Washington University in St. Louis
JAMES MCKELVEY SCHOOL OF ENGINEERING

Mechanical Engineering Design Project
Group J2, MEMS 4110, Fall 2025

TRASH-E (Terrain-adaptive Remote Autonomous Sanitation Hauling Engineer)

The TRASH-E (Terrain-Adaptive Remote Autonomous Sanitation Hauling Engineer) project was created to compete in the 2025 ASME Student Design Challenge. For 2025, the ASME SDC asked for the development of a remote-controlled robot that could collect and deposit trash from receptacles placed around a miniature city. The robot had to adhere to specific size and weight constraints, as well as obey traffic laws in the same manner as a real driver operating a motor vehicle.

We tackled the project through multiple stages. First, we reviewed the rules of the SDC to ensure that any design we moved forward with would satisfy the necessary criteria. We then conducted a customer interview to establish project needs. Afterwards, the four group members of J2 individually imagined different potential design concepts. These concepts were ranked until a single design was chosen to move forward for development. The team researched existing products that employed similar mechanisms to the winning concept. Initial prototypes were constructed, and refinement led the design from a concept to a tangible, working prototype that could compete in a mock competition.

The final prototype consisted of a 4-wheel drive vehicle with a mechanical arm mounted on top. Mecanum wheels allowed the vehicle to pivot around its center axis, resulting in a small turning radius. The arm, powered by high torque servo motors, could carry the weight of the trash it collected. A grasp-type end effector, similar to a garbage truck claw, was implemented to pick up and deposit waste receptacles. Controlling the vehicle was an Arduino WiFi module that produced its own network and allowed teleoperation via laptop.

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1 Introduction

The Waste Collection Challenge encourages the design and creation of a model vehicle powered by a remote control that is able to collect and deliver trash within a small model area. The vehicle must be able to efficiently pick up and dispose of trash in model trash cans while still abiding by car traffic rules. The road has a width of 10 cm to 18 cm. The vehicle must be able to collect bins sized within 3.81cm x 3.81cm x 6.35 cm and 5.08cm x 5.08 cm x 7.62 cm and deliver them directly into the model dumpster without having any of the garbage miss the target. The model garbage will have dimensions of 1.27 cm to 2.54 cm per side. Throughout the project, ensuring safety, adaptability, and a dependable claw-style collection function is essential for the vehicle's success.

2 Problem Understanding

2.1 Existing Devices

2.1.1 Existing Device #1: Trash Grabber

Figure 1: Grainger Trash Grabber

Link: https://www.grainger.com/product/UNGER-Trash-Grabber-Trigger-Handle-2NDR3
Description: The Grainger trash grabber allows an operator to effectively pick up trash using a clamping system. The mechanism works when the user pulls back on the black part of the handle, a cord that lines the poles is then pulled back. That cord is connected at the two far ends of the clamp and with the pulling force, the two ends naturally come together, clamping down on an object between the rubber pads. The system is similar to that of which we will need to use to pick up the trash bins.

2.1.2 Existing Device #2: Garbage Truck

Figure 2: HEIL Rear Load Garbage Trucks

Link: https://www.heil.com/type/rear-loaders/

Description: The HEIL rear load garbage truck is a large scale trash collection vehicle that is operated by multiple workers and is used in neighborhood trash collection. The machine specializes is loading trash after the trash bin is set onto the clip on the back. The vehicle then dumps the trash into the collection area before compacting it with hydraulic presses.

2.1.3 Existing Device #3: Wall-E

figures/Screenshot 2025-09-10 at 6.32.51PM.png

Figure 3: LEGO Wall-E

Link: https://www.target.com/p/lego-disney-and-pixar-wall-e-and-eve-43279/-/A-94152741?sid=&TCID=PDS-230280049&gclsrc=aw.ds&gad_source=1&gad_campaignid=230280049&gbraid=0AAAAAD-5dfYSOp1cSGyMMzBMAPkCExDu0&gclid=Cj0KCQjww4TGBhCKARIsAFLXndSseamf7vS4iw5AzR4bOe-PozifBinqMnQpjTRG-25kOOXNL7oC60kaAkSGEALw_wcB
Description: Wall-E is a trash collecting robot that moves around on two caterpillar tracks for nimble movement through a junkyard. The caterpillar tracks allow for the robot to turn 360 degrees around a pivot at the center of its body. Unlike a car, which must pivot around a point well outside of its body. The robot is setup to compact, store and release trash in its middle body, rather than pickup and dispose of waste collectors (trash cans).

*We understand that Wall-E is technically not real, however, the systems that the LEGO version operate on are very similar to the product we will be producing.

2.2 Patents

2.2.1 Boomless automated side loader for refuse collection vehicle having lift arm with non-extendable upper end (US5702225A)

This patent covers the most generic style of a robotic arm mechanism that is used on a majority of modern garbage trucks. It outlines the standard geometry of the robotic arm components such as the extending arm and clamping jaws. Though the waste collection robot for this project will be built on a much smaller scale than real garbage trucks, this same mechanism provides a wealth of insight on how the robot could collect and dispose of waste successfully. Information is provided on kinematics and force mapping for the two-jaw clamp, which would be extremely useful for replicating the mechanism.

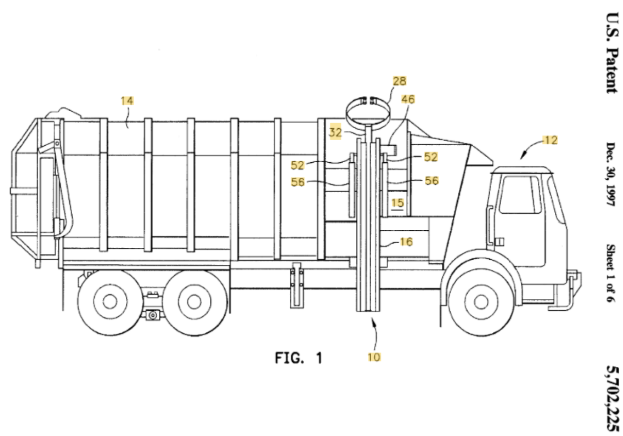


Figure 4: Patent Image for Boomless Automated Side Loader

2.2.2 Electric drive configuration for a skid steered vehicle (US20040121871A1)

This patent covers a generic electric drive configuration for a multi-motor drive train. We are planning to use 4-6 flat-free (foam-filled) pneumatic that will each be independently driven with 2-4 electric motors. This configuration will allow our robot to be both easily maneuverable, and fast. Using flat-free wheels should allow our robot to navigate complex terrains without the risk of punctures. The information provided in this patent will assist us in selecting the electrical components and will detail the mechanical configuration needed for our robot.

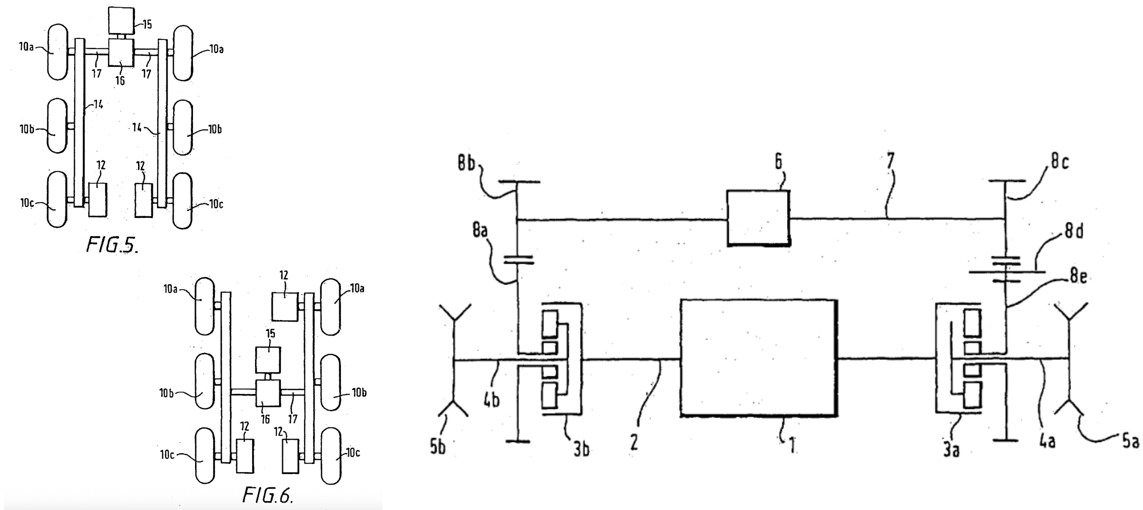


Figure 5: Patent Images for Electric Drive Configuration

2.3 Codes & Standards

2.3.1 Standard Practice for Grasp-Type Robot End-Effectors: Split Force Measurement Apparatus (ASTM F3756-25)

ASTM F3756-25 aligns perfectly with the waste collection robot project. It concerns robots with grasp-type end effectors, which is very likely to be the chosen end effector for our waste collection robot. These end-effectors exactly resemble the grasping mechanisms used on real garbage trucks. The standard outlines a series of test methods for grasp-type end effectors to ensure efficient and successful integration into a control system.

2.3.2 Standard Test Method for Evaluating Ground Robot Capabilities and Remote Operator Proficiency: Obstacles: Variable Height Rails (ASTM E3311)

ASTM E3311 outlines a variable height rail test that would validate the capabilities of our robot's mobility under different conditions. It would also test the rollover, and self-righting tendencies of our system. If used to test our robot, it would highlight key weaknesses of our system and should help us design a better performing robot for navigating the garbage collection task.

2.4 User Needs

The following section presents the user needs for the project. It includes a section summarizing the customer interview and a table illustrating the importance of different interpreted customer needs. The customer in this case is considered to be Dr. Potter who is facilitating the ASME waste collection design challenge for the MEMS 4110 class.

2.4.1 Customer Interview

Interviewee: Dr. James Jackson Potter
Location: Brown 118, Washington University in St. Louis, Danforth Campus

Date: September 5^{th}, 2025
Setting: Dr. Potter presented the ASME AY25-26 Student Design Competition (SDC) challenge [1] to the assigned teams and then answered questions pertaining to the project. Rules and standards for the challenge were clarified. The actual track that our robot needs to perform on was introduced and obstacles were given mock-up visualizations. The interview took place in Brown 118 for 45 minutes.

Interview Notes:
What are the typical uses of the device?

- Replicate the waste collection process exhibited by real garbage trucks by collecting and dumping waste receptacles
- Drive and operate on streets while obeying standard safety and traffic laws

What does a successful design look like?

- Designs must fit inside a 50 cm^3 format
- Designs must be interfaced via one controller and operated by one student
- Drive and operate on streets between 10-18 cm wide and perform its assigned task in 5 minutes

How will we be judged?

- The goal is to properly collect and dispose of as many waste receptacles as possible in the allotted time
- Student teams in MEMS 4110 will compete against one another in the final demonstration

2.4.2 Interpreted User Needs

After the customer interview with Dr. Potter, the given answers were organized and formulated into a customer needs table. The needs are organized in the table by number and each have an associated ranking of importance in terms of the overall project scope.

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	The robot fits within a 50 cm × 50 cm × 50 cm sizing box and is easy to transport	5
2	The robot operates safely and avoids collisions or unsafe movements	5
3	The robot reliably collects 1.27–2.54 cm waste cubes from bins sized 3.81–5.08 cm wide × 6.35–7.62 cm tall	4
4	The robot successfully sorts and delivers garbage to the Landfill and recycling to the Recycling Center	5
5	The robot operates continuously for at least 5 minutes (Initial Testing) and 10 minutes (Elimination Testing) without failure	5
6	The robot obeys road rules, including staying within 10–18 cm wide streets and following traffic signs	4
7	The robot recovers from obstacles (up to 23 cm high hills and 7.6 cm deep potholes) and continues operating	3
8	The robot minimizes spilled or bounced waste during dumping to maximize score	4
9	The robot uses rechargeable dry-cell batteries and can be easily reenergized between runs	3

The rankings of importance attached to each customer need will serve as a compass for the project team while beginning and progressing through the design process. They demonstrate which needs must be emphasized and where resources should be allocated. Prioritized out of the customer needs is compliance with the ASME rules and successful completion of the given challenge.

2.5 Design Metrics

Table 2: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	1	Total weight	kg	5	3
2	1	Total volume	cm^3	$< 125,000$	$< 100,000$
3	1	Ground clearance	mm	> 12	> 20
4	2	Max speed	mph	> 2	> 5
5	5	Intake throughput	pieces/min	> 12	> 18
6	3	Maneuverability, rollover, self-righting from ASTM E3311	Tests Passed	Maneuverability Pass	Pass All
7	1	Ability to grasp objects as specified in ASTM F3756-25	Binary	Pass	Pass

3 Concept Generation

3.1 Mockup Prototype

The mockup allowed us to realize that the tracks on each side allowed the best range of motion for the vehicle. The 4 wheel draft would hinder our ability to navigate through tight areas. We also were able to better understand that the claw feature needed to be located on one side of the vehicle, not in the middle. This is so that it can pick up model cans in tight spaces. Additionally, modeling the lever-like claw allowed us to better envision how the grab-and-drop system will work in our final model. A motor will pull on the spring and once it clamps the bin, the string will continue to be pulled, moving the bin up over the height of the dumping area.

Figure 6: Front View

Figure 7: Top View

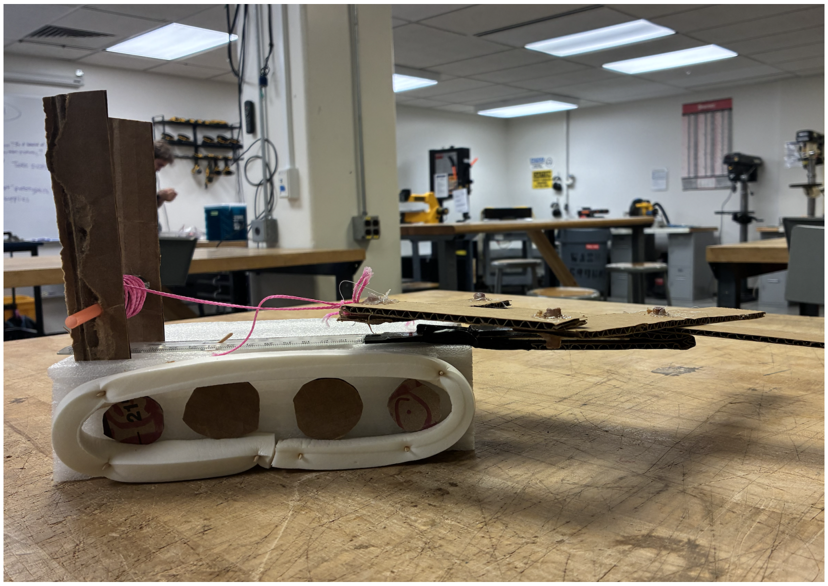


Figure 8: Side View

3.2 Function Tree

A function tree was created to understand what functions are needed from the waste collection robot in order to complete its required task. The tree begins with the basics of needing to be able to drive around and maneuver through tight windows. The rest of the functions revolve around the actions of picking up and depositing of the trash. The movement that is essential for the robot to complete and excel in the competition.

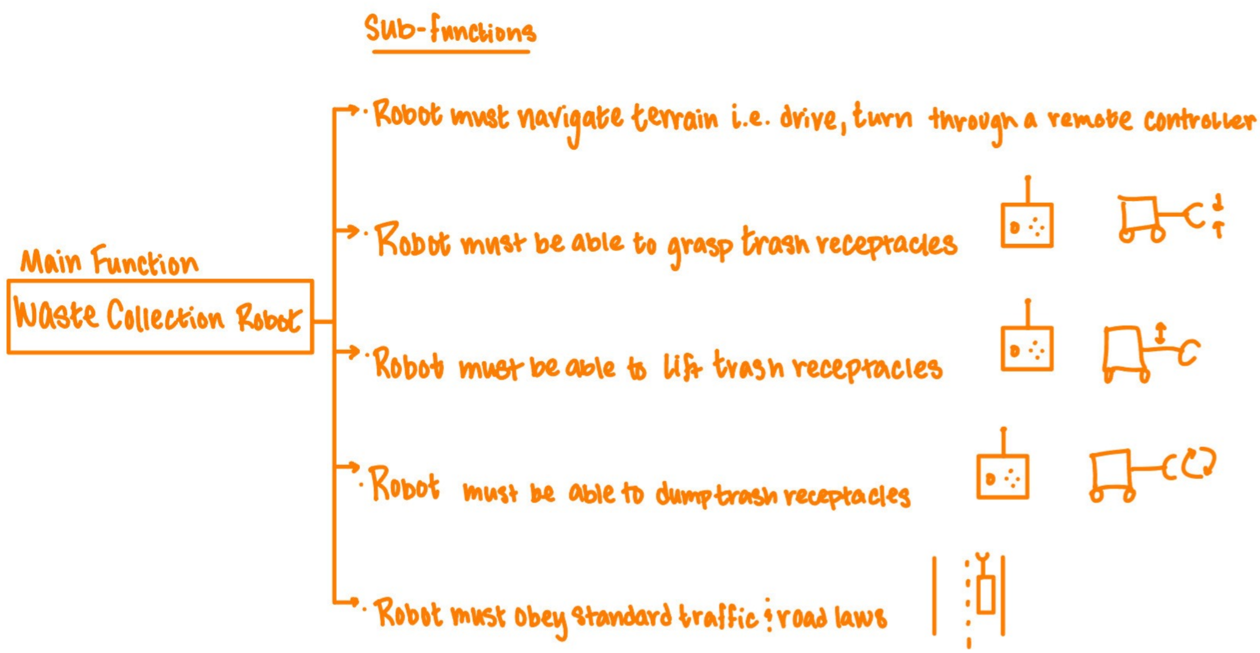


Figure 9: Function tree for robotic trash collector

3.3 Morphological Chart

After the subfunctions of the waste collection robot are designated in the function tree, the next step is to create a morphological, or morph, chart. A morph chart demonstrates different designs that adhere directly to and satisfy each individual subfunction. Then, a final design concept can be established by picking out a design feature from each row of the morph chart.

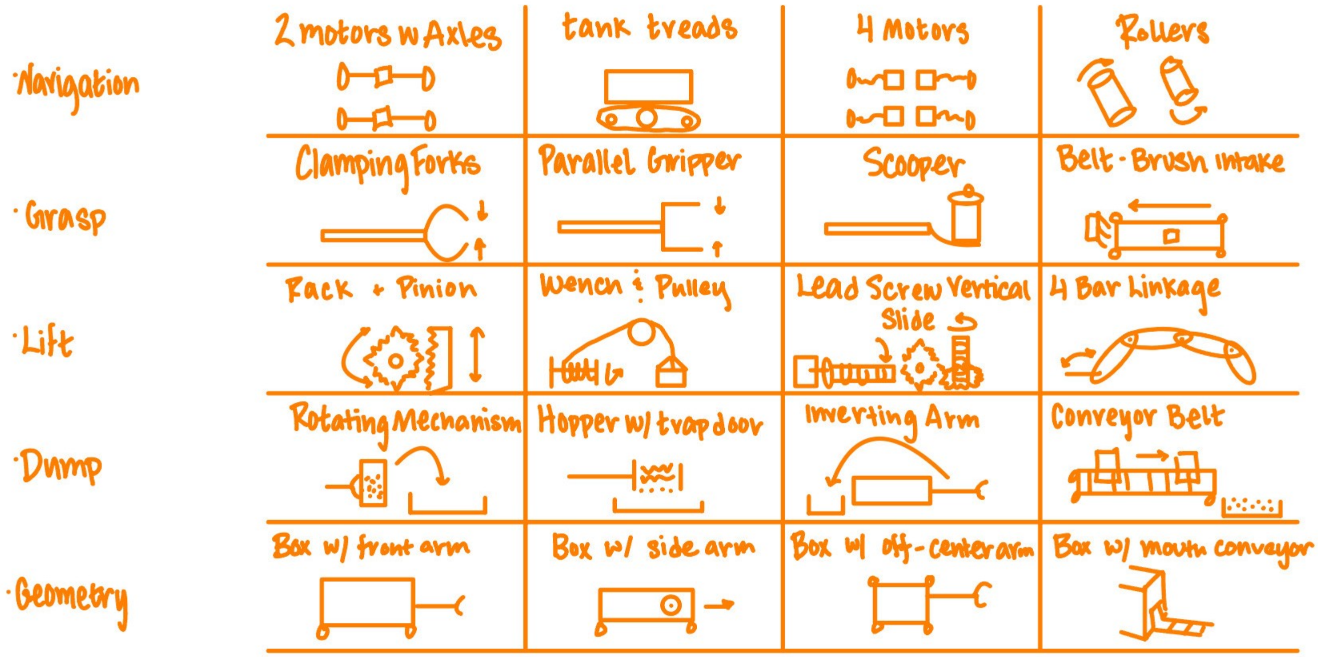


Figure 10: Morphological Chart for Waste Collection Robot

3.4 Alternative Design Concepts

3.4.1 Concept #1: Conveyor Belt Mouth Robot

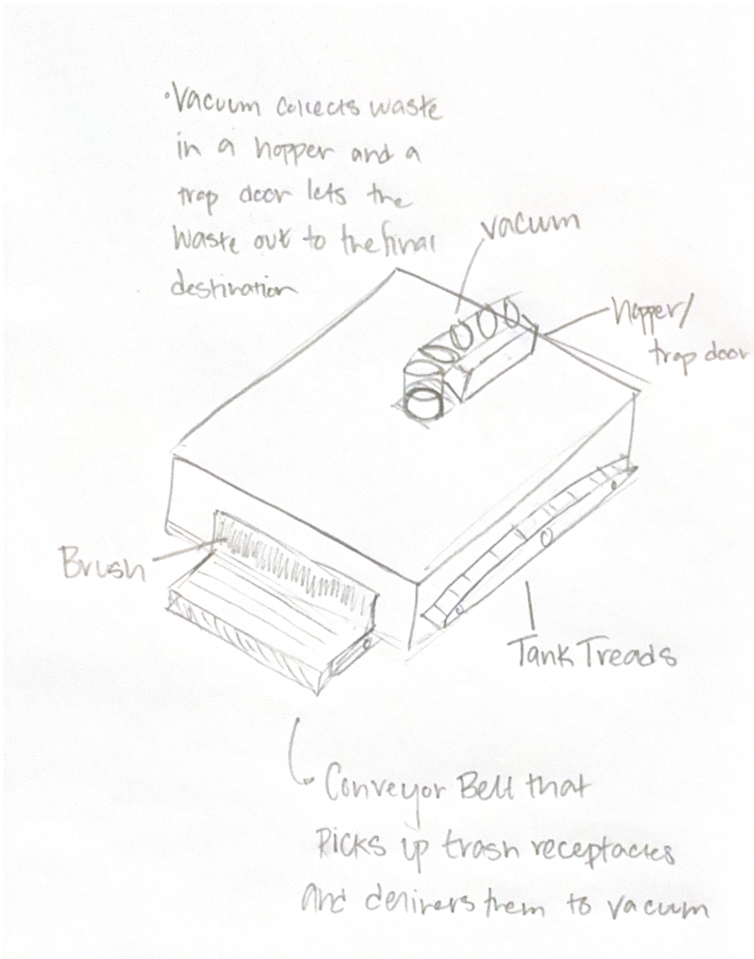


Figure 11: Sketches of Conveyor Belt Mouth Robot Concept

Description: This design uses a unique conveyor belt mechanism to intake each garbage bin. The bins then travel through the body of the robot, and the trash inside is vacuumed into a trapdoor equipped chamber. The trapdoor is controlled via actuators that can open and close when necessary to release the trash into collection areas. In this way, the robot can collect and deliver all of the trash to the collection area in one trip, rather than making multiple individual trips. The robot is driven by tank treads to eliminate the risk of deflation and increase maneuverability over uneven surfaces.

3.4.2 Concept #2: The Machine

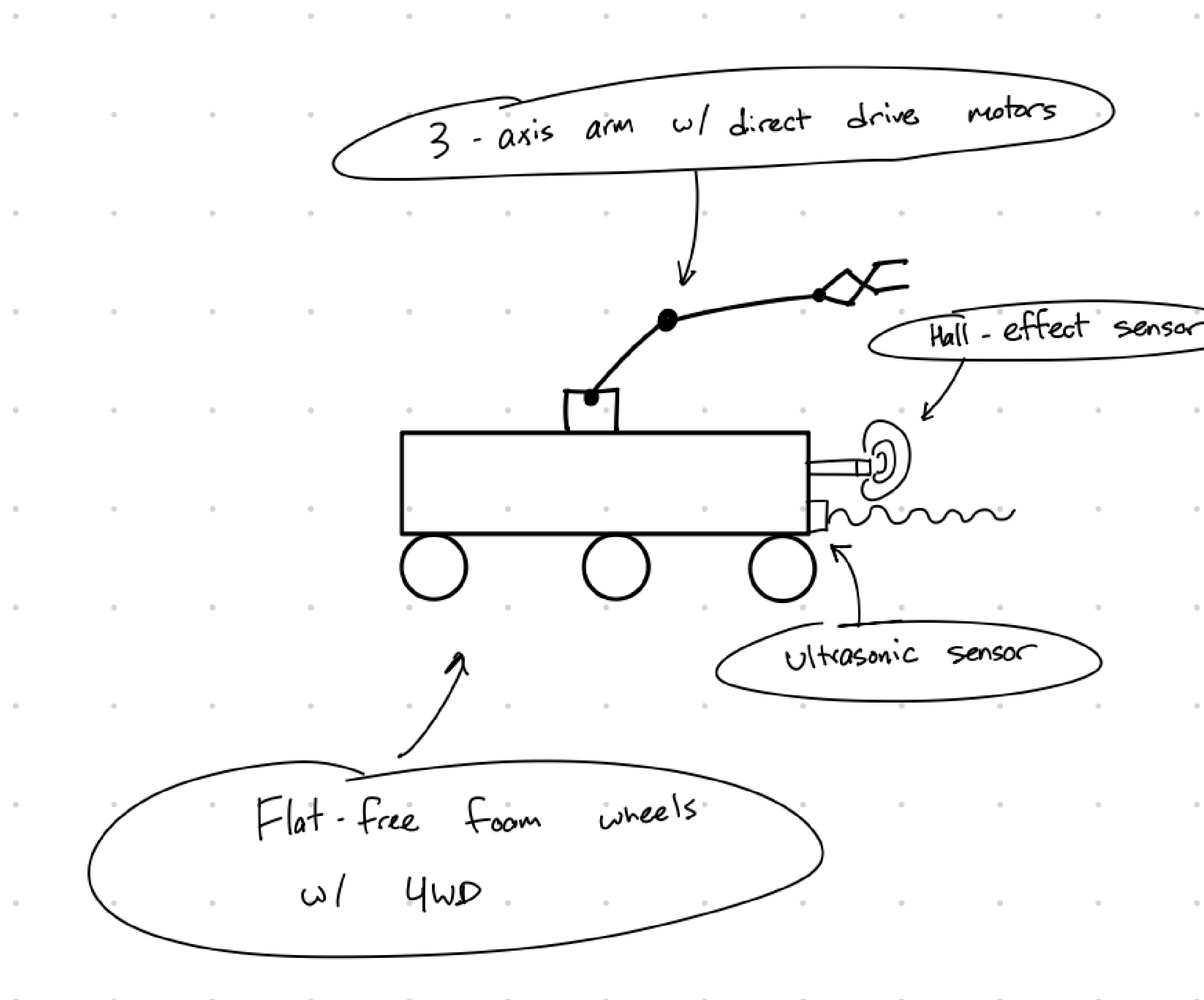


Figure 12: Sketches of "The Machine" Concept

<u>Description</u>: This concept utilizes a direct-driven 3-axis arm with an extendable grabber end-effector to load and unload individual garbage bins. Due to this design, multiple trips are required deliver all of the trash to the collection area. The robot utilizes an ultrasonic sensor for obstacle avoidance and rudimentary environment mapping. The robot also uses a hall effect sensor to validate that it is in place to collect a metal garbage bin. Finally, it is driven by 6 flat-free foam wheels that are controlled by 4 electric motors. This gives the robot speed, maneuverability, and eliminates the risk of punctures.

3.4.3 Concept #3: Wall-E

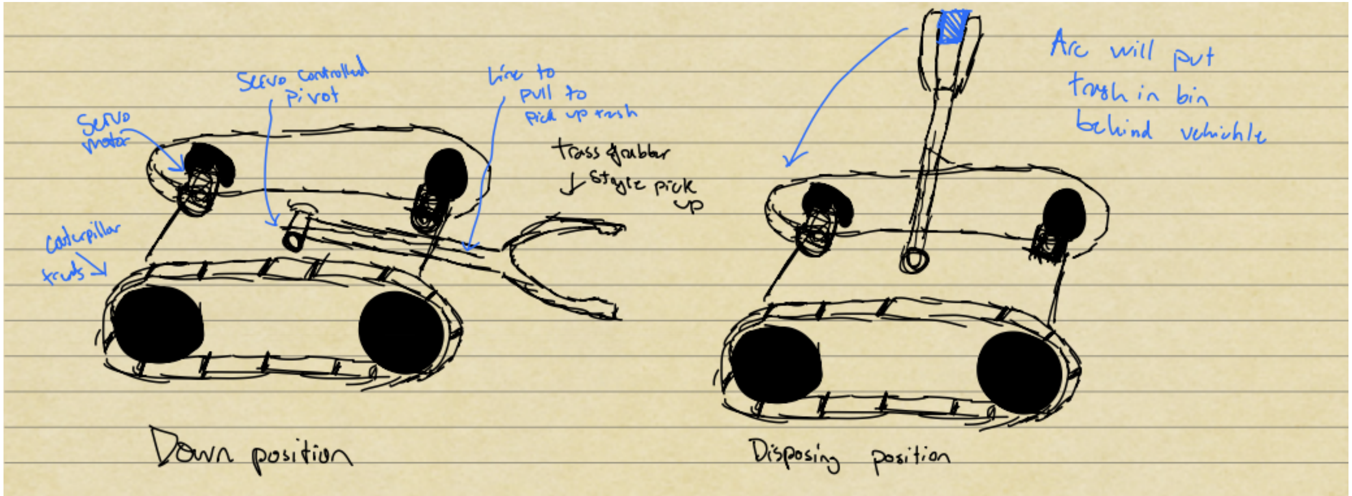


Figure 13: Sketches of "Wall-E" Concept

Description: This design a winch mechanism to control the position of the robotic grabber. This configuration vastly simplifies the controls of the robot, as the operator only needs to control one axis. When the winch is activated, it pulls the arm around a fixed pivot point in the middle of the robot's body. This causes the arm to lift and flip over to the back of the robot, allowing it to pick up and dispense trash in one fluid motion. It is driven by a single-axis servo motor that is connected to tank-style treads for better handling on uneven surfaces.

3.4.4 Concept #4: The Tank

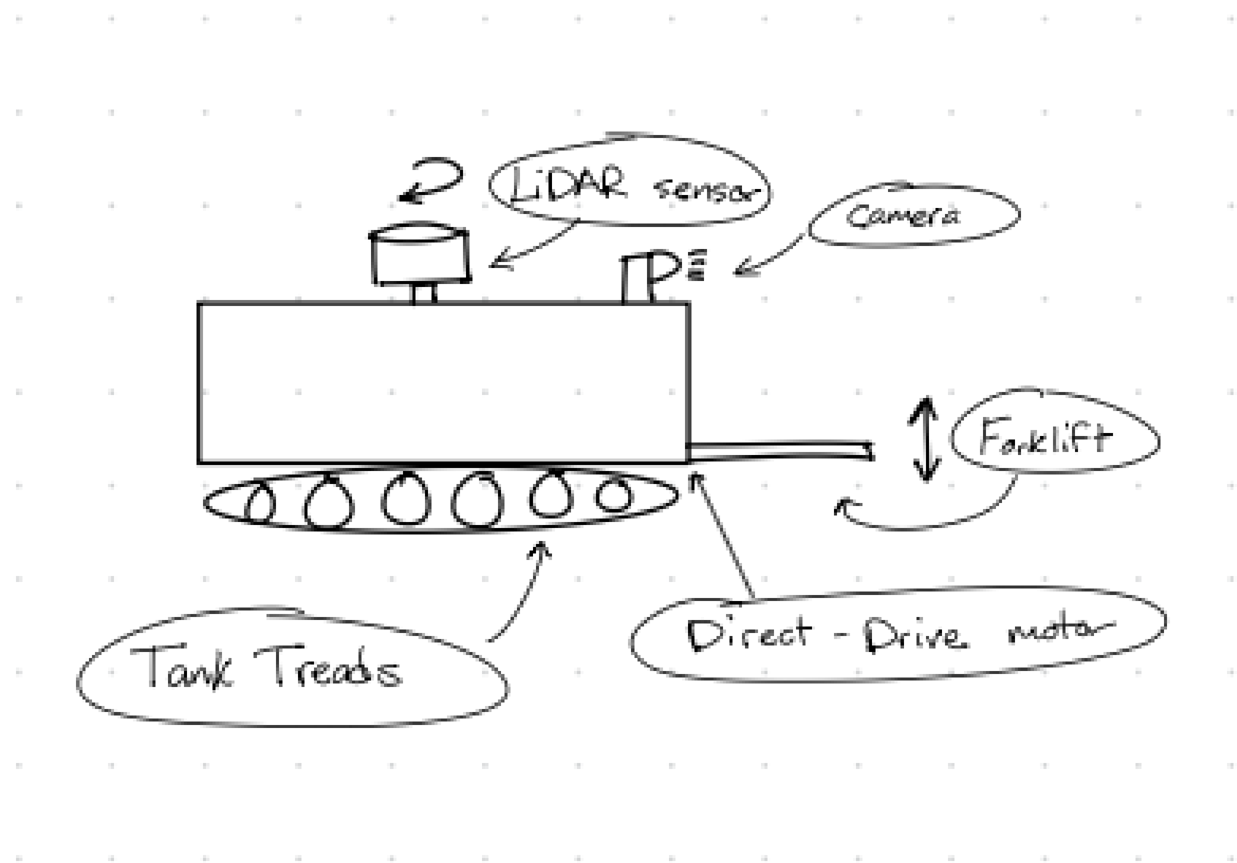


Figure 14: Sketches of "The Tank" Concept

Description: This concept utilizes a direct-driven forklift-style collection system to pick up and drop off trash cans. It uses a LiDAR sensor for advanced mapping of its surroundings, and combines that input with visual data from a forward facing camera. The operator can also utilize this camera to view the area ahead of the robot to confirm it is clear, or in position to properly collect trash. It is driven by tank treads for better traction on uneven surfaces.

4 Concept Selection

4.1 Selection Criteria

The first step in choosing a concept is creating and evaluating selection criteria. Figure 15 depicts the analytic hierarchy process (ahp) used to complete this first step. The ahp individually compares each selection criteria to every other criteria in order to calculate a weight that represents the significance of each criteria to the overall design.

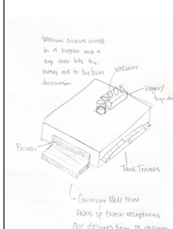
	Weight	Size	Speed	Manuverability	Picking and Placing	Row Total	Weight Value	Weight (%)
Weight	1.00	0.33	0.33	0.20	0.14	2.01	0.05	4.86
Size	3.00	1.00	3.00	1.00	1.00	9.00	0.22	21.77
Speed	3.00	0.33	1.00	0.33	0.33	5.00	0.12	12.09
Manuverability	5.00	1.00	3.00	1.00	0.33	10.33	0.25	24.99
Picking and Placing	7.00	1.00	3.00	3.00	1.00	15.00	0.36	36.28

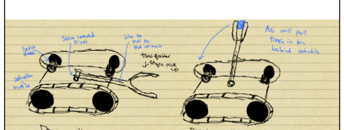
Figure 15: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

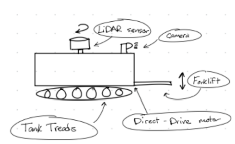
4.2 Concept Evaluation

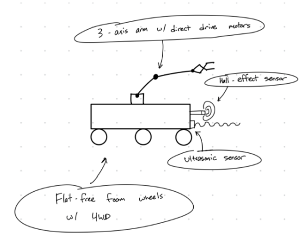
After completing the analytic hierarchy process, the weighted scoring matrix can be assembled. The weighted scoring matrix, observed in Figure 16 compares each of four concepts introduced in Section 4 based on the aforementioned selection criteria. Each criteria is also weighted according to the weight calculated from the ahp. This process ultimately leads to a final concept being selected as the most optimal design to move forward with.

Alternative Design Concepts









Solution Criteria	Weight (%)	Rating	Weighted	Rating	Weighted	Rating	Weighted	Rating	Weighted
Weight	4.86	3	0.1458	4	0.1944	2	0.0972	2	0.0972
Size	21.77	4	0.8708	3	0.6531	4	0.8708	1	0.2177
Speed	12.09	3	0.3627	3	0.3627	3	0.3627	3	0.3627
Manuverability	24.99	1	0.2499	2	0.4998	4	0.9996	3	0.7497
Picking and Placing	36.28	2	0.7256	5	1.814	3	1.0884	5	1.814
	Total Score	2.3548		3.524		3.4187		3.2413	
	Rank	4		1		2		3	

Figure 16: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

4.3 Evaluation Results

The best concept was our second design, which earned the highest overall score in the weighted scoring matrix. This design balances our project needs well, performing strongly in the picking and placing category. The claw and conveyor pickup mechanism are particularly effective at reaching into tight spaces, latching onto the model bins, and dumping them into the desired location. Since this task is arguably the most critical function for project success, it is significant that this concept achieved the highest score in this area. Our winning concept excelled in both weight and size, making it compact and manageable. However, maneuverability received a low score due to the use of treaded tracks instead of wheels. The tread system, while slightly less agile, adds stability and allows it to travel through rough terrain, even though our project does not require it. The system's speed was rated as average, but this was considered acceptable given its ability to navigate confined spaces and proficiency in handling the bins. The design uses standard components, including a tank inspired base, treads, servos, and the claw mechanism, making it practical to design and build. Overall, the second concept proves to be the most effective and efficient design when aligned with our project goals.

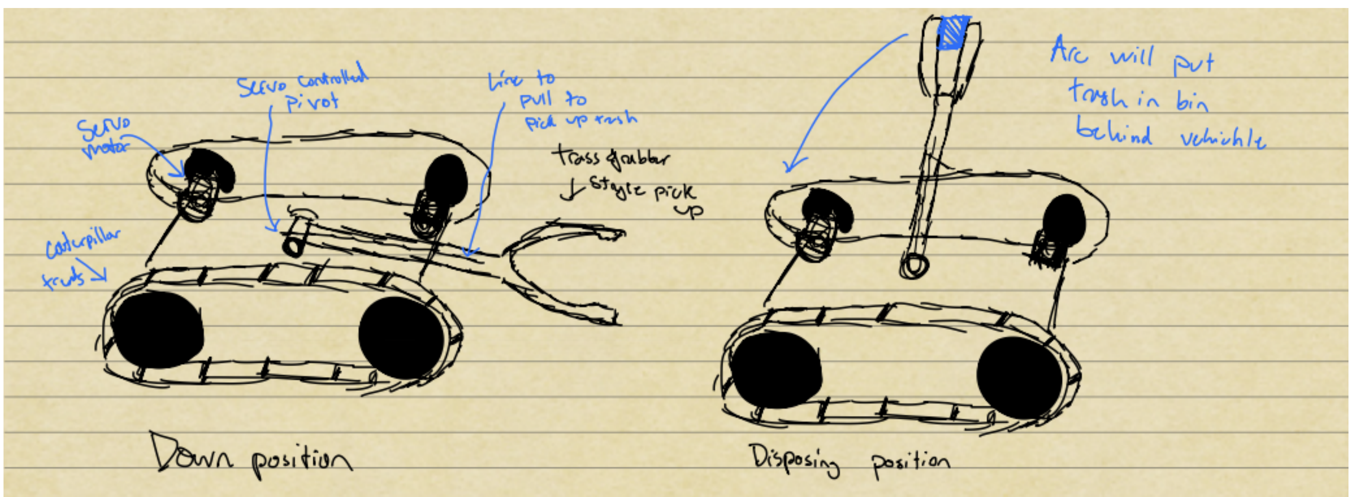


Figure 17: Final Concept Evaluation Results

4.4 Engineering Models/Relationships

4.4.1 Engineering Model 1: Turn Radius

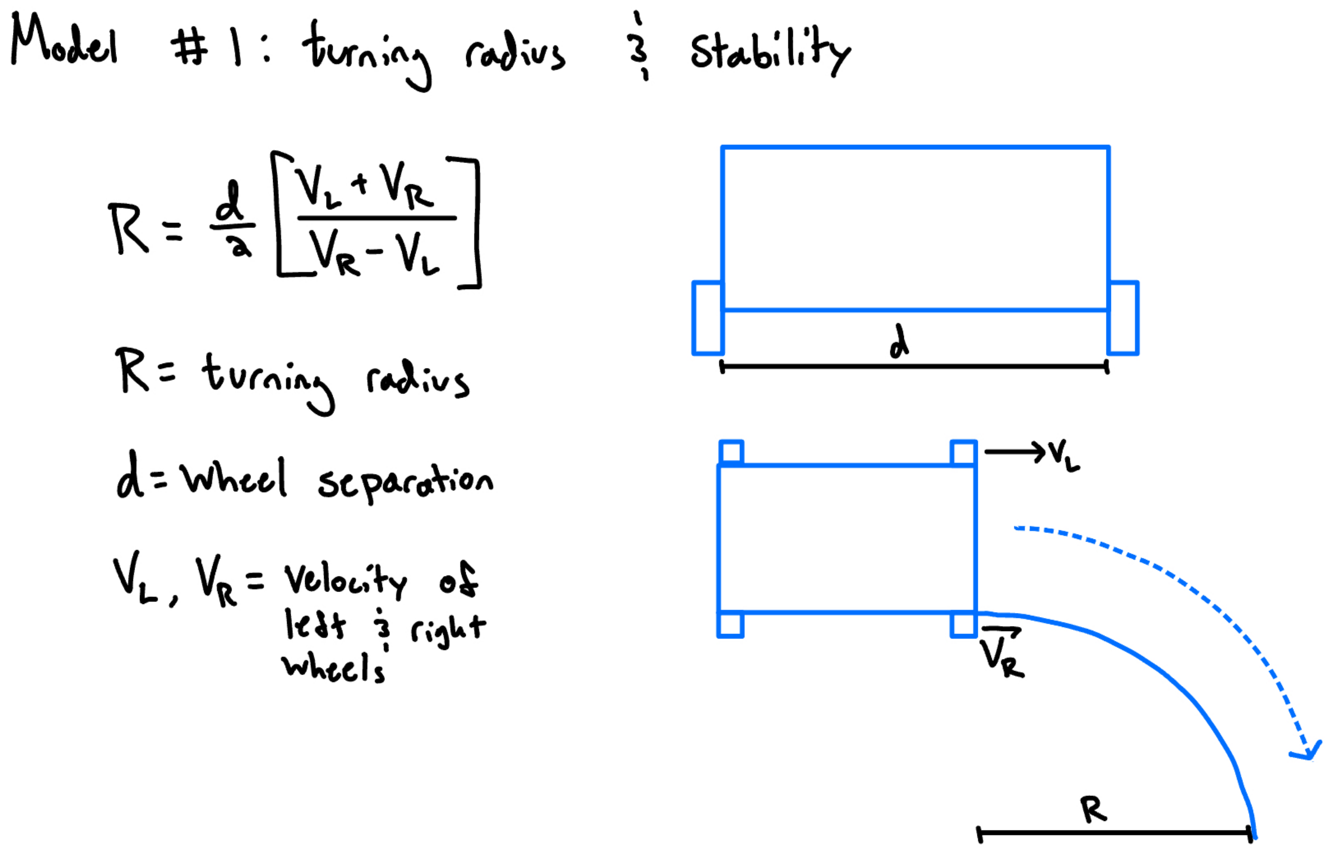


Figure 18: Diagram Showing Turn Radius Model

Engineering Model 1 in fig. 18 explores the turn radius required to clear the corners of the track. Knowing this will help determine design parameters for the body of our car, along with the rotational ability of our wheels. Without clearing the turn radius, our car would not be able to receive full points in the competition.

4.4.2 Engineering Model 2: Clamping Force

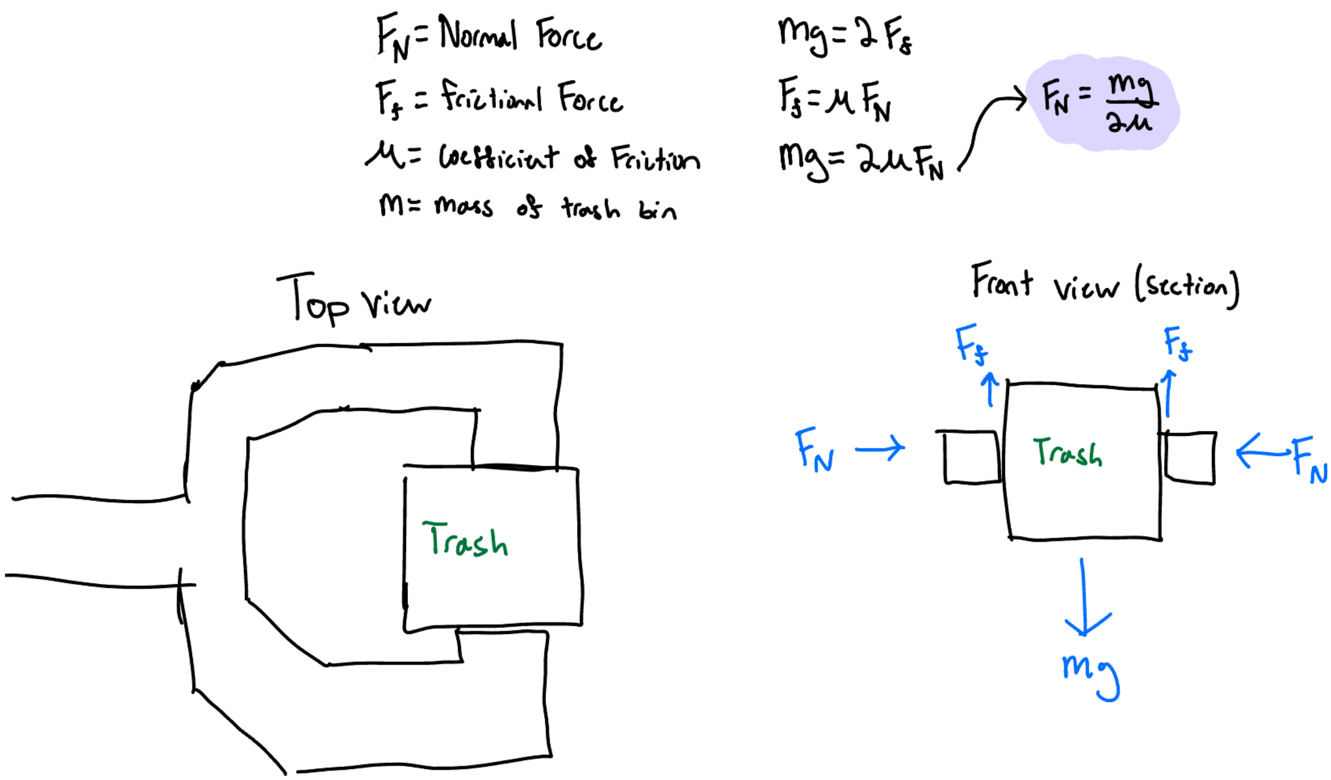


Figure 19: Diagram Showing the Clamping Force Model

Engineering Model 2 in fig. 19 is a free body diagram that explores the clamping force required to lift the trash can off of the ground. Based on the weight of the trash can and the friction coefficient of the material that grips the trash can, a clamping force can be found. Using that clamping force, we can employ a altered version of the torque model shown below to determine the servo to use on the hinge. Some key assumptions are made about the coefficient of friction and the horizontal nature of the clamps.

4.4.3 Engineering Model 3: Torque

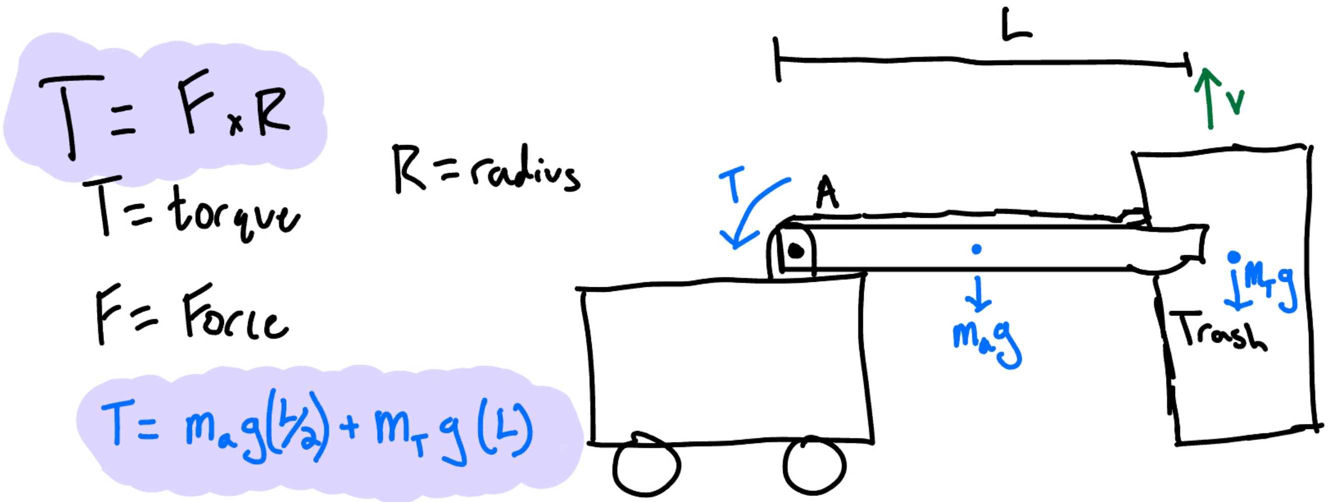


Figure 20: Diagram of Torque Model

Engineering model 3 in fig. 20 considers the torque on the motor at point A, required to lift the trash bin at the end of the mechanical arm. The torque is defined by the equation $Torque = Force * Radius$, with the forces in this case being the mass of the trash bin and the arm multiplied by the gravitational constant. The radius would be the length from point A to the center of mass of the object applying a torque on the motor. This is an important equation for us to consider as the proper torque rating will be required of the motor to lift the trash can off of the ground in order to move the bin towards the receptacle and complete the task at hand. Finding a servo motor is much easier once you know the required torque, rather than guess and checking, an expensive and time consuming process.

5 Concept Embodiment

5.1 Initial Embodiment

The initial prototype we created for our waste collection robot consisted of a chassis driven by 4 mecanum wheels and mounted with a 6-DOF, 3-axis servo arm. The servo arm was modified by removing one motor in addition to a significant portion of the arm housing to fit within the customer and road specifications. CAD models of our initial prototype can be found below.

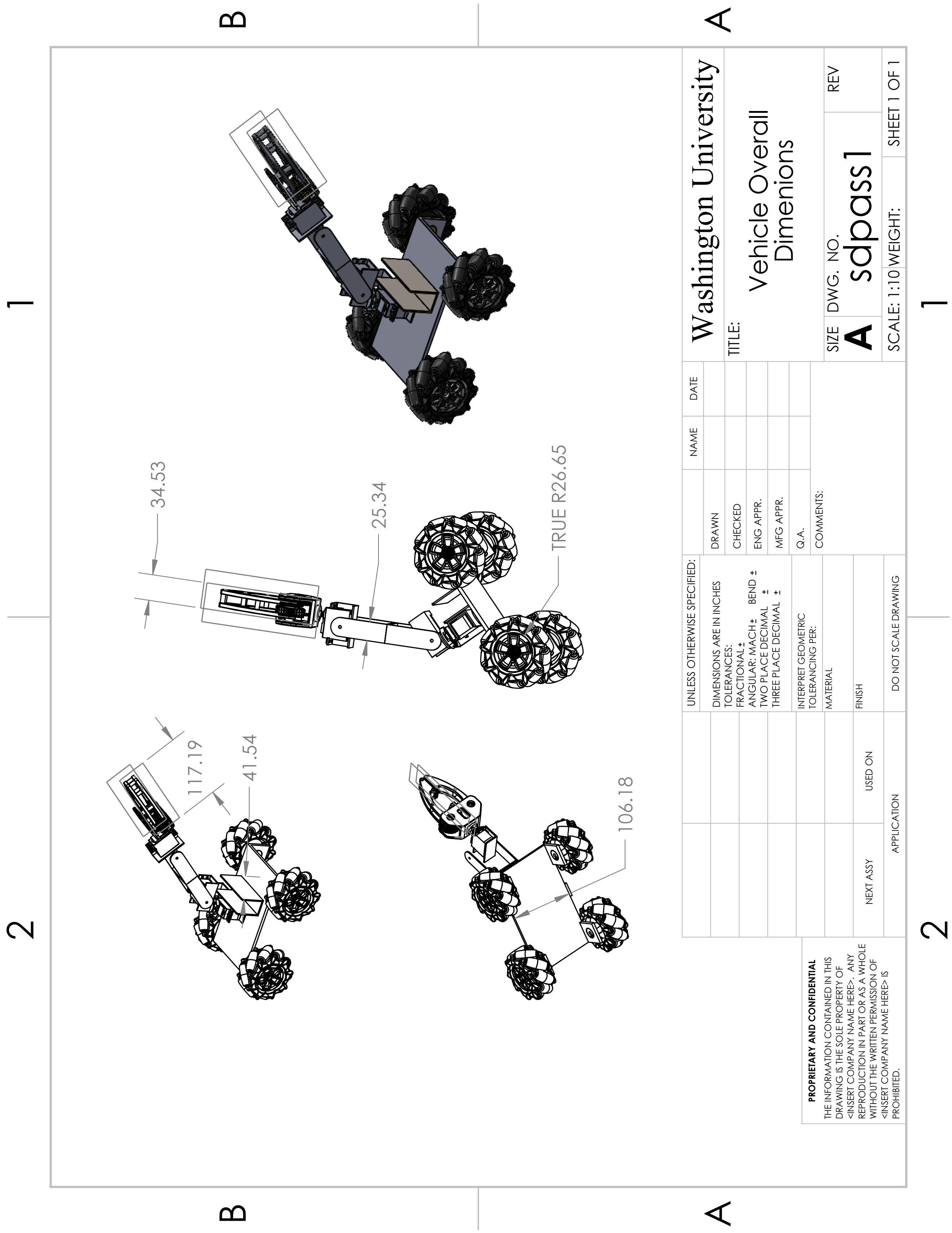


Figure 21: Assembled projected views with overall dimensions

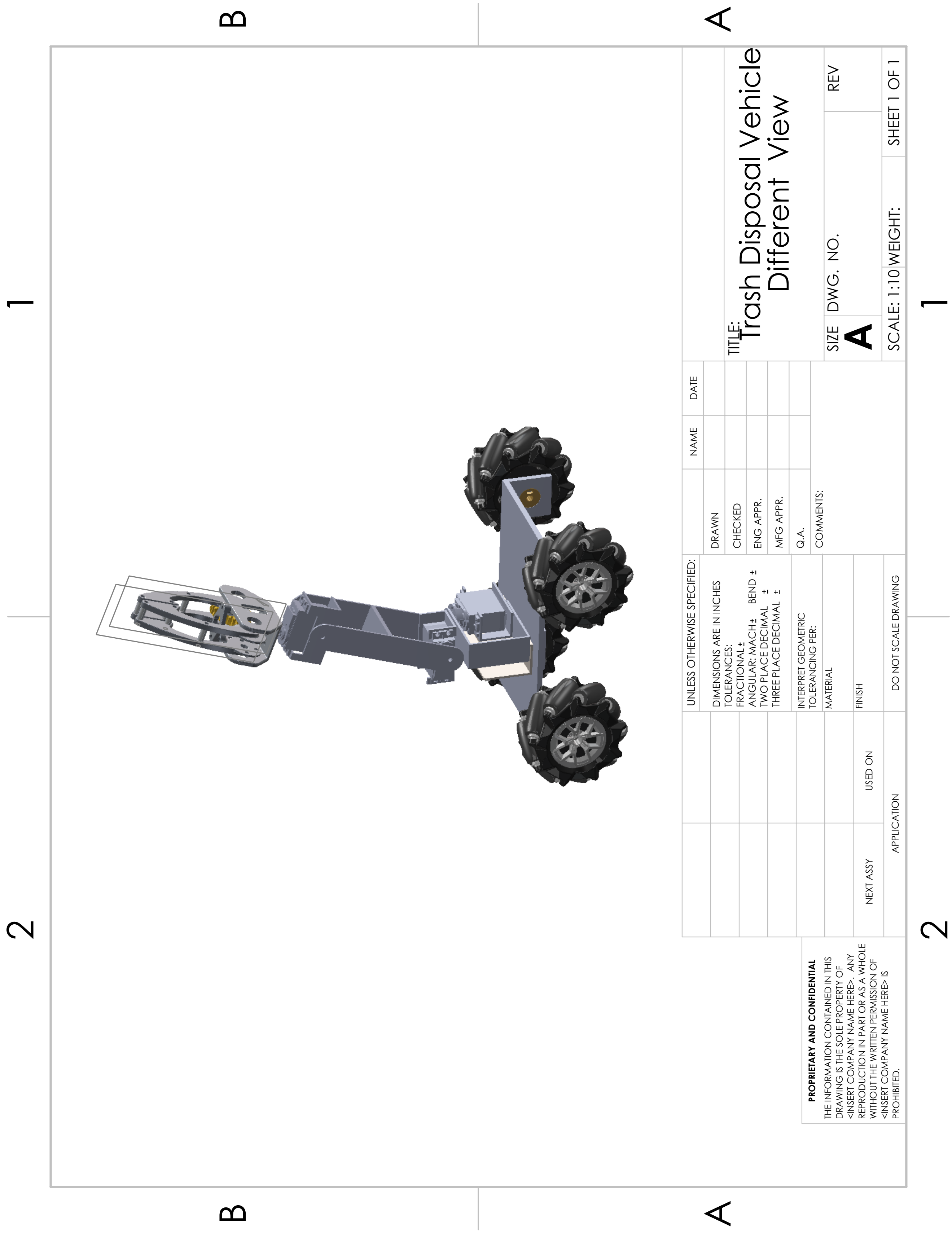


Figure 22: Assembled isometric view with bill of materials (BOM)

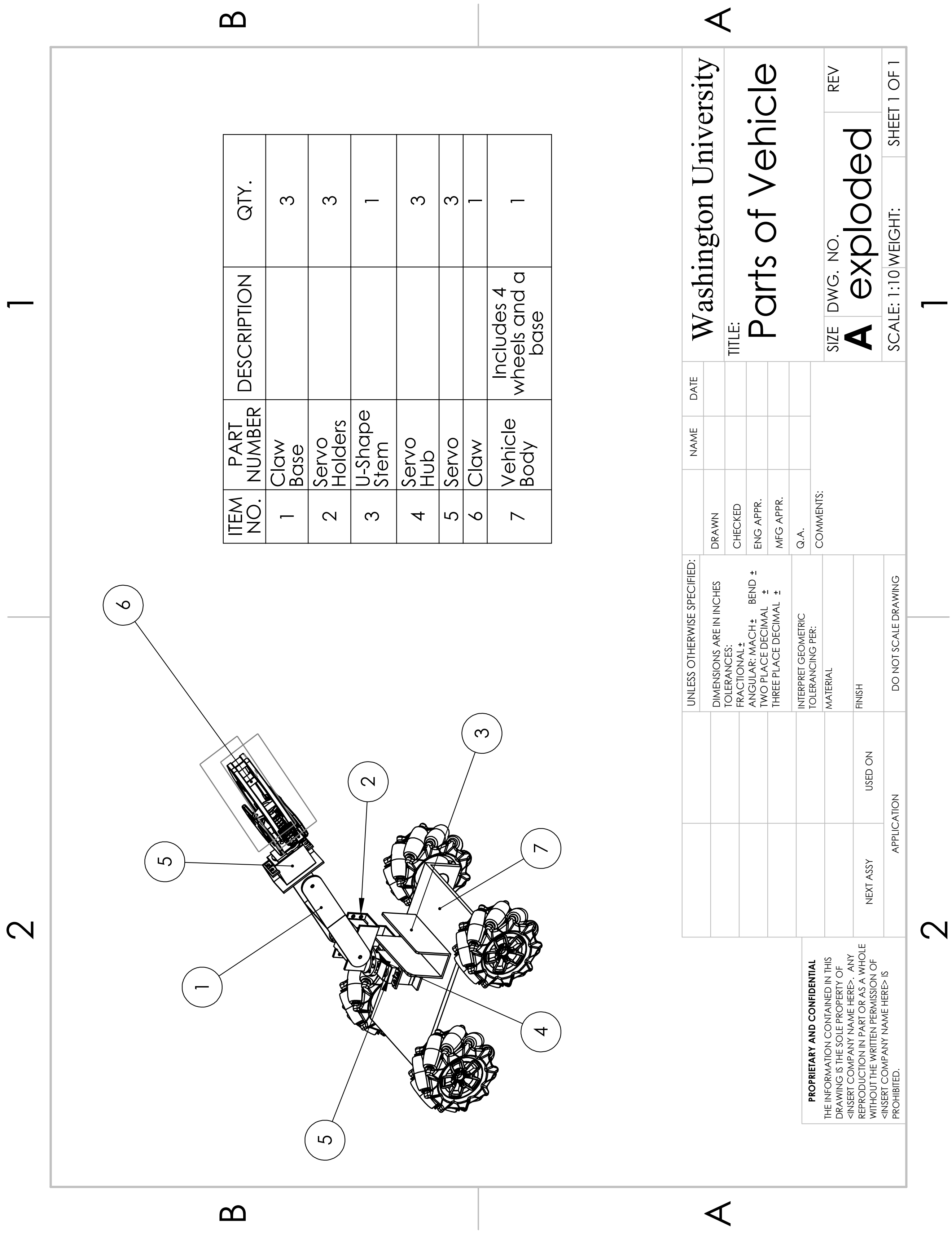


Figure 23: Exploded view with callout to BOM

5.2 Prototype Performance Goals

As the customer, Dr. Potter dictated three different performance goals to assess the success of the initial waste collection robot prototype. They are as follows:

1. **Goal 1:** The device is able to deliver $\geq$ 75% of garbage units to the receptacle within 5 minutes.

2. **Goal 2:** The device is able to deliver $\geq$ 50% of garbage units to the receptacle within 5 minutes and *no traffic violations.*

3. **Goal 3:** *Starting from outside of the Dumpsite*, the device can dump the contents of one full bin ($\sim$ 15 garbage units) into the receptacle with no spilled units. This must be demonstrated $\geq$ 5 times in a row.

5.3 Proof-of-Concepts

The first proof-of-concept that was created featured a nimble chassis design with tank treads to provide mobility and a 3-axis arm mounted on top to collect waste receptacles and dispose of garbage. The small format of the tank chassis worked well for traversing the obstacle course, and the arm was successful at picking up and rotating waste receptacles in order to dispose of them. However, the weight of the arm was too heavy for the tank chassis, and when it was mounted on top, the chassis was weighed down and could not move. Additionally, the motion of the tank-treads that was planned to be mapped to the DXS controller was found to be impossible to configure, given the nature of the controller and it being made for drones.

Moving forward, it was clear a heavier, sturdier chassis and stronger batteries were needed to power the servo motors on the arm. Additionally, stronger motors were needed to power the tank treads to withstand the weight of the arm.

5.4 Design Changes

Since our original concept selection in fig. 17, quite a few things have changed. The overall idea behind the tank drive have not changed, but due to problems with the first set of tanks treads, we have moved to wheels. We are still keeping the tank drive concept to increase maneuverability in tight spaces. However, with the wheels in its place, we have lost substantial traction and balance when moving over the hill. The wheels also increased the vehicles overall size. In the future we will be looking to swap out smaller wheels.

The garbage collecting arm, on the other hand, has seen quite a bit of change. Because our vehicle footprint has increased in size, we could no longer pick up trash cans off center in a confined space. This meant that we had to be able to pivot the arm about more axes than the one. We went forward with an off the shelf 6 axis arm, which we have modified to be lighter and simpler to control, using only 3 axis with a claw attached to the end. This new design allows us to pick up a trash can anywhere in the front half of the car. It also make disposing of the trash much easier, being able to deposit trash from any angle.

Overall, the chassis has also increased in size. We added an upper level to hold the arm, while the electronics are stored on top of the lower surface. This was due to the increase in electronics required to support the 4 servos on the arm, as well as, to keep the arm from colliding with the wheels or electronics.

6 Design Refinement

6.1 Model-Based Design Decisions

6.1.1 Component 1: Torque required to lift trash bin

Using the governing equation for torque: $Torque = Force * Radius$, we can determine if the motor on the robotic arm has enough torque to life the trash can. Shown in fig. 29 below is a diagram of the torque demanding movement.

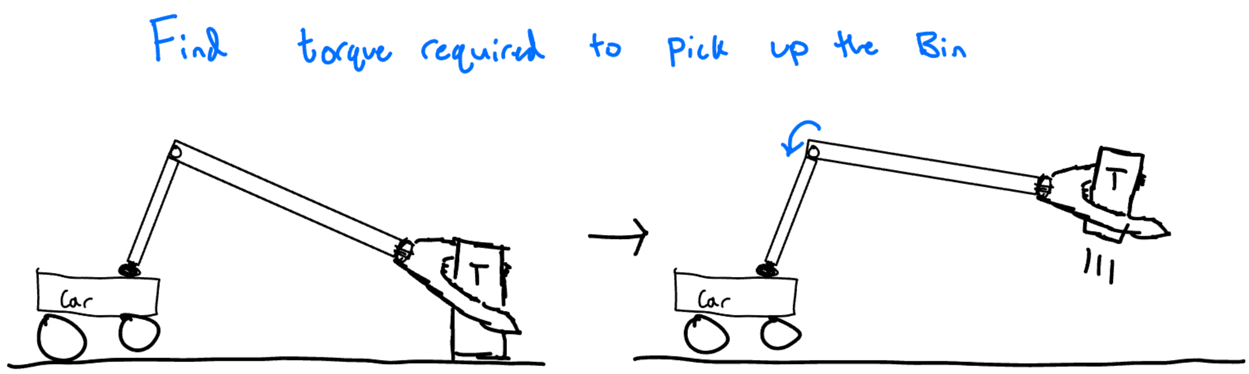


Figure 24: Diagram of robotic arm picking up trash bin

The car will drive up to the trash bin and grasp the receptacle. The servo in question will then rotate the long part of the arm to lift the trash can off of the ground, allowing the car to move freely. Shown in fig. 30 below is the math used to confirm the motor was powerful enough for the task.

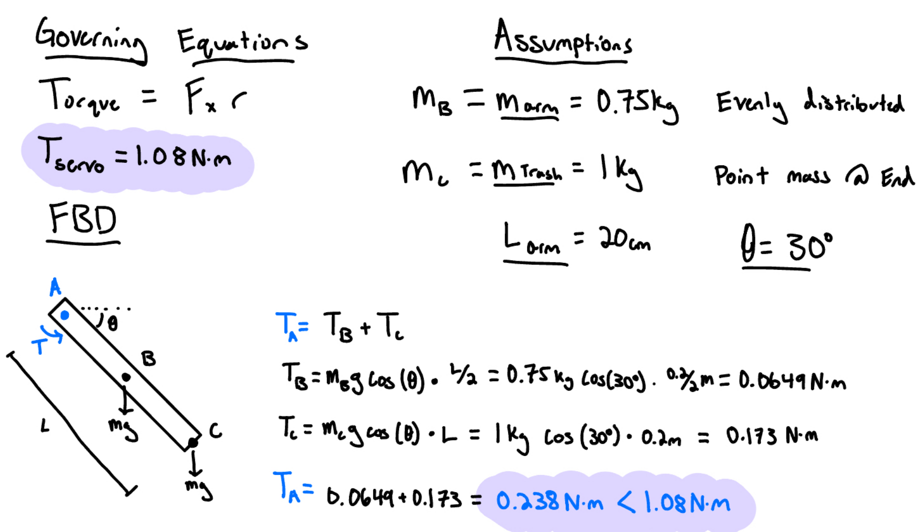
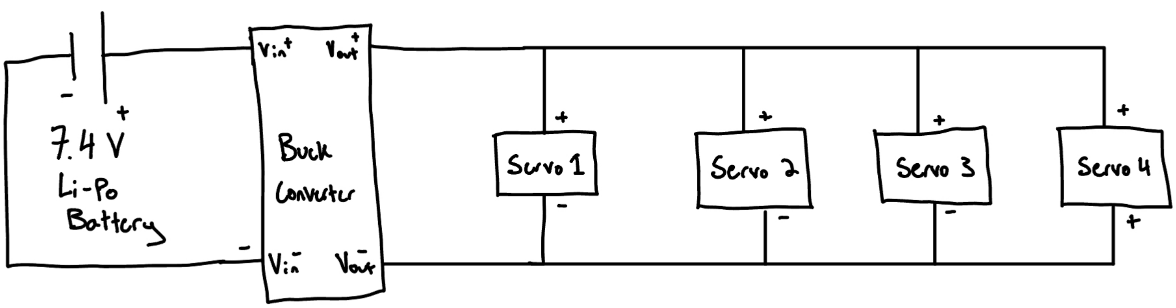


Figure 25: Torque calculations

As mentioned above, the governing equation for torque is $T = F * R$, with F being the force in the perpendicular direction, and radius being the distance from the pivot point to the location the force acts at along the axis. Assumptions and rounding were used to simplify the calculations. Values for the masses, length and angles are shown as rounded figures from their real life values. The mass of the arm is assumed to be evenly distributed and thus can be represented as a point mass at the middle of the arm. This is the same for the trash bin, which is represented at the end of the arm. Per the motor specifications, it has a torque of $1.08Nm$. After calculations, the torque required of the motor is $0.238Nm$, well below the motor's threshold. After having complications with the movement in the initial prototype, a motor with sufficient torque was selected based on these equations.

6.1.2 Component 2: Electronic Mapping

We have iterated and implemented an electronics circuit that allows the robotic arm to function continuously without over-currents or voltage brownouts. In our setup we have a mechanical arm that requires 4 servos to pick up and dispose of the garbage. Powering 4 servos in parallel proved to be challenge for us. In order to finalize our design, we used a electronic circuit diagram to determine the power, amperage and voltage necessary from the battery to run sufficiently. Our maximum mechanical restraints require that we run 4 servos at stall current for 5 minutes. This would never happen practically in the competition, but it is an benchmark we will use to ensure safety of system. Figure 35 displays the overall circuit schematic for the servos and its power supply.



Buck converter Specs:

$V_{out} = 6V$

$I_{max} = 12A$

Servo Specs:

$V_{in} = 6V$

$I_{Stall\,(max)} = 2.5A$

$V_{out} = V_1 = 6V$ (In-Parallel) $\rightarrow V_1 = V_2 = V_3 = V_4 = 6V$

$I_{Stall\,(4\,servos)} = I_1 + I_2 + I_3 + I_4 = 10A$

$I_{max} > I_{Stall} \rightarrow 12A > 10A$

Figure 26: Diagram of Robotic Arm Circuit

Our circuit begins with the 7.4V Li-Po Battery on the left. The battery feeds into a buck converter, which can be simplified to the specs shown below the diagram: $6Vout, 12Amax$. The first thing we need to do is ensure that the voltage and amperage are sufficient for running 4 servos in parallel. The relationship for voltage is as follows: $V_{\text{out}} = V_1 = V_2 = V_3 = V_4$. Knowing that voltage in parallel is equal across the servos, and the motors are rated to run on $6V$, we can confirm the voltage will be sufficient for the motors to run. For amperage, the story is a bit different. The equation for current is as follows: $I_{\text{max}} = I_1 + I_2 + I_3 + I_4$. At a stall current of $2.5A$, the max current required to run all 4 motors is $10A$, less than the maximum current supply from the buck converter of $12A$. The last equation we want to confirm is the power supply being sufficient enough to run the robot for the entire competition. This is shown in fig. 27 below.

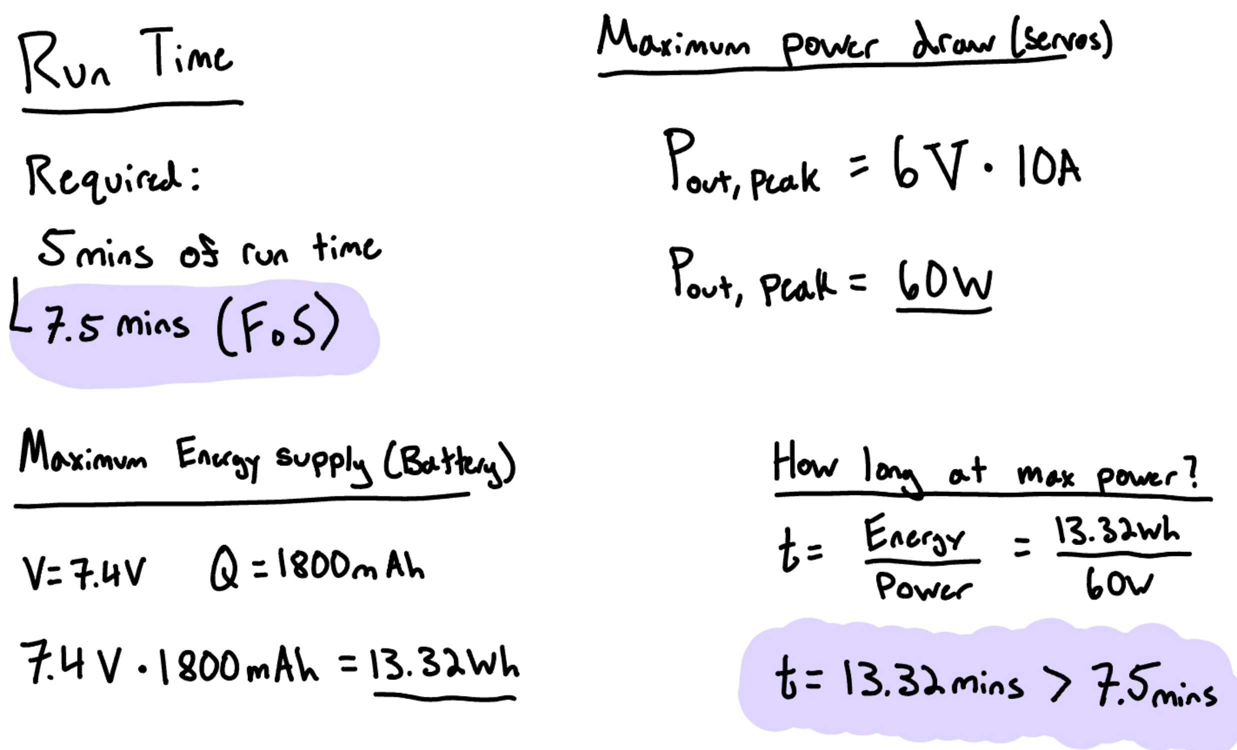


Figure 27: System Power Calculations

Using the same assumptions of constant $2.5A$ current and $6V$ voltage pull from each servo across the entire competition, we will calculate the power draw from the motors against the energy supplied by the battery to find the run time for the system. Given these assumptions, and the equation for power: $P = V * I$, the maximum power draw from the servos will be $60W$. To calculate the energy supplied by the battery we multiplied the voltage supply by the battery capacity to find a $13.32Wh$ energy supply. For the competition we will use a 1.5 factor of safety, designing for a 7.5 minute competition, rather than the standard 5 minutes. Dividing the energy supply by the power required, we find that the system can run for over 13 minutes. This is 5+ minutes over our required run time, satisfying our requirements.

6.2 Design for Safety

6.2.1 Risk #1: Battery Overheating

Description: The vehicle uses a breadboard, jumper wires, a lithium battery pack, and an Arduino shield. If any loose wires create a short circuit, the battery may draw excessive current and begin overheating or producing smoke.

Severity: Catastrophic, since lithium battery failure can potentially lead to fire.

Probability: Likely that overheating or smoke could occur under a short circuit, but full ignition is unlikely.

Mitigating Steps: Neatly organize and secure all wiring, isolate the battery from conductive components, insulate exposed connections, and closely monitor the system whenever power is applied.

6.2.2 Risk #2: Pinch Injury from Robotic Arm

Description: The metal robotic arm uses high-torque servos that often rotate unexpectedly during power-on. While adjusting wiring or repositioning components, fingers may get caught between the arm's linkages, causing a painful pinch or minor cut.

Severity: Critical, as this can result in noticeable bruising or lacerations.

Probability: Occasional, since frequent adjustments are made while the system is powered.

Mitigating Steps: Ensure power to the arm is fully disconnected before making any adjustments. Avoid placing hands near joints during actuation.

6.2.3 Risk #3: High-Speed Impact

Description: The wheel system enables fast lateral and diagonal movement. If a Bluetooth command lags or the system becomes unresponsive, the vehicle may continue traveling and collide with a person in its path.

Severity: Marginal, because the lightweight chassis would likely cause only minor discomfort upon contact.

Probability: Unlikely, as operators maintain awareness during testing and can avoid the vehicle if control is lost.

Mitigating Steps: Test the vehicle at reduced speed, maintain visual awareness, and be prepared to intervene quickly if movement becomes unpredictable.

6.2.4 Risk #4: Electrocution Hazard

Description: The battery pack can supply enough current to create a mild shock if a short occurs. Although the voltage is low, sweaty hands or damaged insulation reduce skin resistance, increasing the chance of accidental shock during wiring adjustments.

Severity: Marginal, since the system voltage is too low for severe injury but may still cause brief shock or sparks.

Probability: Occasional due to continuous interaction with jumper wires and the breadboard during operation.

Mitigating Steps: Replace damaged wires, insulate exposed leads, keep hands dry, and ensure power is off before touching internal wiring.

6.2.5 Risk #5: Vehicle Tipping

Description: The robotic arm is relatively heavy and can extend far outward, raising the center of gravity. On uneven or elevated surfaces, this may destabilize the chassis and cause the vehicle to tip over.

Severity: Critical, because tipping can damage servos, electronics, or wiring.

Probability: Seldom, as the team incorporated a wider base and positioned heavier components low in the chassis to reduce the risk.

Mitigating Steps: Maintain a low center of gravity, use a wide wheelbase, and avoid rapid or extreme arm movement when the vehicle is navigating unstable surfaces.

		Probability of Risk				
	Category	**Frequent** Likely to occur immediately or in a short period of time; expected to occur frequently	**Likely** Quite likely to occur in time	**Occasional** May occur in time	**Seldom** Not likely to occur but possible	**Unlikely** Unlikely to occur
Severity of Risk	**Catastrophic**		Risk #1			
	Critical			Risk #2	Risk #5	
	Marginal			Risk #4		Risk #3
	Negligible hazard presents a minimal threat to safety, health, and well-being of participants; trivial					

Figure 28: Heat Map

Each risk is carefully placed on the Heat Map based on its assessment of severity and likelihood for each risk to occur. Risk 1 reflects the battery overheating and falls in the "catastriophic-likely" region due to its lithium battery. The battery failure is highly likely and when exposed wiring, the chances of a short circuit increases. Risk 2 was categorized as "Critical-Occasional" due to the arms unreliable movement nature. When testing, control was often lost and it would act without any command, increasing the likelihood of a finger getting caught between the joints. Risk 5 is categorized as "Critical-Seldom" since tipping can damage electrical components. Risk 4, electrocution hazard, falls under "Marginal-Occasional" since the system runs at such a low voltage but can happen definitely happen. Finally, Risk 3, high-speed impact, is of least concern since it can only go so fast and is fairly lightweight.

6.3 Design for Manufacturing

Current Part Count: 30
Threaded Fasteners: 46

6.3.1 Theoretically Necessary Components (TNCs)

- **Wheels:** Each wheel must rotate independently to enable the omnidirectional movement required by the mecanum drive system.

- **DC Motors:** Each wheel requires its own DC motor so that the robot can independently control wheel direction and speed, enabling strafing, rotation, and diagonal motion.

- **Robotic Arm Joints with Servos:** Each servo-driven joint must move independently, providing the 6 degrees of freedom necessary for accurate arm positioning and manipulation.

- **Arduino + Motor Driver Shield:** These components must remain separate because they perform different electrical and thermal functions. The Arduino handles microcontroller logic, while the shield handles high-current motor driving.

- **Battery Pack:** The battery must remain separate to allow for easy removal, replacement, and charging.

- **Claw Mechanism:** The claw requires independent movement of its fingers, making it necessary for the gripping mechanism to exist as its own component.

6.3.2 Reducing the Number of Components

The most effective way to reduce the number of TNCs in the current design would be to simplify the robotic arm. The arm currently uses four servos to accomplish a basic task of grabbing a trash bin and dumping its contents. A redesigned arm could theoretically achieve the same function with only two servos: one to actuate the claw for gripping, and one to provide lateral movement for positioning. A separate mechanical dumping mechanism could be integrated to handle the bin-emptying motion while reducing servo count.

Additionally, the Arduino, motor driver shield, and breadboard could be replaced with a single custom PCB. This unified board would integrate the micro-controller, motor drivers, power distribution, and Bluetooth module, significantly reducing the number of individual components while improving reliability and manufacturability.

6.4 Design for Usability

6.4.1 Vision impairment

Individuals who suffer from vision impairment such as red-green color blindness or presbyopia may find it difficult to navigate the waste collection robot via a computer as a remote controller. Any sort of vision impairment will affect the operator's ability to observe the robot's responses to their inputs. Even colorblind individuals may struggle depending on the color of the lane lines and the environment the robot is in. There is not a clear solution to aid individuals with partial blindness, but the stage and obstacles can be constructed with colorblind-friendly material.

6.4.2 Hearing impairment

Individuals who suffer from hearing impairments such as presbycuria may find it difficult to operate the waste collection robot in the case of a motor or part failure. A clear sign of motor failure can be stalling which might be difficult to observe visually in a single motor but there is a clear auditory cue to indicate this kind of failure. One solution would be to always operate the waste collection robot with a teammate who does not suffer from a hearing impairment.

6.4.3 Physical impairment

Individuals who suffer from a physical impairment such as arthritis, muscle weakness, or limb immobilization will certainly find it difficult to operate the waste collection robot via a remote controller. The controller must be interfaced with physically to control the robot, and therefore even arthritis could introduce difficulty in its operation. We have implemented the use of a computer as the remote controller, allowing for people with hindered dexterity to operate the robot with more success, as the inputs require the user to push keys rather than toggle a joystick. However, this does not solve usability for everyone with impairment. One solution would be introducing a control system with LiDAR sensors that allows the robot to automate its waste collection task.

6.4.4 Control impairment

Control impairments such as those caused by distraction, excessive fatigue, intoxication, or medication side effects will also certainly influence the usability of the waste collection robot. These impairments will introduce difficulty in operating the remote controller that interfaces with the robot. Again the solution is presented by introducing a control system that allows the robot to complete its waste collection task autonomously. LiDAR sensors and a machine automated program that can carry out the tasks of the competition could enable the robot to navigate its surrounding environment without a remote operator.

7 Final Prototype

7.1 Overview

Overall, our final prototype was able to complete all 3 of our performance goals. It was able to deliver 6 bins in <5 minutes, delivered 4 bins with minor traffic violations, and dumped the contents of 5 bins into the trash receptacle without spilling. The following section details the final system architecture, and the overall robot.

7.2 Model-Based Design Decisions

7.2.1 Component 1: 4-Degree of Freedom (DOF) Robotic Arm

We chose a robotic arm to pick up and dispose of the trash. The reason we originally chose the robotic arm was for its ability to pick up trash cans that are off axis and in tight locations, as well as, dispose of trash efficiently and effectively. Originally, the arm we were using had 6-DOF. This proved to be too heavy and too complicated for our servo motors and arduino. We quickly realized we needed to follow the engineering principle: *simple is better*. Dealing with the materials we had, we evaluated which axes we absolutely needed, which axes would be nice to have and which are absolutely unnecessary. We briefly tried out a 3-DOF system before landing on the 4-DOF system shown below in fig. 29.

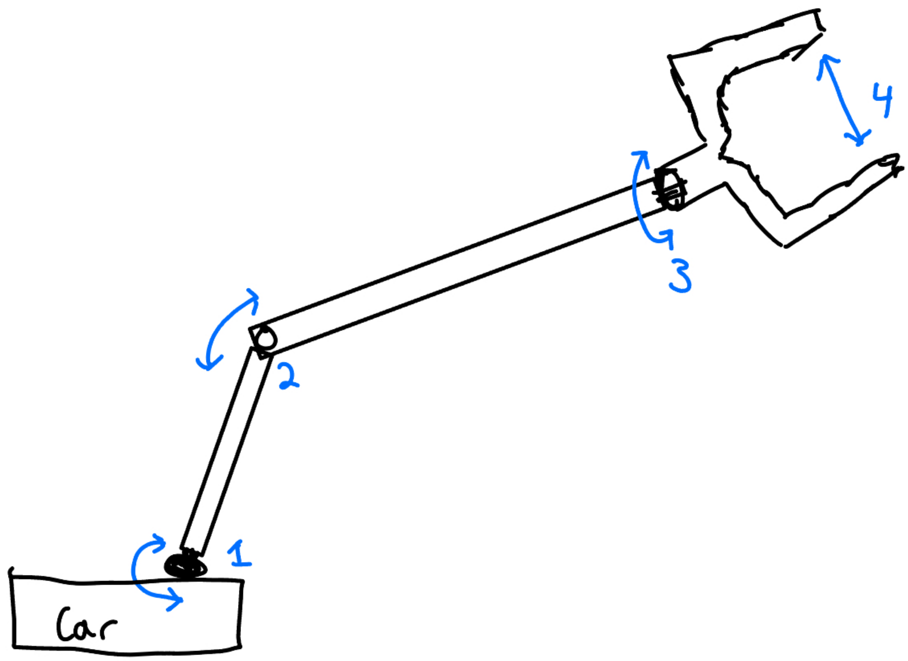


Figure 29: Diagram of Robotic Arm

Figure 30 shows the robotic arm through its applicable range of motions.

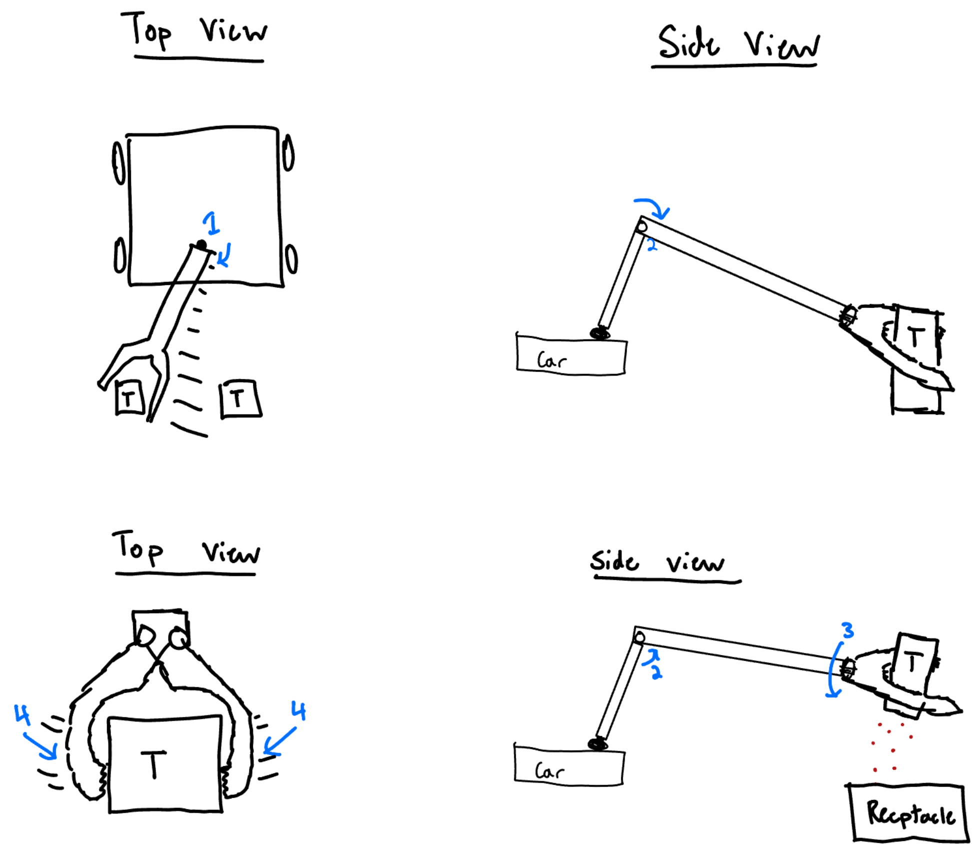


Figure 30: Diagram of Robotic Arm Movements

The first pivot allows the arm to line up with a trash can anywhere in the front 180°'s of the car. The second pivot allows the arm to rotate from touching the ground to sticking 90°'s vertical in the air. The fourth pivot gives the ability to squeeze and release the trash can from the end of the arm. Lastly, the third pivot allows the hand to rotate. This provides the ability to invert the trash can when dumping pieces into the receptacle.

7.2.2 Component 2: Electronic Mapping

We have iterated and implemented an electronics circuit that allows the robotic arm to function continuously without voltage or current brownouts or over-currents. Figure 35 displays the overall circuit schematic for the servos and its power supply.

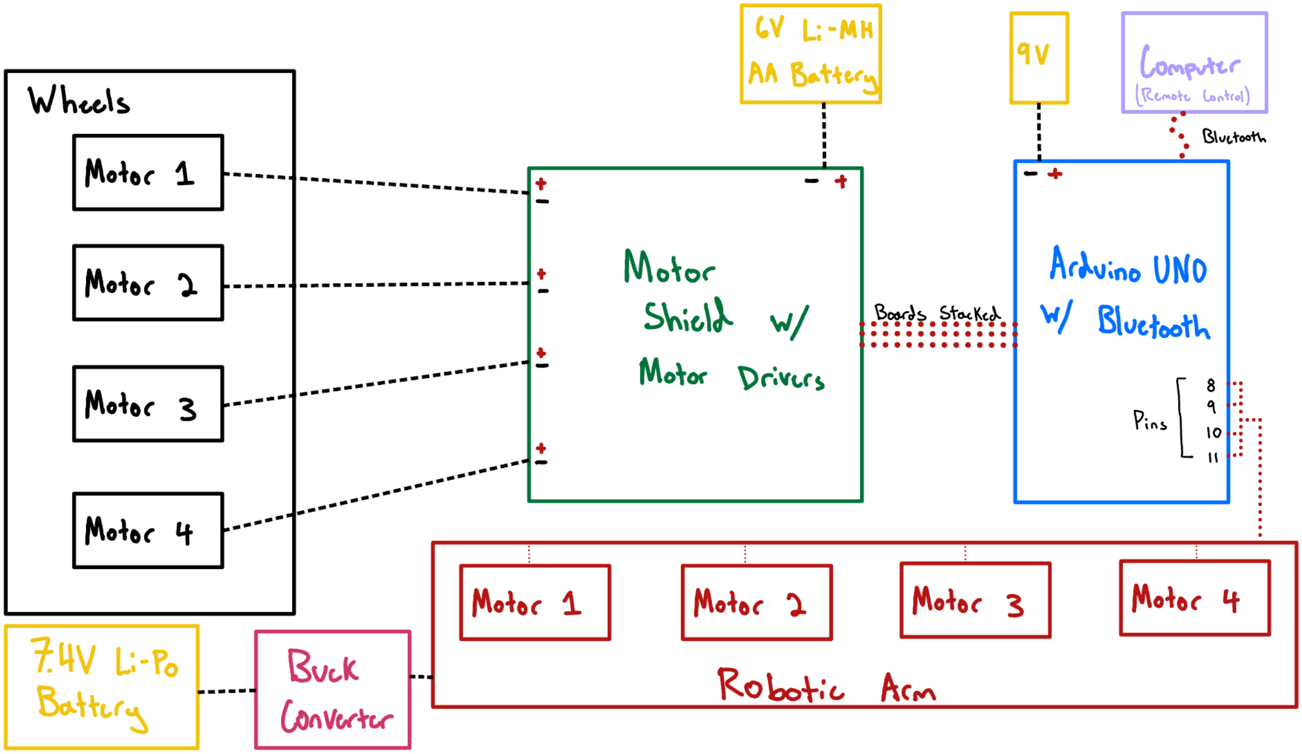


Figure 31: Diagram of Robotic Arm Circuit

Starting from the Arduino, the computer is connected via a WiFi and/or Bluetooth connection, allowing it to act as the remote controller. The Arduino is powered off of a $9V$ battery. It is loaded with code that wirelessly receives the signal from the computer and converts the signal to an output for either the robotic arm or the motors attached to the wheels. Pins 8-11 on the Arduino relay a signal between 0.5 and 2.5 to the servos on the robotic arm. The number dictates the position from 0°to 180°. The servos are powered by a $7.4V$ Li-Po battery. Chosen for its high amperage range that is needed when all 4 servos are at a $2.5A$ stall current. The buck converter acts as a safety mechanism, stepping down the voltage to the servo's $6V$ required voltage. The Arduino sends signals to the wheel motors through the motor shield, which is stacked neatly above the Arduino, sharing many pins. The motor shield contains two of its own TB6612FNG dual H-bridge motor drivers which can each run two servos at a time. The motor shield and motors are powered by a $6V Li - MH$ AA Battery, chosen for its budget friendly price, sufficient amperage and acceptable voltage.

7.3 Final Prototype Photos

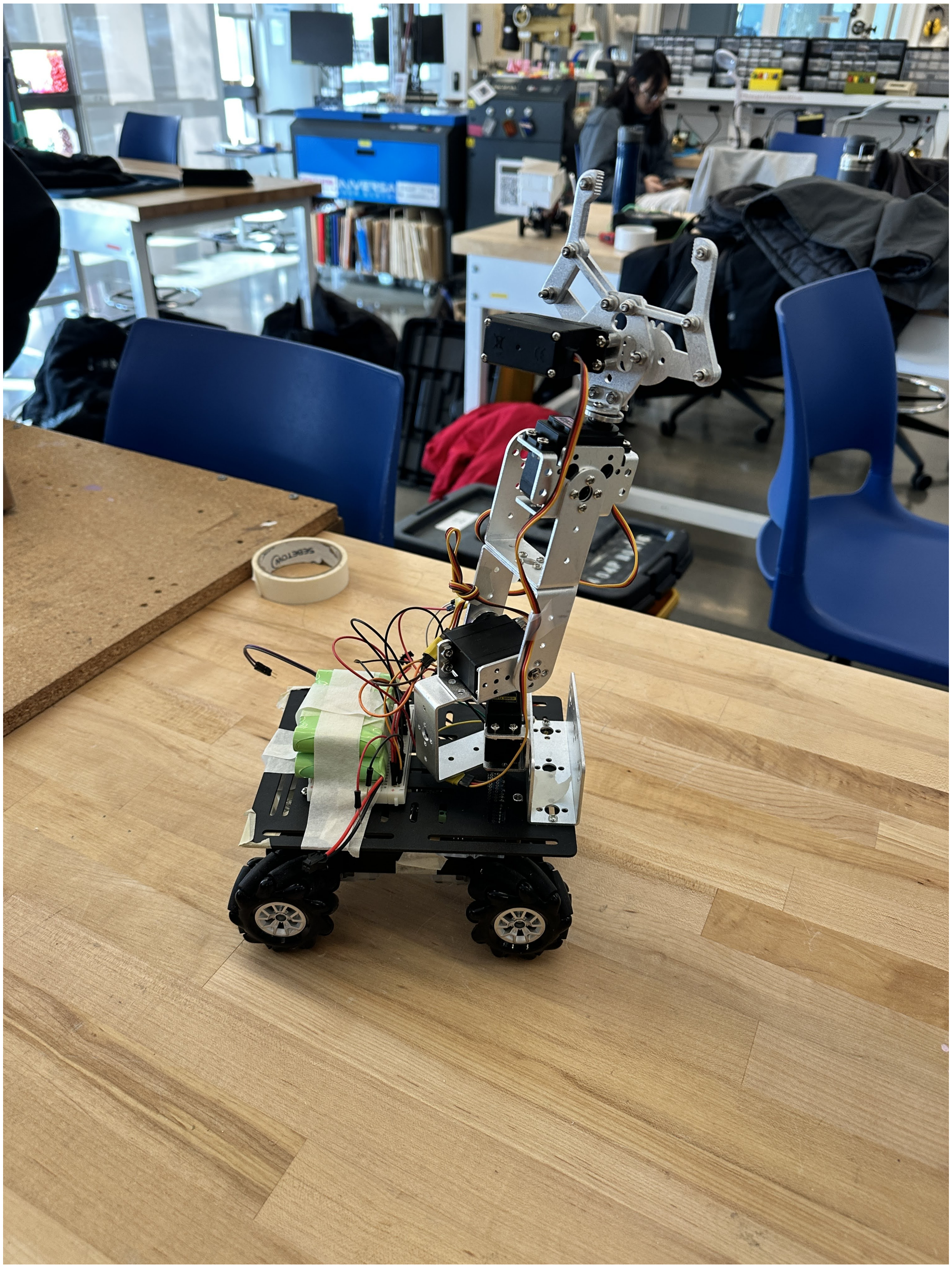


Figure 32: Final Robot Assembly

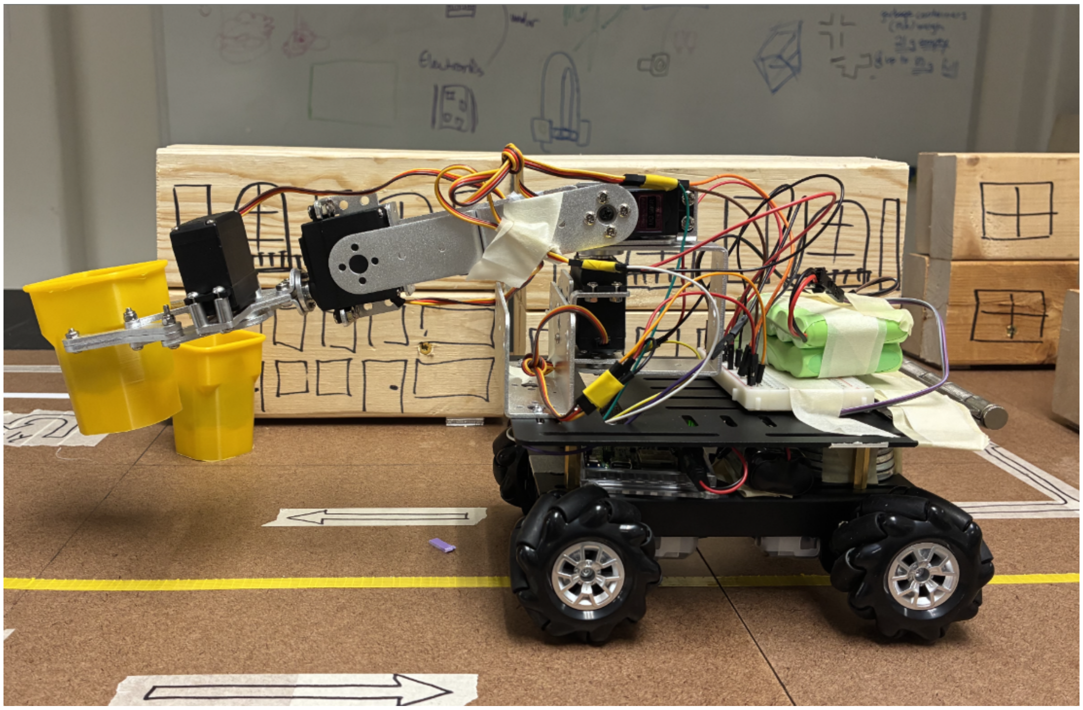


Figure 33: Robot Statically Holding a Trash Can

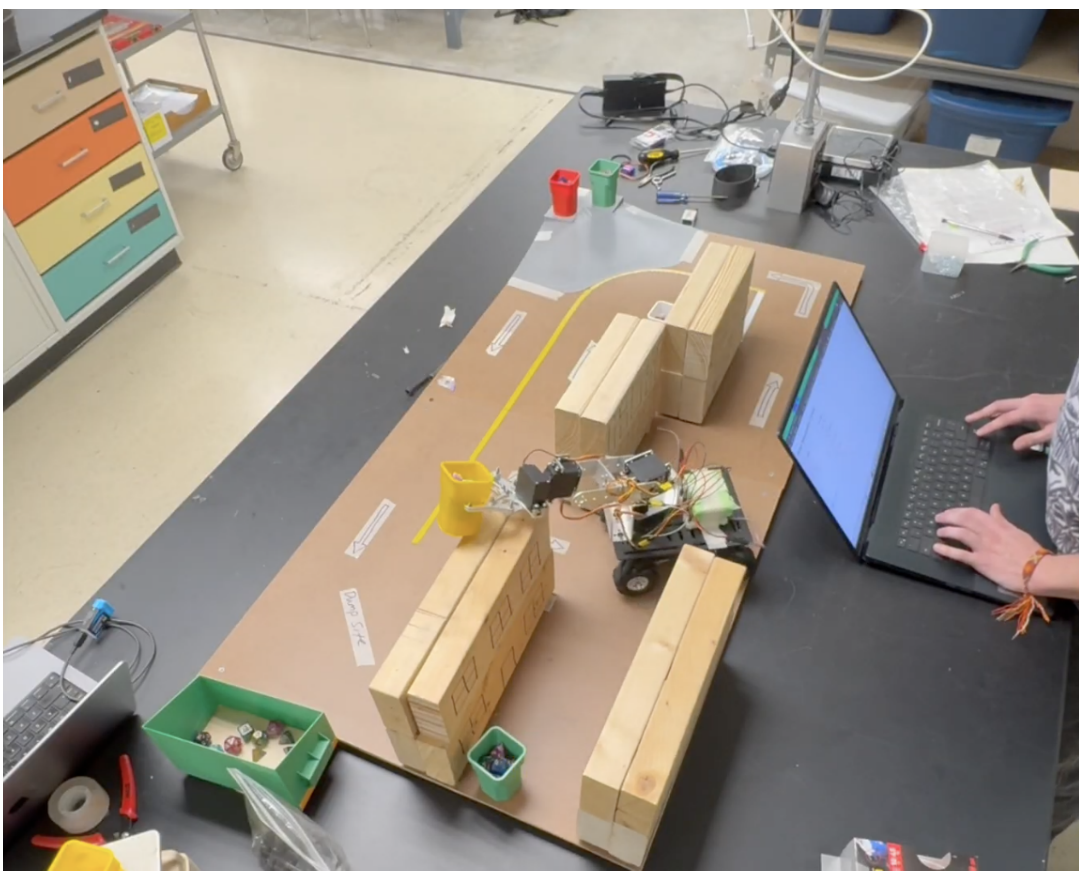


Figure 34: Robot Navigating the Mini City with a Trash Can

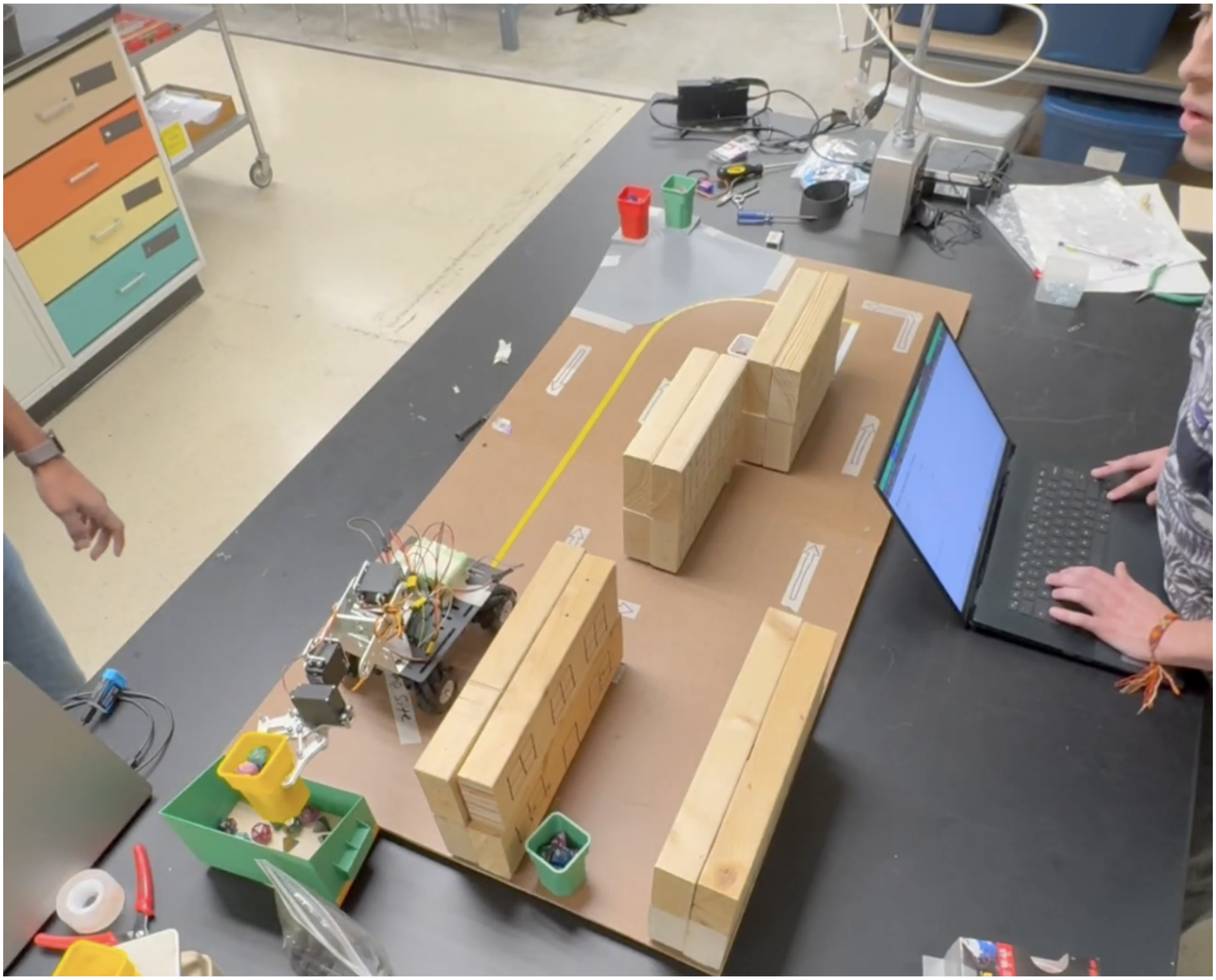


Figure 35: Robot Dispensing a Trash Can into the Receptacle

Bibliography

[1] ASME. *AY25–26 Student Design Competition Rules: Waste Collection Challenge*. 2025. URL: https://efests.asme.org/.