SEAL Team 6

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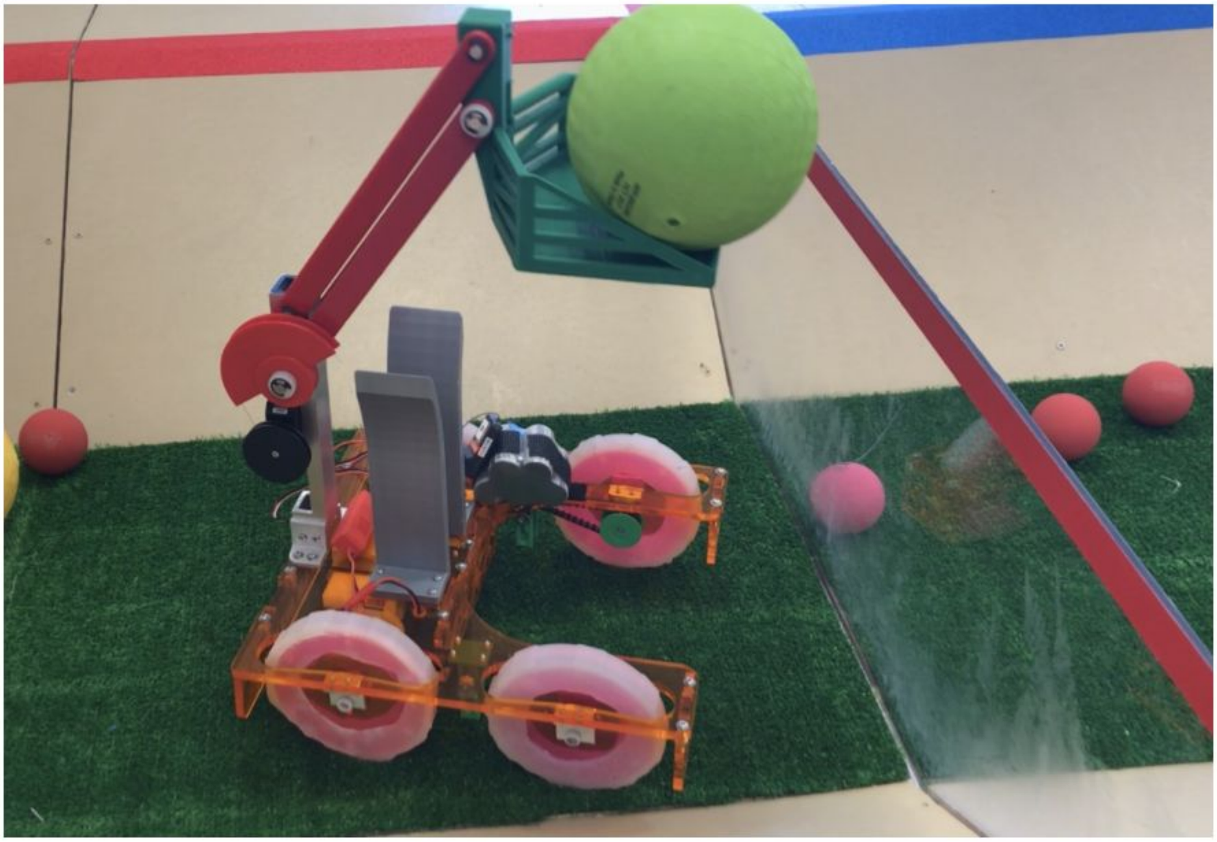

Fig. 1 - Our completed robot in action

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Abstract

The goal of this project was to create a remote-controlled robot to participate in a competition known as Turf Wars. Two opposing robots competed head-to-head to achieve the least number of points by transporting large and small orbs (worth 5 and 2 points each, respectively) across or over a center barrier in a span of four minutes. Each side started with 3 large orbs and 8 small orbs. In the process of creating this robot, we considered three potential designs: a bulldozer, a conveyor belt, and a scooper lift. After assessing each on many different criteria, including (but not limited to) transport capacity, power requirement, and weight, we decided to use the lift in our final design. Unlike other teams opting to lift orbs over the wall, we used a four bar linkage to keep our scooper parallel with the ground, which allowed us to utilize the wall to keep balls in the scooper on the way up. This proved to be a very effective design that worked well to transport balls over the wall quickly. The addition of a four wheel drive added to our defensive strategy capabilities. In competition, our robot placed second as a simple bull-dozing design proved to be equally effective but significantly faster.

Constraints

In designing our robot, we had to take the following constraints into account:

- The robot must be constructed using only provided materials.
- The design must be able to fit in a 12"x12"x12" "Box of Justice," but remote-controlled mechanisms may expand out of that range.
- The robot must use at least 2 screwdriver motors and at most 4 other actuators (servos or other screwdriver motors).
- The robot must at least be able to drive up the 15° ramp
- The robot must mostly utilize machining techniques learned in class

Criteria

Based on these constraints and the overall goals of the robot, we decided to assess each of our potential solutions using the following criteria:

- **Speed** - how quickly the mechanism would be able to pick up balls and transport them. Since time is a constraint, extra speed was also a key consideration.
- **Complexity** - how intricate the transport mechanism would be. This was a key factor as higher complexity would increase risk of failure, difficulty to control, and labor needed to fabricate the mechanism.
- **Capacity** - the number of orbs that the mechanism can transport in one pass. The larger the capacity, the less number of actions needed to transport more balls across the boundary.
- **Effectiveness** - how consistently the mechanism would be able to deliver balls to the other side once the balls were picked up. This was another significant consideration since dropped balls would require extra time to retrieve.

- **Versatility** - the degree to which the mechanism could transport both large and small orbs. The ability to transport both orb sizes was important because although large orbs were worth more points per orb, slightly more small ball points were available (16 small orb points vs. 15 large orb points).

- **Climbing Capability** - speed and facility with which the robot could ascend the hills. Originally, we did not think that this would be an important factor, since our strategy was to stay in the valley to eliminate the time needed to climb the hill. However, after seeing other teams' robots transport balls across the center barrier and leaving them on the hills, this became a much more important factor. Our final lift design is very adept at climbing the hills.
- **Weight** - This was quite an important factor, since it determined the winner in the case of ties. In fact, we seeded first because we had a lighter weight than the second seed.
- **Power Requirement** - The amount of power required to operate the transport mechanism. This factor could affect battery life as well as the speed of the mechanism.
- **Ability to Reach over Center Barrier** - As our strategy was centered around remaining in the valley to eliminate the time needed to ascend the hill time and time again, the ability for a mechanism to transport balls over the center barrier was a significant factor in our choice.

Alternative Solutions

Bulldozer

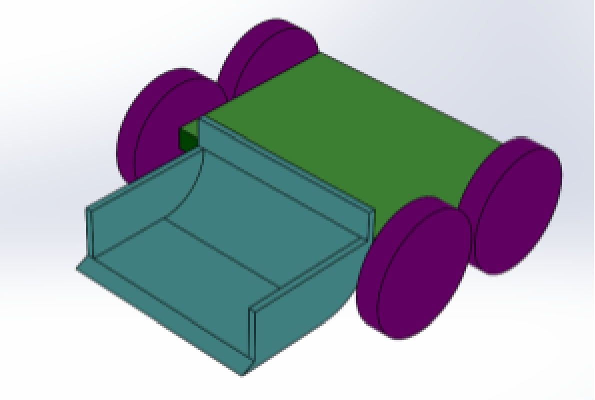


Fig. 2 - Hypothetical bulldozer design

The bulldozer design would use a bulldozer-like ball collector at the front of the robot to hypothetically allow for mass transport of orbs up the hill and across the center boundary. Even though our strategy was centered around remaining in the valley to save time, we still considered this design due to its potential for mass transport and its simplicity. Moreover, it would have a minimal power requirement due to its lack of moving parts. However, we found that keeping small balls in the collector while going up the ramps was actually quite difficult, significantly reducing the potential for mass transport. Thus, we decided against this design.

Conveyor Belt

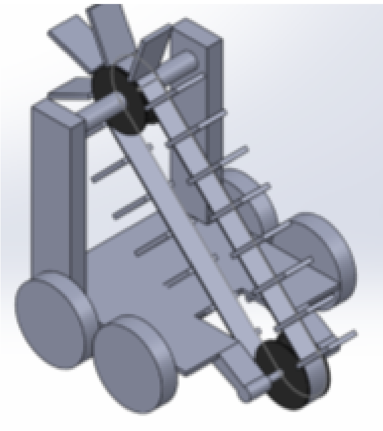


Fig. 3 - Hypothetical conveyor belt design

The conveyor mechanism would scoop balls up off the turf using treads in a continuously-operating conveyor-belt-like mechanism (Fig. 3). It would use this conveyor to transport the balls up the robot and high enough so that they could be dropped over the center barrier. It would provide the over-the-wall advantage as well as mass transportation, provided that the mechanism itself did not fail. However, we eventually decided against this design because the reliability of picking up the balls with the treads was questionable. Additionally, the complexity (and likelihood of failure) would be very high, due to the high number of moving parts. Moreover, this mechanism would most likely not be able to pick up variously-sized orbs.

Scooper Lift

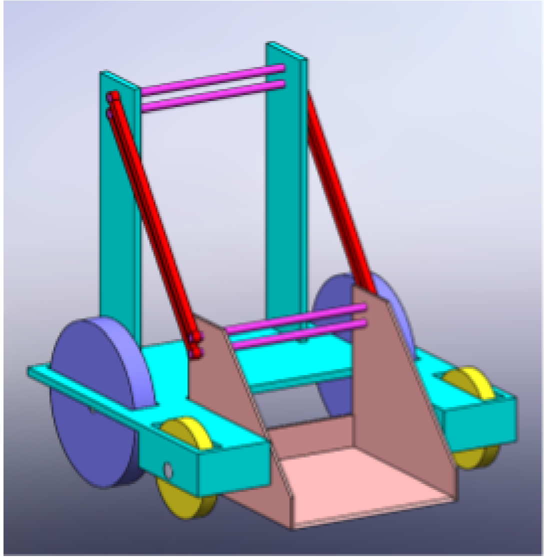
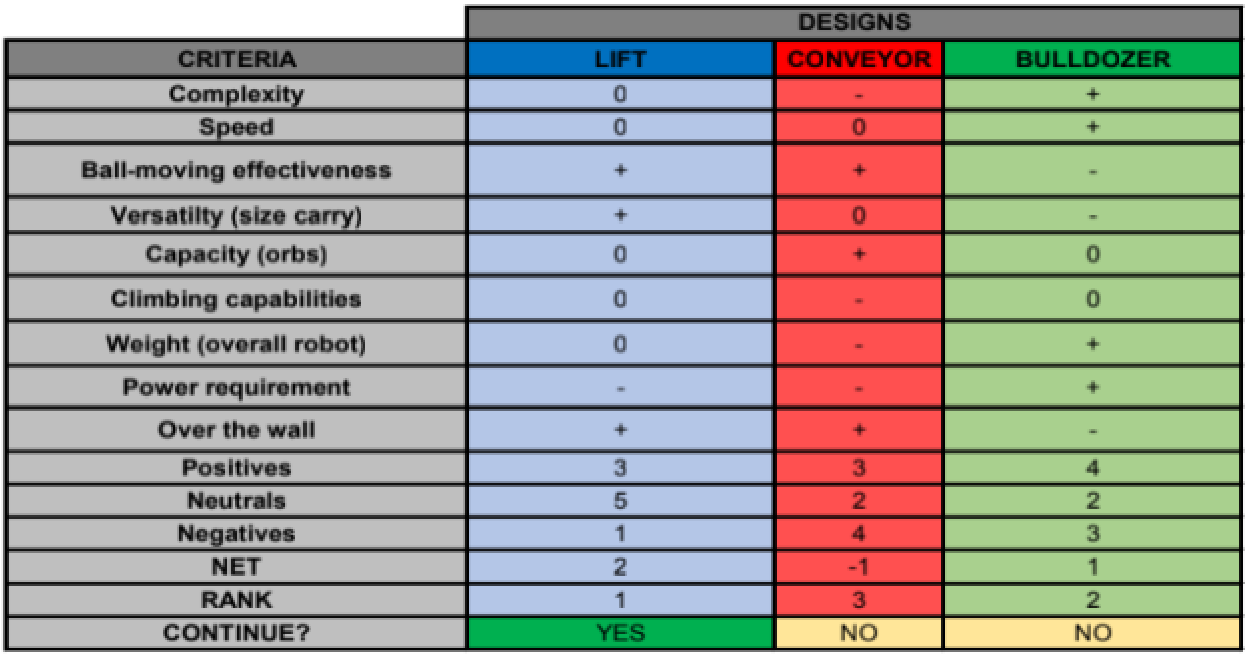


Fig. 4 - Initial Scooper lift design

The scooper lift mechanism would use a four bar linkage mechanism positioned in the front middle of the robot and mounted by a tower at the rear of the robot. The scooper would pick up balls by cornering them against a wall, and thus forcing them into the scooper. The scooper would then raise up to a sufficient height that the robot could be rammed into the wall and have any balls in the scooper fall across the center barrier. It offered relatively low complexity as well as the ability to carry both orb sizes. The disadvantages of the lift were that extra power would be required for the lift, ball capacity would be slightly limited, extra time would be needed to lift the arm due to torque, and that it would require a skilled driver. However, in practice, we discovered that even with balls in the scooper, the servos provided enough torque to be able to operate the lift at a very reasonable speed.

We assessed each of the potential models relative to each other on each of the aforementioned criteria using a Pugh matrix, and once all the results were tallied, the scooper lift had the highest net positive rank (Table 1). Thus, we proceeded with designing the lift mechanism.



	DESIGNS		
CRITERIA	LIFT	CONVEYOR	BULLDOZER
Complexity	0	-	+
Speed	0	0	+
Ball-moving effectiveness	+	+	-
Versatilty (size carry)	+	0	-
Capacity (orbs)	0	+	0
Climbing capabilities	0	-	0
Weight (overall robot)	0	-	+
Power requirement	-	-	+
Over the wall	+	+	-
Positives	3	3	4
Neutrals	5	2	2
Negatives	1	4	3
NET	2	-1	1
RANK	1	3	2
CONTINUE?	YES	NO	NO

Table 1 - Pugh matrix containing ball transport mechanisms and criteria.

Analysis

To narrow down our three designs to one we decided to build prototypes from foam core. One prototype for each design was built. We tested the ball moving ability of each foam core prototype in the arena and made small improvements. We also built each of our robots in Solidworks. We selected our robot using a pugh matrix and did torque calculations to see if our robot would be able to successfully climb the ramp and move the balls. After that, though trial and error, we made small changes to improve our design and the resulting robot was fully functional and met all of our requirements.

Foam Core

After we decided on three possible designs for our robot we started to build our foam core robots. We realized that the conveyor belt was very complex and the added complexity increased the chances of failure. Hence by testing the foam core model inside the arena we realized that picking up and dropping balls was going to be a huge challenge. Because of the 12 inch height constraint it would be very hard to drop the balls over the middle barrier with the conveyor belt system.

While testing the bulldozer design we came to the conclusion that is was very simple. However, we realized that due to the steepness of the ramp it was not the fastest way of ball transportation. We also found that the base plate couldn't be too close to the ground as while we were moving the foam core in the arena, the base plate would hit the edge of the ramp. After making the modification of moving the base plate higher, the bulldozer foam core design could climb the ramp with fewer issues.

After we finished testing our foam core models in the the arena we rated each design in the gantt chart and came to the conclusion that the scooper lift design was the most successful one.

Center of Gravity Activity:

In lab we used the green test robot because it had the most similar dimensions to our actual robot. We placed the majority of the testing weight towards the rear end of the robot, to simulate the weight distribution to our actual design. While we were pushing the robot up the ramp we realized that our robot had a high risk of tipping over due to a center of gravity over the rear wheels. As a team, we concluded that we had to move the center or mass of our robot closer to the middle and to do so we placed our battery over our front wheels. In its final form our robot was very stable.

Drive Train Torque:

Although our original strategy did not require our robot to constantly climb up and down the ramps, for strategic purposes, we calculated the required amount of torque needed to climb up the incline. Below are formulas and the parameter required to complete the calculation.

Parameters

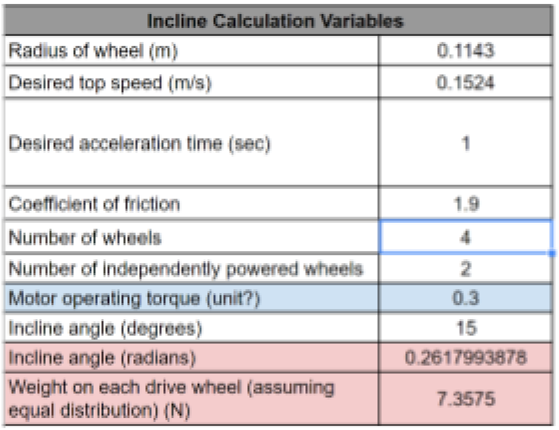
mg = *vehicle weight*
m_w = *weight on each drive wheel* (*assuming equal distribution*)
R = *radius of wheel*
v = *desired top speed*
t = *desired acceleration time*
μ = *coefficient of friction*
n = *# of independently powered wheels*
T_M = *motor operating torque*
FS = *factor of safety*
θ = *incline angle*

Formulas

$$\tau_w = \frac{mgR}{n}\left(sin(\theta) + \frac{v}{gt}\right) \qquad \tau_{max} = \mu\, m_w g cos(\theta) R$$

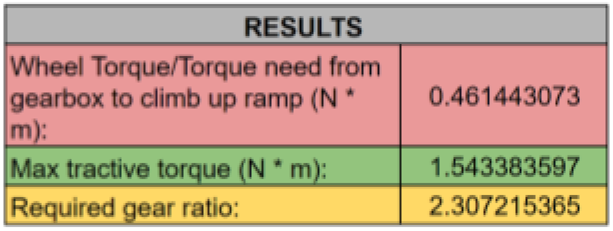
$$\text{GR} = \frac{(FS)\,\tau_w}{\tau_M}$$

Initially, the team intended to only climb up the 15 degree incline, with only two wheels being powered directly from the gearbox. From the calculations, we determined that we would need to have a gear ratio of more than 2:1 to sufficiently power the robot to climb the ramp. Since our gearbox has a gear ratio of 3:1 and outputs more than 462 mNm of torque (Table 3), we concluded that our robot easily make it up the ramp without any major issues.



Incline Calculation Variables	
Radius of wheel (m)	0.1143
Desired top speed (m/s)	0.1524
Desired acceleration time (sec)	1
Coefficient of friction	1.9
Number of wheels	4
Number of independently powered wheels	2
Motor operating torque (unit?)	0.3
Incline angle (degrees)	15
Incline angle (radians)	0.2617993878
Weight on each drive wheel (assuming equal distribution) (N)	7.3575

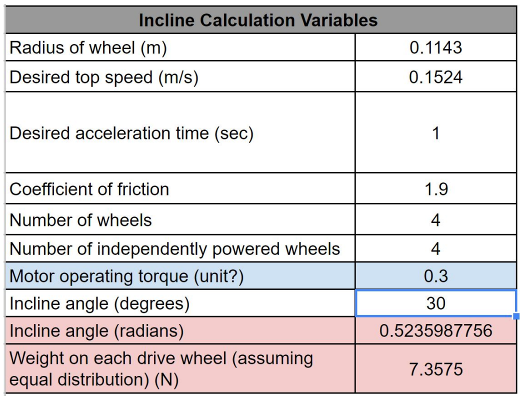
Table 2. Input variables for torque calculator



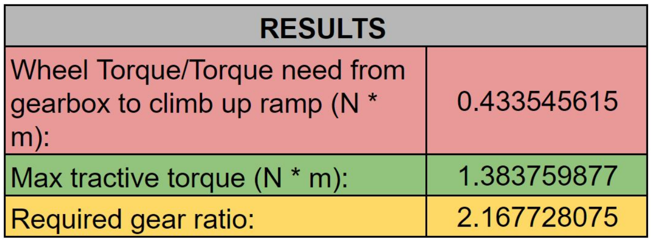
RESULTS	
Wheel Torque/Torque need from gearbox to climb up ramp (N * m):	0.461443073
Max tractive torque (N * m):	1.543383597
Required gear ratio:	2.307215365

Table 3. Results of torque calculator

However, we realized that in order to counter the strategy where opposing teams would push balls on the steep incline side, we realized that we needed to be able to climb up the 30 degree incline. We hypothesized that adding four-wheel drive capability was the key to us solving this design challenge. It required the least amount of work in terms of modifying our gearbox. Through the calculations below, we concluded that adding four-wheel drive was enough to get us over the ramp since the number of wheels powered increased, which reduced the torque required that each wheel had to provide. Furthermore, we did not need to change our gear ratio since a 2.2 : 1 ratio was needed at minimum, which the gearbox already provided.



Incline Calculation Variables	
Radius of wheel (m)	0.1143
Desired top speed (m/s)	0.1524
Desired acceleration time (sec)	1
Coefficient of friction	1.9
Number of wheels	4
Number of independently powered wheels	4
Motor operating torque (unit?)	0.3
Incline angle (degrees)	30
Incline angle (radians)	0.5235987756
Weight on each drive wheel (assuming equal distribution) (N)	7.3575



RESULTS	
Wheel Torque/Torque need from gearbox to climb up ramp (N * m):	0.433545615
Max tractive torque (N * m):	1.383759877
Required gear ratio:	2.167728075

Lift Servo Torque:

To determine the necessary gear/pulley ratio to find the for our servo we calculated the torque necessary to lift the orbs and the lift mechanism itself, which includes the arms and the basket. Below shows the parameters and formulas that were used to determine the torque needed.

Parameters

$m_{orbs} = mass\ of\ orbs\ (sum\ of\ small\ and\ large\ orbs)$

$m_{lift} = mass\ of\ lift\ mechanism\ (arms\ and\ basket)$

$FS = factor\ of\ safety$

$v = desired\ velocity$

$l = length\ of\ arm\ for\ lift$

$t = time\ to\ achieve\ desired\ velocity$

Formulas

$$T_{req} = FS(T_a + T_{grav})$$

$$T_{grav} = m_{lift} g l + m_{arm} g (\frac{l}{2})$$

$$T_a = (m_{basket} l^2 + \frac{1}{3} m_{arm} l^2) \frac{v}{tl}$$

Assuming that we would need to lift three small orbs, since three small orbs weigh more than a single large orb and that would be well within our basket's capacity, we used the following parameters to get a resulting torque requirement of at least **2.1 Nm**.

$m_{orbs} = 0.15\ kg$

$m_{lift} = 0.6\ kg$

$m_{basket} = 0.36\ kg$

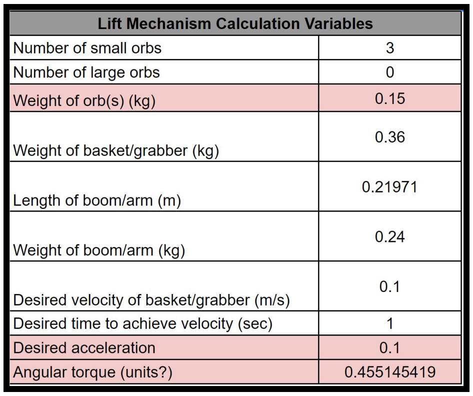
$m_{arms} = .24\ kg$

$t = 1\ s$

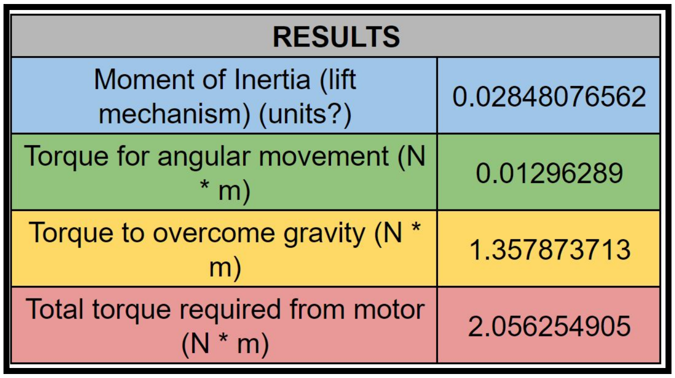
$l = 0.21971\ m$

$FS = 1.5$

$v = 0.1\ m/s$



Lift Mechanism Calculation Variables	
Number of small orbs	3
Number of large orbs	0
Weight of orb(s) (kg)	0.15
Weight of basket/grabber (kg)	0.36
Length of boom/arm (m)	0.21971
Weight of boom/arm (kg)	0.24
Desired velocity of basket/grabber (m/s)	0.1
Desired time to achieve velocity (sec)	1
Desired acceleration	0.1
Angular torque (units?)	0.455145419



RESULTS	
Moment of Inertia (lift mechanism) (units?)	0.02848076562
Torque for angular movement (N * m)	0.01296289
Torque to overcome gravity (N * m)	1.357873713
Total torque required from motor (N * m)	2.056254905

Since our servos have a stall torque of 0.500 Nm and 0.3237 Nm at 6V and 3.3V, respectively, we will need to use a compound gear ratio to increase the amount of torque outputted. Assuming that we will output 0.3 Nm from the servo each time, since this is a safe operating range for the servo in each case, we would need a gear ratio of about 6:1 to ensure that enough torque is provided to utilize the lift mechanism.

Drivetrain Testing:

For our first iteration of our design we printed out a base plate that was the same width as our modeled rubber wheels. When we went to install the wheels the tolerances were not as precise as anticipated and the wheels did not spin freely. In order to fix it quickly, we used a dremel tool to make the necessary space for the wheels to turn and have play. From there we went to testing the design and noticed that it worked sufficiently on the 15 degree ramp while still struggling on the 30 degree ramp. This was not something that we worried about because our initial strategy was to only remain down on the arena. Next we recut our base plate with some key modifications that we learned from the initial test: wider wheel gaps and more precise tolerances on the acrylic molded wheels.

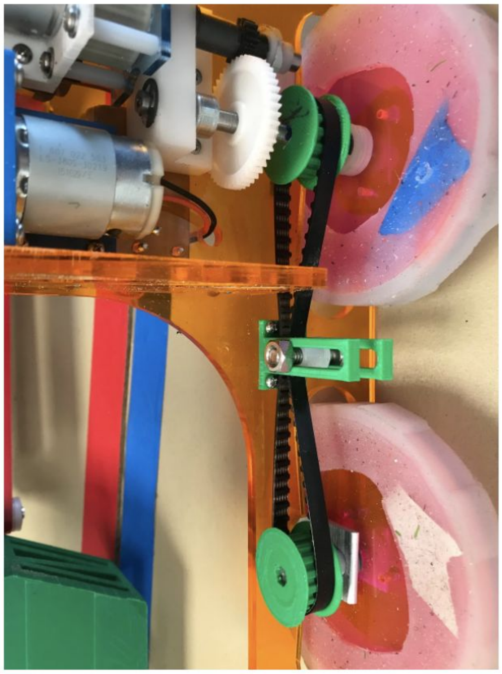


Fig 4.1 - Four wheel drive mechanism with pulleys connected by a timing belt with a tensioner.

Shortly after creating the new base plate, we realized that some of the other teams had a strategy of dumping balls in a way where they would not fall down to the lower arena. Once we learned of this we had to modify our robot to be able to climb the 30 degree slope so we could block and push back these balls. We modified each side of our robot with a timing belt, a 3D printed tensioner, and timing pulleys that connected the front and rear axles. During initial testing it proved very capable and showed it could easily transport our robot and load (1-3 small orbs or 1 large orb) up the gradient.

The only issue we ran into after that modification was stress on the chassis. Because we now had torque on the front axles there were large moments being sent through relatively thin material. During one of our many practice rounds we snaped our base plate in half. We redesigned it with more material and stronger geometry. Since then, we haven't had any issues with our drivetrain (aside from spring pins breaking occasionally).

Final Solution

After evaluating each design option our group decided to choose the scooper design. Our final robot was within every design requirement and achieved all of the goals we set.

Functionality:

Our finished robot accomplished all the goals we set. It was able to climb up the 30 degree ramp in order to block the incoming balls from the opposing team. Our robot used a scooper that had a 4 bar linkage. The orbs would be loaded on to the sooper with the help of the front wall. After the orbs were loaded, the scooper would be lifted with a winch system that was attached to the the servo motor with a fishing line. The fishing line would pull on the upper winch pulley, which would rotate a hex axle and the scooper arms. As a result, balls would be lifted. Once the balls were over the wall they would be released onto the other side of the arena by ramming the front of the robot into the wall. We had many rounds of testing in the arena and robot is able to move orbs over quickly. The high speed and the high efficiency of our robot made our robot successful in the competition.

Fig. 4.2 - The completed lifting mechanism using two winch pulleys connected by fishing line and powered by a continuous servo motor.

Criteria:

Our robot has achieved all the goals we set at the beginning of the design process. These are:

- Our robot can go up the steep (30 degree) ramp quickly.
- It is within 12x12x12 inches therefore it will fit in the box of justice.
- Can push balls over the middle wall.
- Doesn't have too many motors to decrease complexity and chances of failure. 2 DC motors and 1 servo motor.
- Has four wheel drive.
- The robot can turn in place.

Advantages:

- Our robot is able move more than one orb at a time. The scooper can fit one large and four small orbs, and the lift mechanism can lift as many orbs over the wall as could be stacked on top of the scooper.
- Our robot is mostly made out of 3D printed and laser cut materials in order to have a smaller tolerance, and decrease errors.
- The robot is relatively lightweight (2800 grams).
- It doesn't need to climb up ramp to score.
- The robot can very quickly climb up steep ramp.

Disadvantages:

- Driving the robot requires practice, and controlling the lift also requires manipulation of the position of the robot relative to the wall.
- The bumpers tend to break during repeated collisions, an action necessary to our strategy.
- The wheels tend to get worn out over time.
- The fishing line wears out over time and is more susceptible to snapping.
- Orbs can get caught under the chassis and hinder mobility.

Competition Performance:

Seal Team 6 came in 2nd in the competition. The robot had a major issue on the first round. We had a mechanical failure in its drivetrain where the spring pin that held the 48 tooth gear in place broke, which caused the shaft that was attached to the wheel to spin freely. Therefore, the robot was not able to move forwards and backwards. To make things worse our front right bumper broke off as well. This happened because we went down the ramp very quickly, and we had not done a proper assessment of the status of the robot before the round. To fix this problem we had to use a life and change our spring pin. The process of changing the pin took around three minutes which caused us to loose the round. After the correction, our robot won every round except the final. We were content with our overall execution during the competition. After a considerable amount of practice, Tom also did a great job driving and was one of the main reasons why we won.

Improvements:

We had several problems with our robot during the testing process. The first problem was that our robot had a high of a center of gravity, which caused our robot to be unstable. To fix this we could have lowered our base plate and made our wheels smaller. This lowered our clearance to the ground and made the robot more stable. To compensate, we used shorter bumpers to prevent them from breaking off during the ramp climbing process. The rear bumper also functioned as a wheelie bar, and kept the robot from flipping backwards while on the bottom of the arena. The center of mass was still far to the rear of the robot, so ramps had to be climbed backwards and descended forwards. This could have been fixed by better distributing the weight of the robot, but this would have made it heavier and slower. Another problem we ran into was the fishing line getting caught inside of the pulley (composed of a servo horn). To solve this we used two servo arm horns and a rubber band on top of our pulley to guarantee that the fishing line would stay in. This still was not a foolproof method, and it required checking after every round of competition.

We also ran into the issue of our spring pins occasionally breaking. To resolve this problem we could have used a half inch 4-40 screw as a fastener to secure the gear on the shaft but only thought of this during the competition. The screw would have been sturdier and prevent the robot from breaking, but we did not have the time necessary for implementing the change. Another improvement that we could have made was to make our robot a bit wider. If we had made our robot wider then we could have put bumpers on both sides of the robot. This would prevent balls from getting stuck underneath our robot and balls could not have gotten stuck underneath it. One final aspect we could have improved on our robot would have been a modification of our scooper. In its current form it was challenging to drop the orbs over the middle wall. The scoop could have had a mechanical drop feature that would have a servo controlling the unloading feature. If there was a more refined method of funneling balls into the scooper with different front bumpers, the intake of orbs could have also been improved.

Final Design Specifications

Mass (g)	2,800
Width (inches)	11.0
Length (inches)	11.2
Height of top of base plate (inches)	3.1

Maximum height (inches)	16.5
Undercarriage clearance (inches)	2.9
Turning radius (inches)	0
Drivetrain gear ratio	3:1
Servo gear ratio	6:1
Diameter of wheels (inches)	4.25
Orb capacity of scooper	3 Small OR 1 Large

Appendix

Bill of Materials:

Name of part	Material	Manufacturing technique	Quantity
Wheel	¼” acrylic and Ecoflex 00-50	laser cutting, molding	4
Baseplate	¼” acrylic	Laser cutting	1
Front Bumper	¼” acrylic	Laser cutting	2
Front Bump Stop	¼” acrylic	Laser cutting	1
Rear Bumper	¼” acrylic	Laser cutting	1
Gearbox	N/A	Standard part	2
L bracket shaft support	Delrin	Milling, drilling	2
Rear Drive Axles	¼” Hex rod 1215 carbon steel	turning	2
Motor Output Axles	¼” Hex rod 1215 carbon steel	turning	2
Front Drive Axles	¼” Hex rod 1215 carbon steel	turning	2

Gear, 48T, 32 DP, 20° Pressure Angle	Acetal	Standard part	2
Gear, 16T, 32 DP, 20° Pressure Angle	Acetal	Standard part	2
Timing belt pulley	PLA	3D printing, drilling	4
Belt Tensioner	PLA	3D printing	2
Timing Belt, 15" Outer Circle, 1/4" Wide, XL Series, .200" Pitch	Urethane	Standard part	2
Slotted Spring Pin, 1/16" Diameter, 1/2" length	18-8 Stainless Steel	Standard part	4
¼ Shaft Collars	18-8 Stainless Steel	Standard part	2
Aluminium Tower	6061 Aluminium	Milling, drilling	1
Al Angle Iron 3/16" thick, 1-1/4" x 1-¼ Tower supports	6061 Aluminum	milling, drilling	2
Vertical Arm Guides	PLA	3D printing	2
Cut Servo Pulley	PLA	3D printing	1
Lifting arms	¼” acrylic	Laser cutting	4
Front Basket	PLA	3D printing	1
Lift Normal Axles	¼” diameter 6061 aluminum	Turning	3
Lift Drive Axles	1215 carbon steel	Turning	1
E-clip for 1/4" shaft	Black-phosphate steel	Standard part	16
¼” bushing	Nylon	Standard part	12
¼” Washer	Nylon	Standard part	40

Continuous Rotation Servo	N/A	Standard part	1
Rounded Head Screw, 4-40 Thread Size, 3/8" Long	Passivated 18-8 Stainless	Standard part	30
Rounded Head Screw, 4-40 Thread Size, 1/2" Long	Passivated 18-8 Stainless	Standard part	8
Rounded Head Screw, 4-40 Thread Size, 3/4" Long	Passivated 18-8 Stainless	Standard part	12
Flat Undercut Head Screws, 4-40 Thread Size, 5/8" Long	Passivated 18-8 Stainless	Standard part	4
Rounded Head Screw, ¼ 20 Thread Size, 3/4" Long	Passivated 18-8 Stainless	Standard part	2
#4 Flat washer	Zinc-Plated Steel	Standard part	34
Hex nut 4"-40	18-8 Stainless Steel	Standard part	18
Hex nut 1/4"-20	18-8 Stainless Steel	Standard part	2
Servo adaptor	Unspecified	Standard part	2
Battery Pack, 6.0 V, 4200 mAh	N/A	Standard part	1
Radio Receiver, 6 Ch, 2.4 GHz	N/A	Standard part	1

Radio Transmitter, 6 Ch, 2.4 GHz	N/A	Standard part	1
Motor Controller	N/A	Standard part	2
Velcro	unspecified	Standard part	2

Lift Tower Engineering Drawing

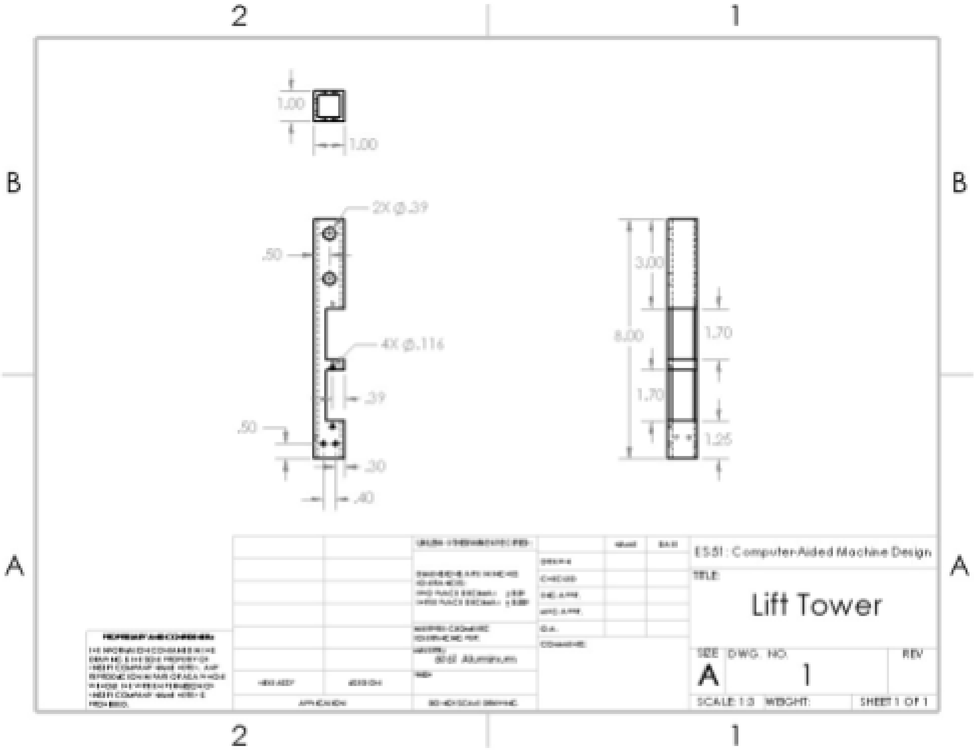


Fig 5 - Engineering Drawing of Aluminum Lift Tower

Basket Axle Engineering Drawing

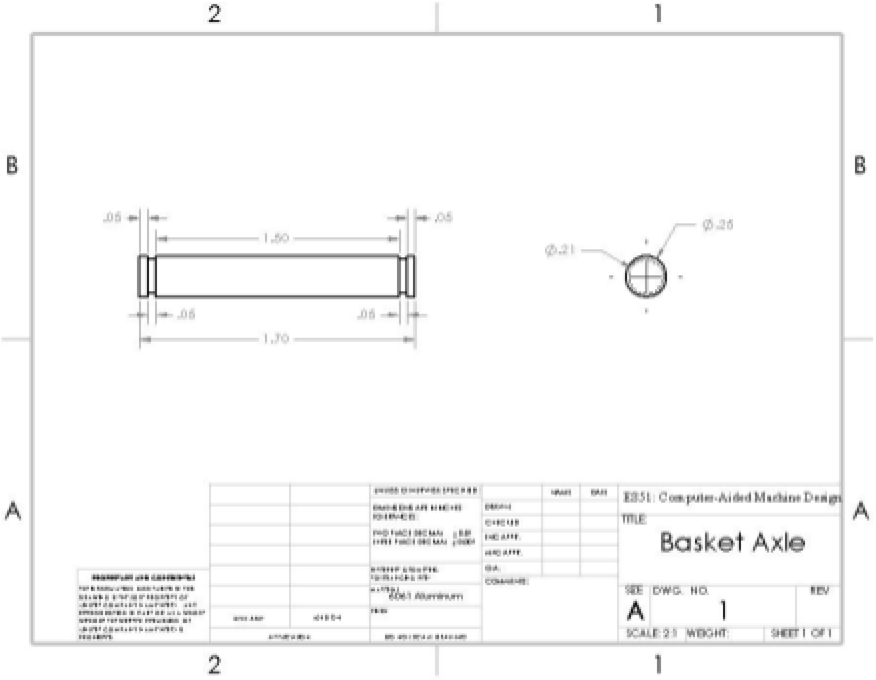


Fig. 6 - Basket Axle Engineering Drawing

Tower Shaft Support Engineering Drawing

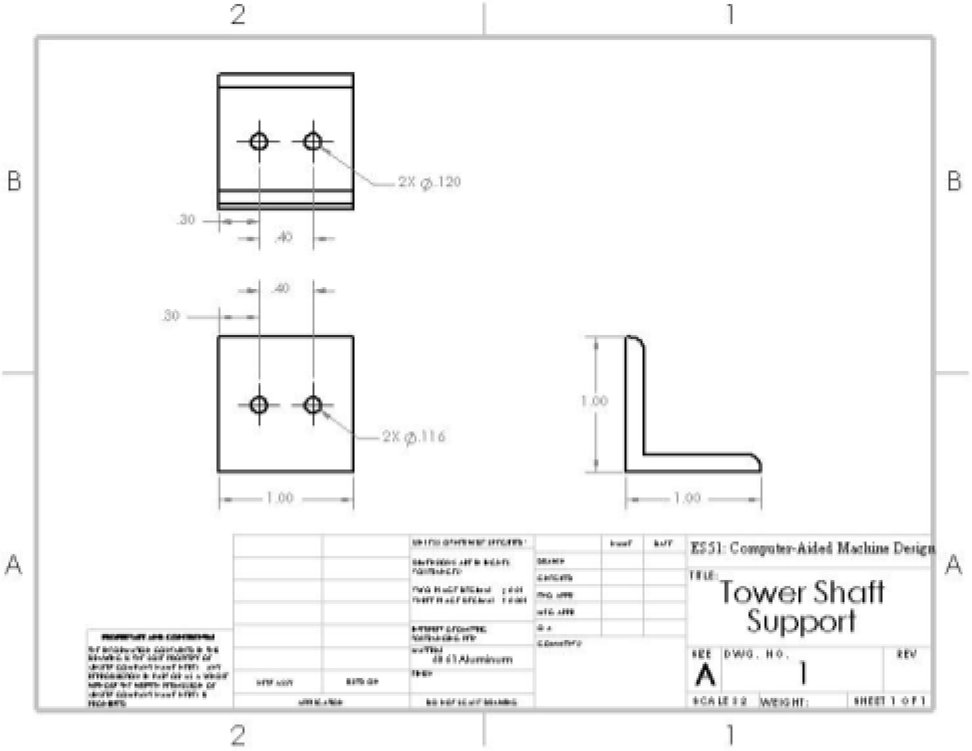


Fig. 7 - Tower Shaft Support Engineering Drawing

Final CAD - Isometric View

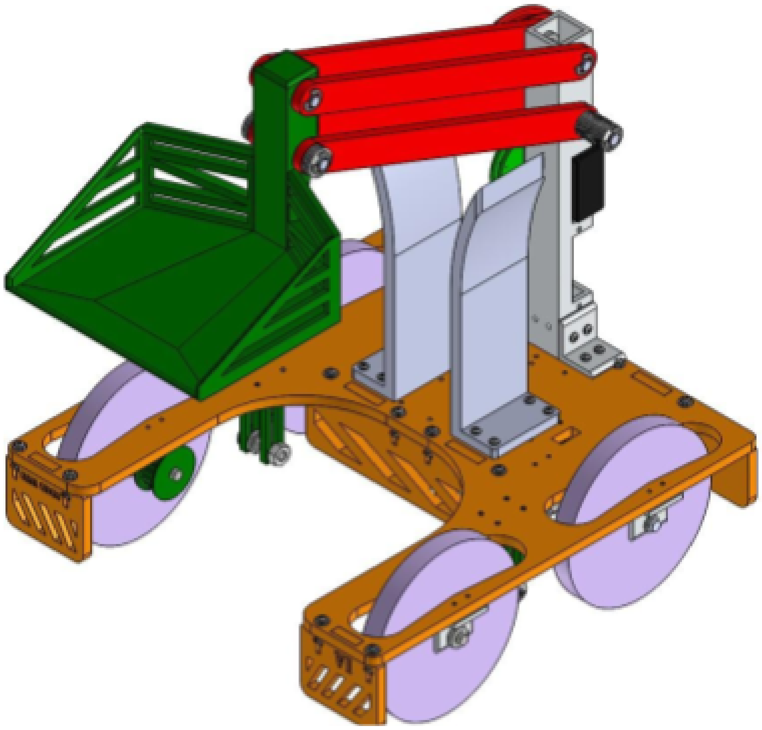


Fig. 8 - Final CAD - Isometric View

Final CAD - Bottom Drivetrain View

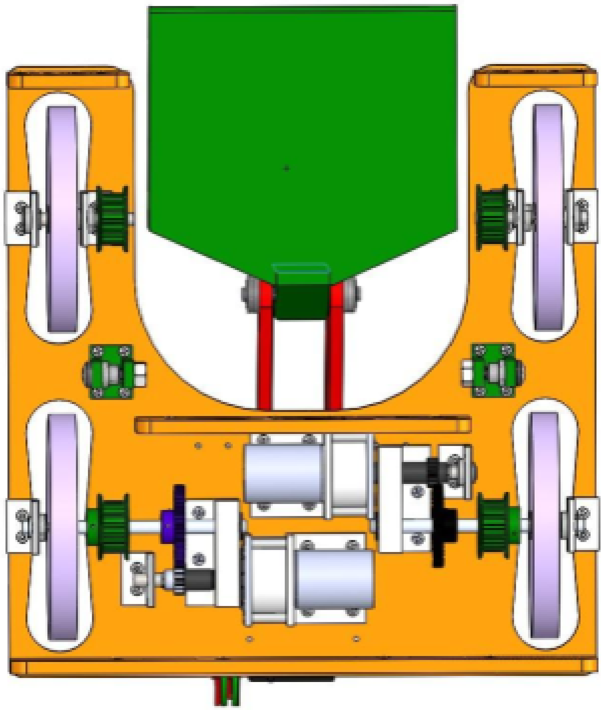


Fig. 9 - Final CAD - Drivetrain View

Exploded Isometric View

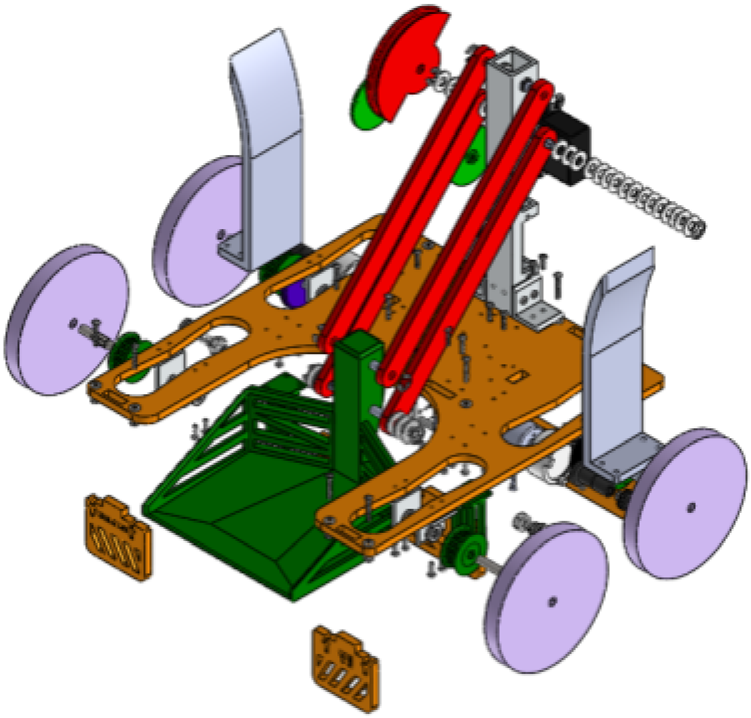


Fig. 10 - Exploded Isometric View

Exploded Bottom View

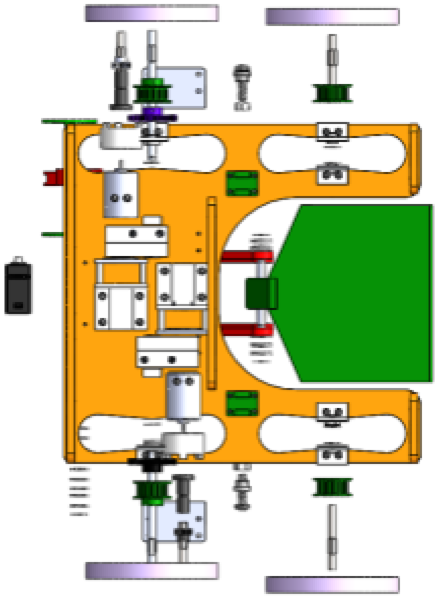


Fig. 11 - Exploded Bottom View

Final Robot-Isometric View

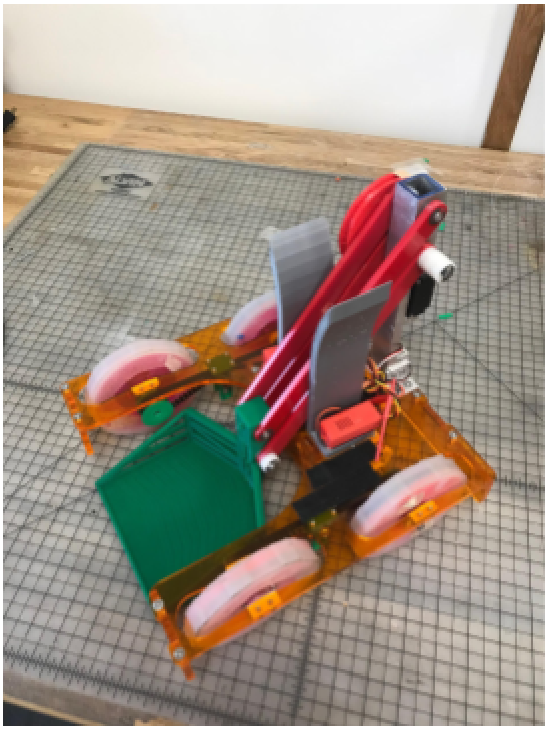


Fig. 12 - Final Robot Isometric

Final Robot-Bottom View

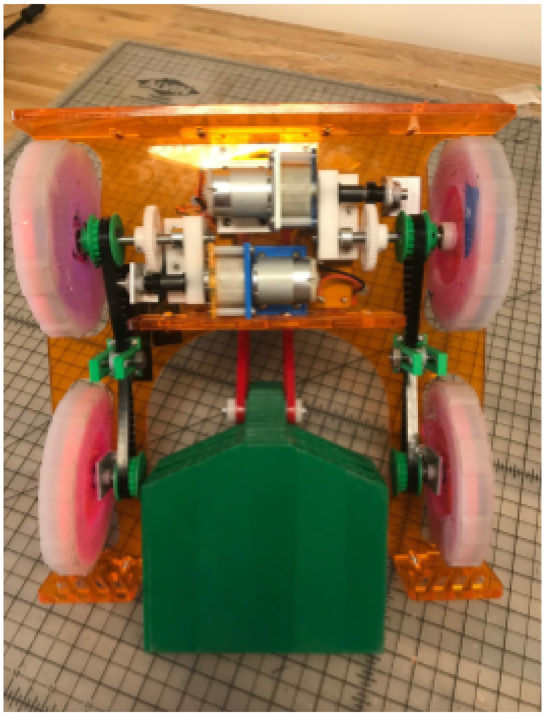


Fig. 13 - Final Robot Bottom View

Final Robot- Right View

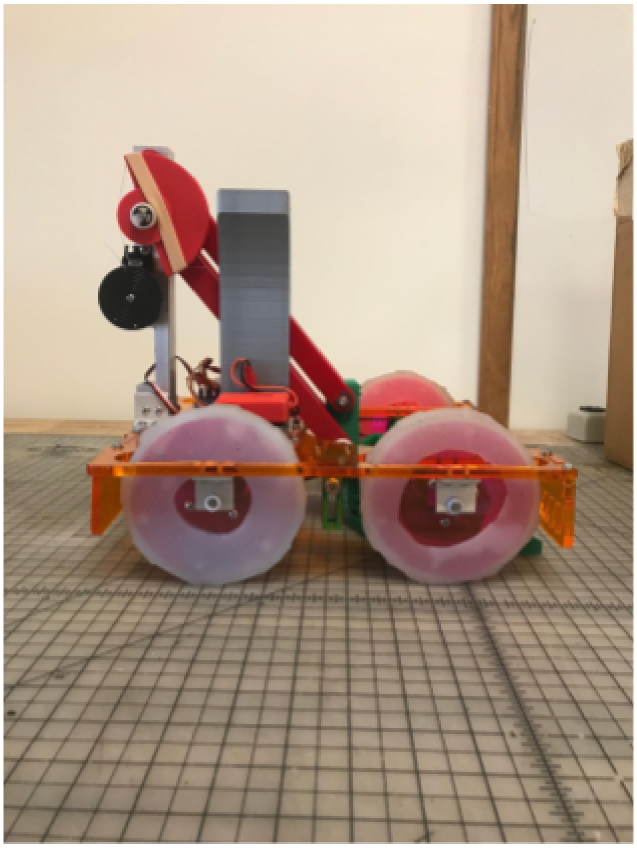


Fig. 14 - Final Robot Right View

Final Robot Assembly

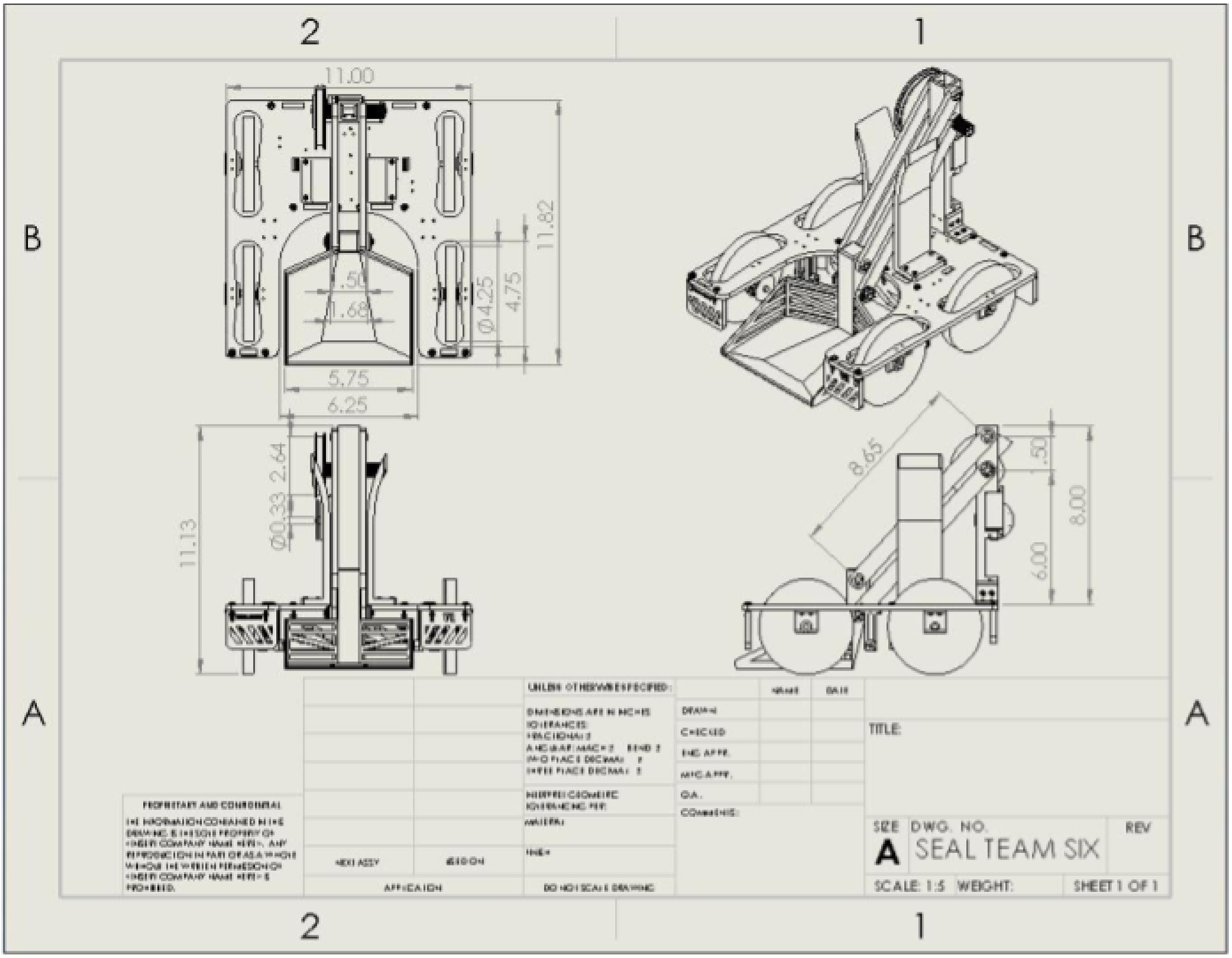


Fig. 15 - Final Robot Assembly