the end for extra impact

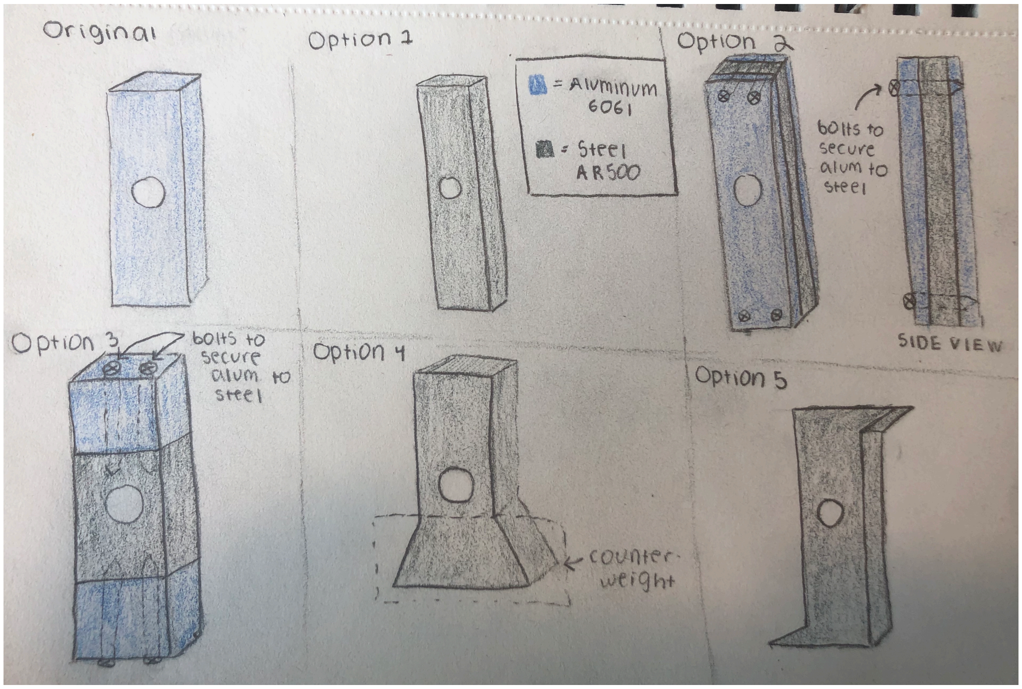


Figure 9: Sketches for five alternative weapon blade designs.

Option 1: Smaller steel blade
This was the first design improvement we considered for the weapon blade, because it requires the least change. With this design, the blade's mass would remain the same (since the full robot weight is less than 0.1 lb below the 12lb weight limit), thereby decreasing the dimensions of the blade. We keep the blade length the same because any longer would prevent the blade from rotating about the shaft (as it would hit the ground), and making it shorter would decrease Richard's ability to hit the opponent. We also have a minimum width of the weapon pulley diameter, as making the blade less wide than the pulley would add

difficulty in securely connecting the blade to the pulley.

Option 2: Sandwich design, aluminum and steel layers

This design was inspired by the commentators at competition, as one of their guesses to our weapon design was a combination of aluminum and steel, in layers. In considering alterations to the weapon subsystem design, it seemed worth including this idea as an option. The benefit of a hybrid-material weapon is that the overall size of the weapon can be larger than an all steel weapon, allowing us to hit the opponent with a larger surface area. This option is marginally better than the all aluminum option, because the steel portion of the weapon can add some more stability. The ”sandwiching design” could either be a steel core with a layer of aluminum on either side, or the opposite, with aluminum core and steel exterior.

A steel core with layers of aluminum would allow the aluminum to act as an ablative weapon, where we expect it will face some damage, but the core of the weapon is strong enough to maintain functionality. In between matches, we could replace the outer layers, rather than having to replace the entire weapon. This option is not ideal, however, because the weapon blade is not a very expensive component in the robot. For reference, our current weapon blade costs about 20% of any motor in the robot.

The aluminum core with layers of steel is another option, which would allow the outer portion of the blade to be more robust while the center is softer and lighter. This design would be particularly good against horizontal spinners, but would be vulnerable against other vertical spinners or hammers, which could easily make contact and destroy with the aluminum core. Again, the weight and potential cost savings of replacing some of the steel with aluminum (rather than using an all steel weapon) are outweighed by the weakness this design could pose in the weapon effectiveness. It would also be overly complicated for little gain, which goes against the Kinetic subteam’s 2021-2022 goal of keeping things simple unless there’s a real reason to making more complicated design choices.

Option 3: Steel center with aluminum tips

This idea resulted from determining the previous ”sandwich” design option, with the curiosity of whether aluminum tips would be a useful design. Similarly to the steel core and aluminum layers design, the aluminum tips in this design would serve as an ablative design, which is meant to get destroyed and damage, but will hold the opponent off for long enough that they can’t cause significant damage to the functionality of the robot. This is not a smart design choice though because ablative designs make sense for armor, like in the chassis, but not in the attack mechanism. The attack mechanism is not meant to get destroyed, so it doesn’t make sense to design the weapon blade such that it is expected to get cut up by the opponent. It’s important to note that our opponents’ weapons were mostly in tact by the end of each match, suggesting that we should ensure the weapon is as robust as we can make it.

Another serious flaw with this design option is the mounting of the aluminum tips to the steel center. We would need to drill a hole into the length of the aluminum and into part of the steel (which is hard to machine) and secure the pieces together with screws. This introduces more failure modes because the screws keeping the aluminum and steel together could break in the middle of a match, which would risk the usability of the weapon.

Option 4: One tooth blade design

Early on in the design phase last semester, the subteam considered making a one tooth vertical spinner. We knew that we would make either a one tooth or two tooth blade, because blade with more than three teeth distribute the blade weight among more teeth, thereby decreasing the effectiveness of each tooth when it hits the opponent.

The benefit of having a one toothed blade is that the one tooth can be more massive and powerful than each tooth in the two tooth design. Since the blade has such a high rotation rate, the fact that the blade would hit the opponent at only half the rate would not be an issue. The reason we decided to pursue the two toothed design was for manufacturability sake, as the team chose maximizing manual machining as one of our goals this year.

With a one toothed design, we would have one main extrusion that would be long enough to reach the opponent, and a counterweight that is wider and much shorter, as shown in Figure 9. While there is some promise with this design option, we want to preserve main aesthetic design of Richard since this is only an upgrade of our original robot, rather than a complete redesign.

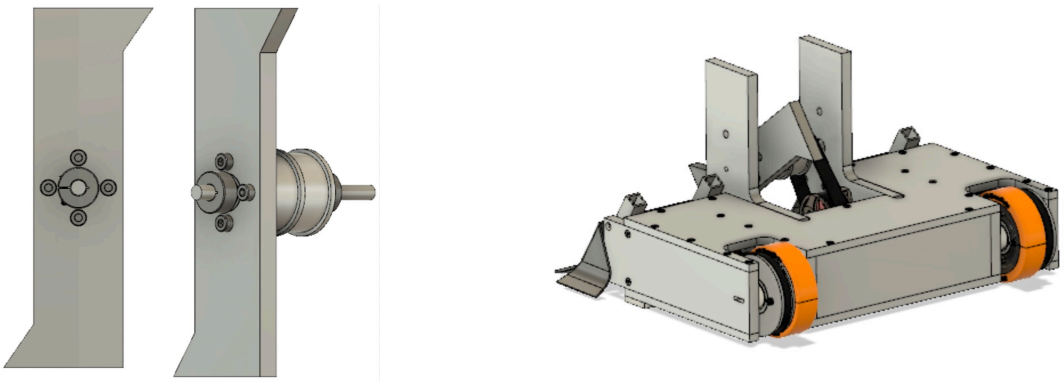
Option 5: Small steel blade with steel spikes
The last option we consider as a design improvement is a slightly smaller steel blade with steel spikes at either end of the weapon length. This is an idea we had when we originally designed our weapon, but decided against implementing it in Richard Version 1 for the sake of simplifying our design. Now, looking back at our competition performance, we realize that our weapon would have performed better with the spikes attached to the end. The purpose of the spikes is to add more cutting capabilities to the weapon, as the current weapon blade only uses blunt force (at a high speed) to cause damage to the opponent. When we were at competition, the builder of Krunk, the robot who later placed first in the competition, advised us to add spikes, since he has found success in appending spikes to his vertical spinner and explained that we would have been able to cause more damage if we did the same.

The most cost effective design approach would be to bolt the spikes onto the rectangular blade, however this could make the spikes more prone to breaking off of the blade. This also adds an additional failure mode, where the bolt connecting the spike to the blade could break if the opponent hits our weapon (which is the same concern addressed in the third blade improvement option).

The more expensive but durable alternative is to get the blade waterjetted such that the blade is one consecutive piece of steel. While this is a very expensive option, it is one that should prevent us from needing as many spare blades since the weapon will be significantly stronger than our current solution.

Final verdict: Small steel blade with steel spikes
Since this design option has proven success in the past, is one we previously desired and considered, and has been suggested to us by more experienced builders, we have decided to pursue the steel blade plus steel spike design.

6.4 Overview of Weapon subsystem V.2



(a) Weapon subsystem re-design.

(b) Weapon redesign in full robot assembly

Figure 10: Revamped weapon subsystem.

The weapon subsystem redesign features an AR500 steel weapon blade with spikes on either end, held to the robot chassis by a 1/4” carbon steel shaft. In order to keep the full robot weight under 12 lbs, the blade width and thickness were decreased and excess material was removed from the pulley. There were considerations about decreasing the pulley diameter in order to allocate more weight to the weapon blade and shaft, but this would increase the spin-up time of the weapon, which is a variable we want to preserve.

6.4.1 Upgraded weapon shaft and mounting: Steel shaft secured by shaft collars and 3D printed spacers

As discussed in Section 6.2.1, the most effective way to improve the weapon shaft mounting is by replacing the current solution with a shaft collar and 3D printed spacer on either side. The selected shaft collar can be found on McMaster. It is a carbon steel clamping shaft collar with an inner diameter of 1/4". We will 3D print the spacers in our team's 3D printer and expect to adjust some of the dimensions until the spacer fits correctly. In order to shift to this mounting method, the shaft length increased such that the shaft reaches the outer edge of each mounting plate.

In terms of shaft collar and spacer placement, we originally considered placing these elements on the outer sides of the mounting plates, as shown in the sketches in Figure 8. However, placing the joining elements on the outside of the chassis adds another failure mode for the weapon subsystem in competition, in addition to adding considerable weight by requiring a much longer weapon shaft.

6.4.2 Upgraded weapon blade: Two tooth, steel blade with spikes

Using Option 5 from Section 6.3, we modified the weapon blade design to be a 0.5"x1.5"x6" blade with 1 inch long spikes. In redesigning the weapon blade, we chose to keep the blade length the same. When we trimmed down the robot's weight to be back under 12lbs, we considered decreasing the blade length as one of the first options. However, since we already had some issues making contact with the opponent with 6" blade, decreasing length would make weapon even less effective.

The spike geometry was determined using this Wikipedia page about rake angle, which was suggested to us by the builder of Krunk at competition [5]. Since we are using steel, the rake angle of the spike is within the recommended 8-12 degree range, so we chose the upper limit with the hopes that this increases the impact Richard will deliver to the opponent. One of the reasons we pursued the upper limit for the rake angle is because this allows us to have the most mass possible at the end of the blade. Maximizing the mass at the end of the blade increases the inertia and thereby will enable our weapon to have more impactful hits when in contact with the opponent.

6.4.3 Other design modifications to keep Richard under maximum weight

Other minor changes were made to the subsystem design in order to decrease the overall weight include repositioning the screws that connect the blade and pulley so they are closer to the axis of rotation, and decreasing the number of screws from 6 to 4 to decrease weight. Changing the diameter of the weapon shaft also resulted in a smaller hole in the pulley and blade, and caused us to replace the existing bearings with ones that have a smaller diameter.

7 Appendix

7.1 Weight calculations for Weapon shaft alternatives

Aluminum Rod
Density of aluminum 6061: $0.0975 lb/in^3$
Volume of rod:

$$\text{Volume of cylinder} = \pi \times (radius)^2 \times length \tag{5}$$

$$V_{rod,alum} = \pi \times (0.25in)^2 \times (4in) \tag{6}$$

$$V_{rod,alum} = 0.785in^3 \tag{7}$$

Weight of rod:

$$\text{(weight of rod)} = \text{(density)} \times \text{(volume)} \tag{8}$$

$$W_{rod,alum} = 0.0975lb/in^3 \times 0.785in^3 \tag{9}$$

$$W_{rod,alum} = 0.0766lb \tag{10}$$

Steel Rod
Volume of the rod is the same as the aluminum rod.
Average density of carbon steel: $7850kg/m^3 = 0.284lb/in^3$

Weight of rod:

$$\text{(weight of rod)} = \text{(density)} \times \text{(volume)} \tag{11}$$

$$W_{rod,steel} = 0.284lb/in^3 \times 0.785in^3 \tag{12}$$

$$W_{rod,alum} = 0.223lb \tag{13}$$

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