Turf Wars Final Report
ES51

Team 8: NAFTA
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Abstract

ES51 teaches many basic theoretical engineering lessons, and, to gain practical understanding of these skills, ES51 tasked the NAFTA team with creating a robot. The goal of this robot is to win the Turf Wars Competition, a game centered on transporting large and small “gems” (porous rubber truncated icosahedrons) to a team’s goal. These gems come in two sizes. Successfully transporting a larger gem to a team’s goal gains them two points, whereas transporting a smaller gem only results in one point. Each team transports as many gems as possible within a four-minute period, and so maximizes their score. In transporting gems, robots must surmount an incline of 15 degrees or a steeper incline of 30 degrees. The NAFTA team concluded that maximizing the number of gems a robot could transport per trip would be the most effective approach to maximize points. To this end, a robot with a skewer, holding area, and gated off-ramp was created; the skewer used the holes of the gems to grasp and deposit them into the holding area on the robot, and the gated off-ramp allowed the gems to roll into the goal when released.

Concept Development

Constraints

The rules of the Turf Wars competition set out initial constraints for the robot. First, the robot had to be able to fit inside the “Box of Justice”, a cube of 12 inches. Secondly, the team had to stick to those presented in the list of approved materials. Additionally, the team had to use the fabrication methods the team learned in class to build critical components. These fabrication methods include milling, laser cutting, turning (lathe), 3D printing, drilling, and molding. The team did have a limited amount of acrylic sheets and had a limit of 15 cubic for 3D printing. For the actuators, the team had a maximum limit of 6 and the team had to use at least 2 electric screwdriver motors as a minimum. The total current could not exceed 9 amps. All these components had to be controlled by a radio controller and similar equipment. Finally, the robot setup could not take more than 2 minutes to complete.

Criteria + Alternative Solutions

Aside from the initial constraints, the robot had to be able to collect gems and score them into one of the goals, traverse the playing field, and 15° and 30° ramps. Taking all of this into consideration, the team established the strategy to be to score as many gems as possible at the same time to avoid going up and down the ramps a lot of times. This being said, the team all decided to prioritize the number of gems over their size or color (excluding those of the opponent).

With the constraints, objectives, and strategy in mind, the team started to brainstorm different ideas on what the design of the robot could look like. The team initially came up with three ideas, titled "Scoop”, “Moving Bar” and “Pinball.” The first design (Figures 1 and 2) consisted of a scoop that would move up and down collecting gems. It would deposit them inside the body of the robot, a box to store the gems.

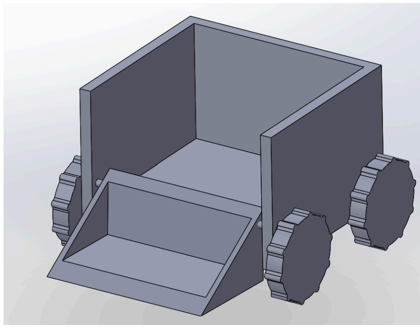
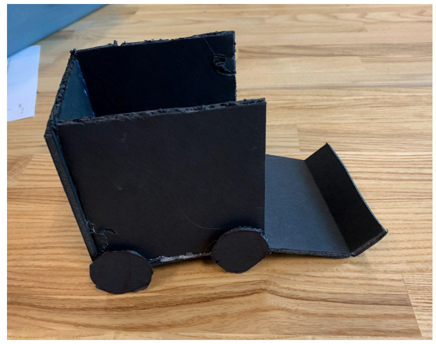
 

Figure 1: Scoop SolidWorks Model , Figure 2: Scoop Foam Core Prototype

The moving bar design (Figures 3 and 4) consisted of a similar area where the gems would be stored, but the method of collection would be different. For this design, the team would have a bar that would extend up and out from the robot. The bar would then go down to capture a gem and then back in sliding the gem to the box with it. This box would also have an inclined plane that would allow the balls to easily roll out into the goal.

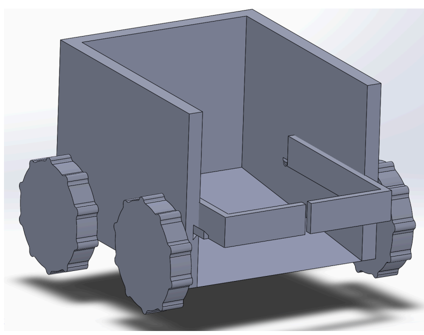
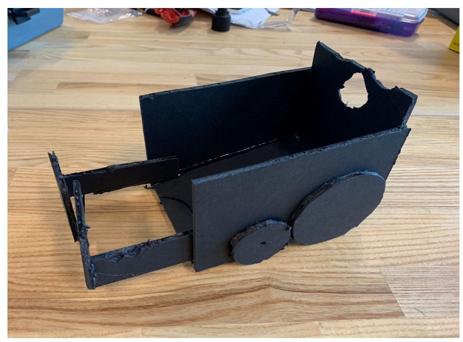
 

Figure 3: Moving bar SolidWorks Model , Figure 4: Moving Bar Foam Core Prototype

The pinball design (Figures 5 and 6) would implement a similar inclined plane to allow gems to roll out. The way to collect gems consisted of a conveyor belt in an inclined plane that would continually bring gems in from the field. To aid in the collection, there would be one small arm on each side of the ramp that the team would maneuver.

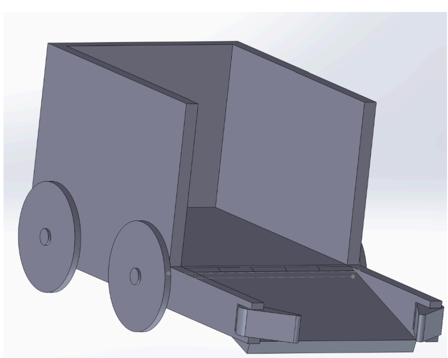
 

Figure 5: Pinball SolidWorks Model , Figure 6: Pinball Foam Core Prototype

To decide between these three initial designs, the team put together a Pugh Matrix (Table 1) which evaluated them based on different criteria the team considered important. The team determined these criteria based on its strategic objectives and what the team considered to be the most vital towards winning the game. It decided to give the most weight to shooting goals successfully since, even if the robot complies with the rest of the components, if it can't score then it would not be possible to further the objective of winning the game. This is the determining criteria in terms of the score and hence the team's Pugh Matrix reflects that. The next criteria the team gave most importance to was picking up and releasing gems quickly since time will be of the essence when competing. Medium importance was given to easy turning and stability since these are extremely necessary for the robot to traverse the field, but don't directly affect the score. The lowest weight was given to moving quickly, since if the robot could pick up and release gems quickly then this doesn't have to play a big role. Additionally, the speed range the team would be able to achieve with each design doesn't vary that much.

Criteria	**Weight**	**Scoop**	**Moving Bar**	**Pinball**
Moving Quickly	2	0	0	-2
Stability	3	-3	+3	0
Shooting goals successfully	5	0	+5	+5
Easy turning capability	3	+3	0	0
Picking up and releasing gems quickly	4	-4	0	0
Total		-4	8	+4

Table 1. Pugh Matrix used to choose decide between the team's initial three designs

Based on the above matrix, the team decided to go for the moving bar design which the team titled Design 1.0. This is what the team presented for Design Review; however, feedback forced the team to reconsider its idea. The original design may be very complex since it would involve linear motion, which would be very hard to achieve. The team then went back to the brainstorming stage focusing on simplicity this time.

The team developed Design 2.0 (Figure 7) which was based upon the idea of simply rolling the ball into the goal rather than lifting it to collect it. The design would have a rolling cylinder along with two arms that would push the ball forward and keep it from going to the sides at the same time. The team built the drivetrain for this prototype but then found several issues with the idea. The team realized that having only two wheels and a caster wheel made the design too unstable and also realized that the arms hit the ramp first when trying to drive up it. Additionally, there were some issues with friction with the arms and the gems when trying to turn. To solve all of this, the team came up with Design 2.1 (Figure 8) where simply replacing the side arms with two additional caster wheels. The team noticed however that this would present problems with scoring since there was no way to push the gem inside the goal without driving into it.

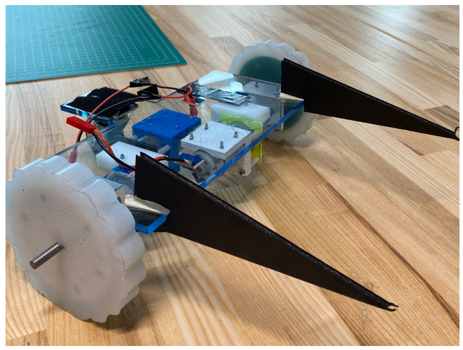


Figure 7. Design 2.0

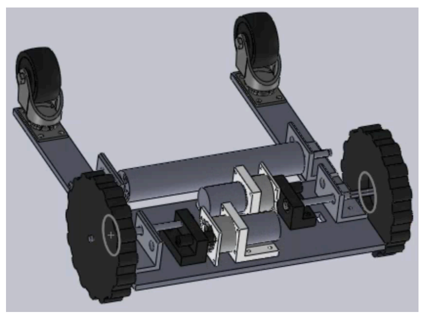


Figure 8. SolidWorks Model for Design 2.1

Based on all the issues the team faced with this design, it opted for a completely new idea: Design 3.0 (Figure 9). This had a new pickup mechanism that consisted of a skewer that would drive into the balls and then rotate to drop them off in a box behind it. The gems would then be released into the goal by having the back part of the box be a backdoor that opens down. There would also be an inclined plane inside of the box so that the gems would roll down easily, using some of the ideas from initial designs. This design then allowed us to collect several gems at a time too.

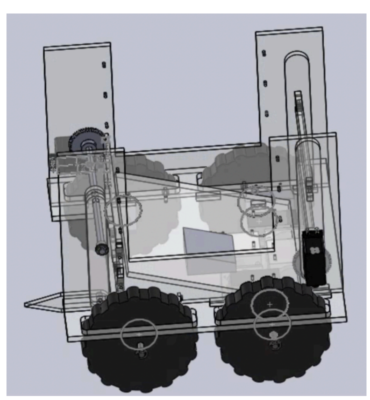


Figure 9. SolidWorks Model for Design 3.0

The team constructed a new Pugh Matrix (Table 2) to make a decision among these designs. Based on the differences between each design, the team switched some of the criteria. Since all of the designs would move at a similar speed, the team got rid of this criteria and replaced it instead with how simple the design was. The team also added the criteria of picking up several gems at a time since this was a key differentiating factor.

Criteria	**Weight**	**Design 1.0**	**Design 2.0**	**Design 2.1**	**Design 3.0**
Simplicity	2	-2	+2	+2	0
Stability	3	+3	-3	-3	+3
Shooting goals successfully	5	+5	+5	-5	+5
Easy turning capability	3	0	-3	-3	+3
Pick up several gems at a time	4	+4	-4	-4	+4
Picking up and releasing gems quickly	4	0	-4	-4	+4
Total		10	-7	-17	+19

Table 2. Pugh Matrix to decide between Design 1.0, 2.0, 2.1 and 3.0

Based on this Pugh Matrix, it was clear that Design 3.0 was superior to the rest and hence, it was chosen as the final solution (which will be further discussed in a later section of the report).

Analysis

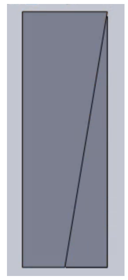


Figure 10. Milled incline piece
(6 inches long, 2 inches and 1 inch
high for top and bottom sides,
respectively)

There were several issues in the current version of the robot. One was the gear for one of the servo motors, which was obstructed by the acrylic underneath it. The team determined the radius of the gear that maximally passes through the bottom acrylic and modified the piece such that a gap existed for the gear.

The acrylic was cut, and now there exists a pass for this gear. The analysis conducted was particular to the width of the gear that was obstructed by the acrylic.

Similarly, small adjustments were made in the acrylic to reflect changes that were observed, such as of the motor drill holes.

The incline plane was made from delrin (left) such that the shortest end was 1 inch high, and the longest end was 2 inches high. The length of the inclined plane is 6 inches.

When initially testing, it was found that the large gems became stuck and wedged against the acrylic, even when the back door was open. Via testing, it was determined that the angle of the incline must not be steep enough. Thus, an incline of 45 degrees was milled for the incline. This angle was too large, so the original incline was kept. It was determined that the strategy for gem collection would be focusing on collecting the small gems first, and after that collecting the large gems. This strategy would ensure that the large gems would not become stuck on the back door, and thus allow for the gems to exit when the back door was opened.

The sides of Design 2.0, as defined in the second design review, had friction on the sides of the arms such that it was difficult to move the robot efficiently and maneuver the gems. The third caster wheel made the robot unstable and the sides of the robot, when descending down the ramp, hit it.

Design 2.1 entailed the consideration of caster wheels for the sides of the robot. This would allow it to avoid the sides hitting the ramp first. However, there were still issues with the caster wheel stability as well as with the rolling cylinder. Design 3.0 aimed to remove these barriers in previous designs by introducing the skewer mechanisms for picking up gems, as well as the back-door mechanism for offloading the gems.

Finally, the team undertook several calculations verifying that its motors would be able to aptly drive their respective components. Figure 11 shows the calculations for the main drivetrain;

figure 12 shows the calculations for the back ramp servo; finally, figure 13 shows the calculations for the skewer's servo.

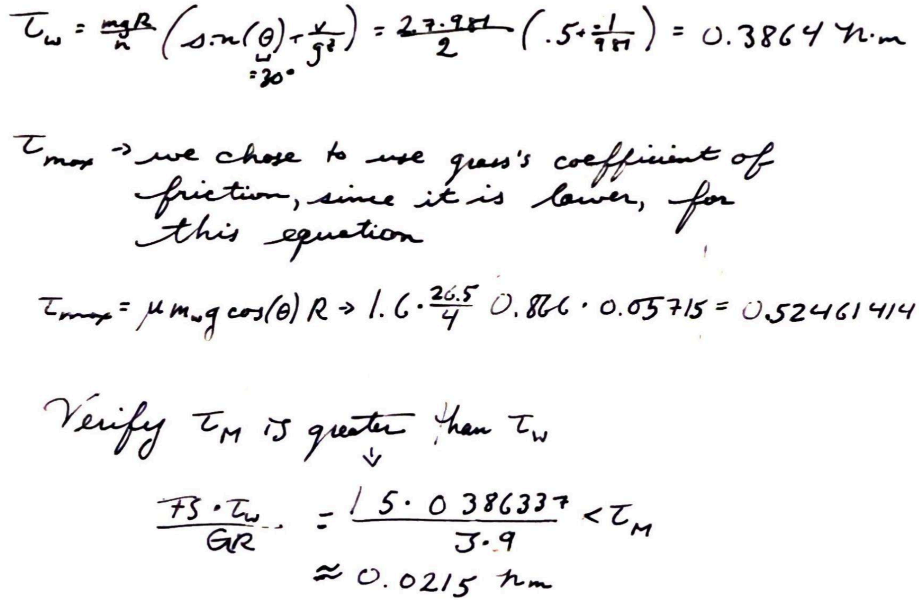


Figure 11: Drivetrain calculations

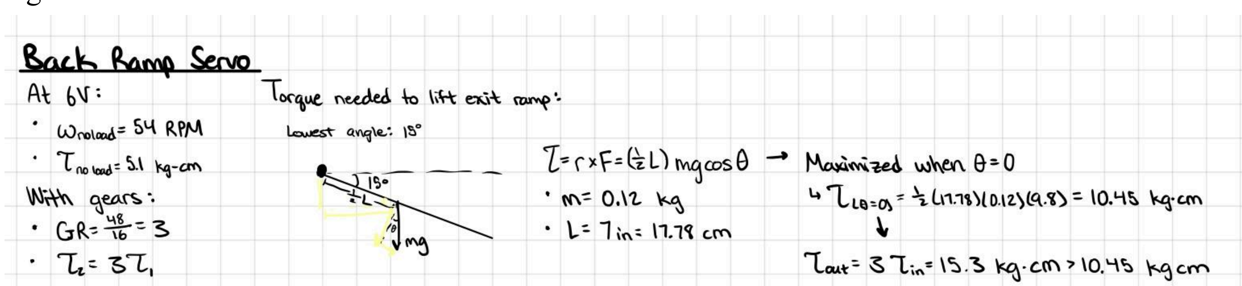


Figure 12: Back Ramp servo calculations

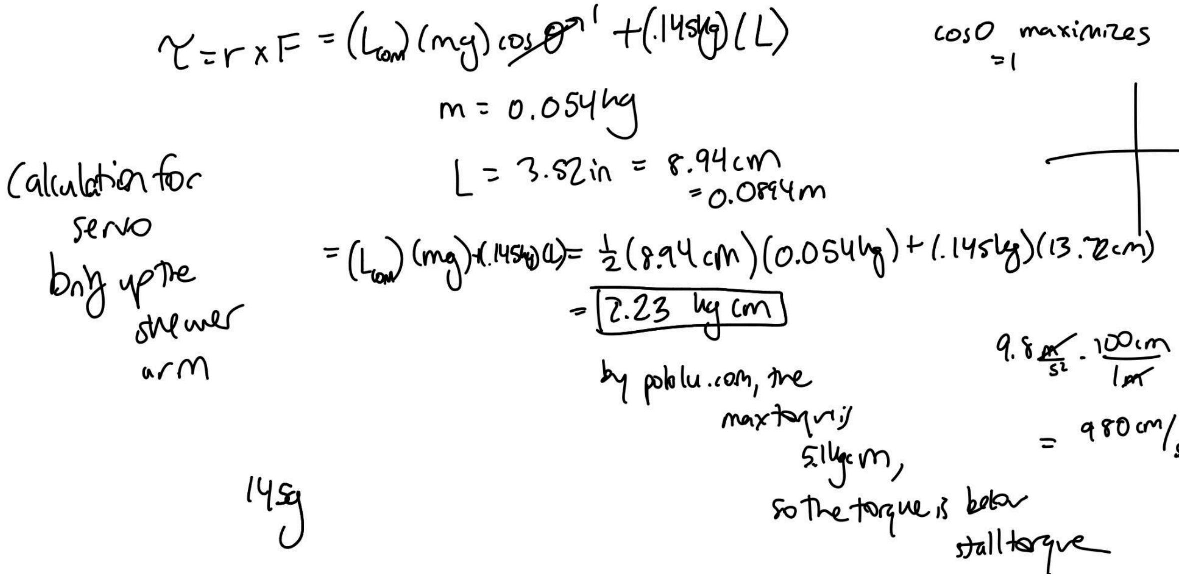


Figure 13: Skewer Calculations

Final Solution

The final robot, Design 3.0 is able to maneuver around the Turf Wars field, with four wheels, two wheels on the same side linked by timing belts. Such a configuration allows for tighter turns, since all of the wheels are effectively powered and diametrically opposed. First, setup involves connecting the motor controllers to the receiver and the receiver to the battery pack, which goes underneath the highest part of the inclined plane that is then placed on top. Once the competition has started, the robot approaches a gem (small ones first) and the person controlling the robot activates the servo that controls the rotation of the spear, thereby "skewering" the chosen gem, lifting it up over the front wall, and allowing gravity to deposit it in the robot's holding area. After this process is repeated by the team's controller three or four more times, depending on the size of the gems, the robot drives up one of the inclined planes to deposit the gems in the goal. Since picking up more gems was prioritized over simplicity of design (i.e., less/no servos, minimal weight), the heavier final robot comfortably travels up the 15° incline. Additionally, with the timing belt-connected wheels, the robot can travel either with the spear facing into or opposite the direction of travel. Regardless, once the robot reaches the area right in front of the goal, it will spin so that it is oriented with the back door facing the goal. Then, the back door will be lowered via a servo and the gems will slide down the incline plane and into the goal.

Design 3.0 fulfills all of the constraints of the Turf Wars competition. The robot fits within the 12 in^3 "Box of Justice" with no more than a tenth of an inch to spare; the design maximized the allowed space so as to be able to carry the most gems. Only approved materials were used: delrin, acrylic, silicon, wax molds, fishing wire, nuts and bolts, steel rods and hex shafts, e-clips, 3D-printed material, plastic gears, screwdriver motors and planetary gearboxes, continuous servos, and the radio controller along with its associated parts. Two screwdriver motors and two continuous motion servos were used. Total acrylic and 3D-printing used was less than the material allocated. Setup takes significantly less than two minutes as well. Moreover, the team's criteria are satisfied. The robot was optimized with regard to maximizing the number of gems it could score—the number of gems it could hold being a proxy for that—while being easily maneuverable with a small turning radius and a low center of gravity to enable it to ascend the inclined ramp. Having decided not to pursue an earlier design that involved linear motion, simplicity in the use of servos was especially considered. As a result, only rotational motion was used. Another point the team considered was the stability of the design since Design 2.0 had that as an issue when driving up the 30° incline. With four wheels and a center of gravity of only 3.76", the desired level of stability was achieved. Additionally, as weight is an important factor in the competition, opting for fishing line to complete the side walls to reduce the total volume of acrylic thus minimized weight.

Having discussed some of the advantages of the robot, it is useful to consider its disadvantages and how the team would improve the design given 2-3 weeks of time. Occasionally, and particularly with large ones, gems would get stuck on the spear and not fall into the holding compartment, possibly due to increased friction but likely because the angle of the spear when attempting to drop the gem was not sufficiently below the horizontal. While not critical, a solution for the aforementioned issue is experimenting with different spear designs such as one that can get a negative angle below the horizon but then snap back to perfectly horizontal when it is lowered to pick up the next gem. In addition, as the team began driving the robot, it discovered that, while motor calculations were correct as to the motors, themselves, several gears were not able to handle the motors' load. One possible solution: mill the gears out of metal, or a similarly stronger material (the weakness and flexibility of plastic is a major cause of this problem).

Final Design Specifications

Overall Mass	3.665 kg (including all electronics)
Dimensions	12" x 11.5 x 10.75
Undercarriage Clearance	1.5"
Turning Radius	0"
Drivetrain Gear Ratio	216
Radius of Wheels	2.25"
Deposit Servo Axle Width	8.25"
Holding Area Incline	9.963 degrees
Wheelbase	5.5"

Appendix

BILL OF MATERIALS

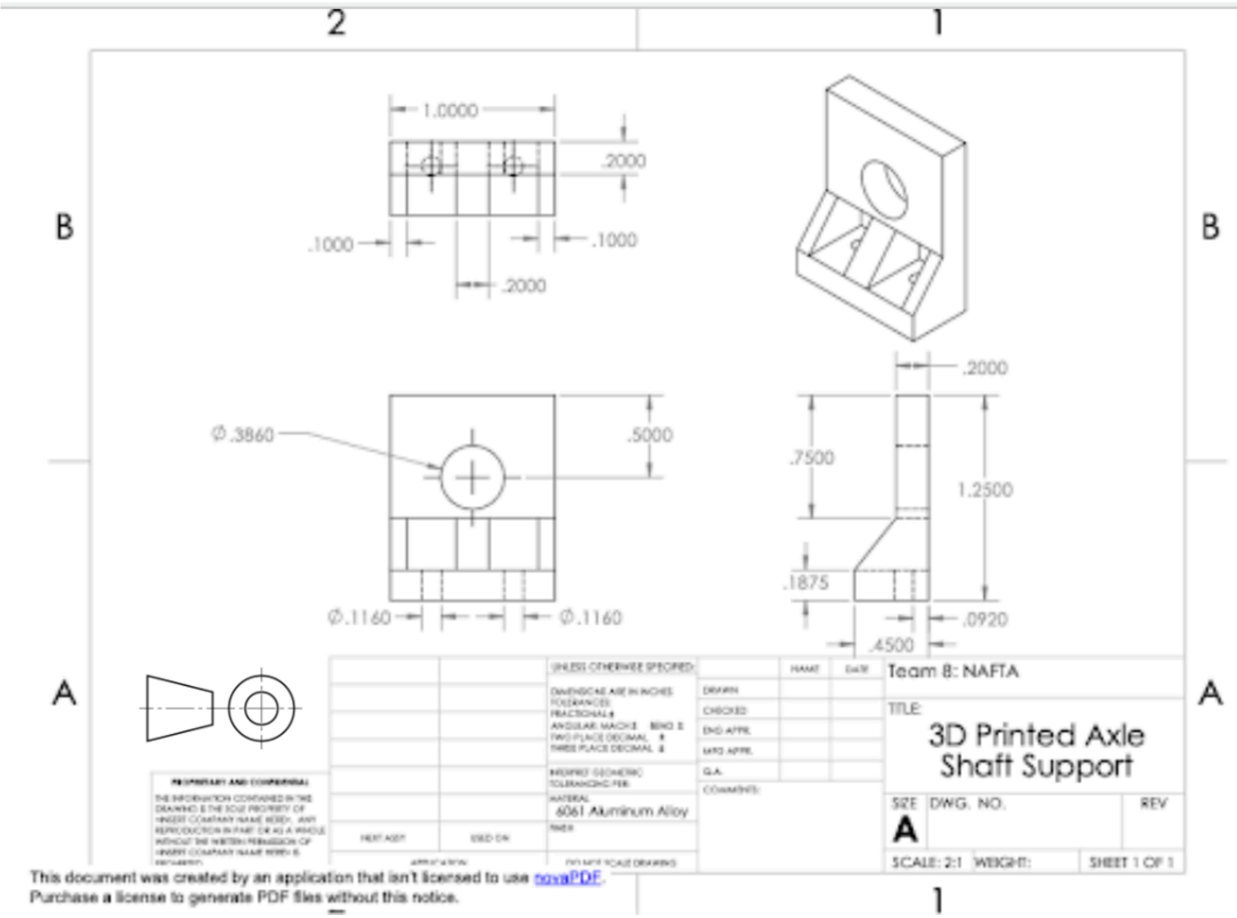
ITEM NO.	Part Name	DESCRIPTION	Material	QTY.
1	Hex Nut 1/4"-20 Thread Size	For spear subassembly	18-8 Stainless Steel	2
2	Threaded Rod 1/4"-20 Thread Size, 5 Inches Long	For spear subassembly	18-8 Stainless Steel	1
3	32P, 16 Tooth, 25T 3F Spline Servo Mount Gear	For servo subassemblies	Acetal	2
4	Hex Nut, 1/4"-20 Thread Size	Used in spear subassembly	18-8 Stainless Steel	2
5	98804A487	Threaded Rod	18-8 Stainless Steel	1
6	Acetal Plastic Gear 16 Teeth 32 Pitch	For gearbox - broached	Acetal	2
7	Acetal Plastic Gear 48 Teeth 32 Pitch	For servos and gearbox - broached	Acetal	4
8	Aluminum Shaft Support	For smaller gear shaft on gearbox	6061 Aluminum	2
9	Aluminum Shaft Support - Shorter	For non-driven wheels	6061 Aluminum	2
10	3D Printed Axle Shaft Support	Supports wheel axle on the outside	PLA	4
11	Battery	Provides power to all motors	Sub-C 4200mAh 6.0v NiMH	1
12	Delrin Shaft Support	Milled - For gearbox	Delrin	2
13	Drivetrain Base	Lasercut	1/4" Acrylic Sheet	1
14	E-Clip	E-Clip 0.25" ID	1060-1090 Spring Steel	10
15	Exit Ramp Cross Beam	For exit ramp subassembly	1/4" Acrylic Sheet	2
16	Exit Ramp Support	For exit ramp subassembly	1/4" Acrylic Sheet	2
17	Fishing line	For chassis walls	Nylon	17.3’
18	Flange Bushing ID 1/4" OD 3/8"	Used in multiple sub-assemblies	Nylon	12
19	Front Wall	Lasercut	1/4" Acrylic Sheet	1

20	Hex Drive Shaft	From Screwdriver	Plain Carbon Steel	2
21	Hex Shaft - Back Wheels	Back wheel axle - For gearbox	Plain Carbon Steel	2
22	Hex Shaft - Front Wheels	Front wheel axle	Plain Carbon Steel	2
23	Inclined Plane	Inclined plane in chassis	1/8" Acrylic Sheet	1
24	Inclined Support	Support for chassis inclined plane - milled	Delrin	1
25	Lasercut Front Plate	Lasercut - for gearbox	1/8" Acrylic Sheet	2
26	Left Chassis Wall	Lasercut	1/4" Acrylic Sheet	1
27	Low-Strength Steel Hex Nut	For chassis T-slots and axle supports	Zinc-plated low-strength steel	33
28	Locknut 4-40, Low-Strength Steel	For attaching servos to chassis	Low-Strength Steel	5
29	Metal Gear-Shaft Interface	Metal Circle with 6 Notches from Screwdriver - For gearbox	Various metals	2
30	Motor	Motor from screwdriver for drivetrain	Various metals and plastics	2
31	Motor controllers/drivers	Regulates speed of screwdriver motor	Various metials and plastics	2
33	Motor Mount	3D Printed for gearbox	PLA and ABS	2
35	General Purpose Flat Washer Off-White, 1/4" Screw Sz, .48" OD, .05"-.07" Thk	Used in multiple sub-assemblies	Nylon	10
36	Pan Head Machine Screw, 4-40 Thread 0.5" Length	Used in multiple sub-assemblies	Passivated 18-8 Stainless Steel	17
37	Pan Head Machine Screw, 4-40 Thread 1.25"	For gearbox assembly	Passivated 18-8 Stainless Steel	8
38	Pan Head Machine Screw, 4-40 Thread 3/8" Length	Used in multiple sub-assemblies	Passivated 18-8 Stainless Steel	6
39	Pan Head Machine Screw, 4-40 Thread 5/8" Length	For chassis T-slots	Passivated 18-8 Stainless Steel	25
40	Pan Head Phillips Screw, 4-40 Thread 0.25"	For gearbox assembly	Passivated 18-8 Stainless Steel	2
41	Passivated 18-8 Stainless Steel Phillips Flat Head Screw	For gearbox	316 Stainless Steel	4

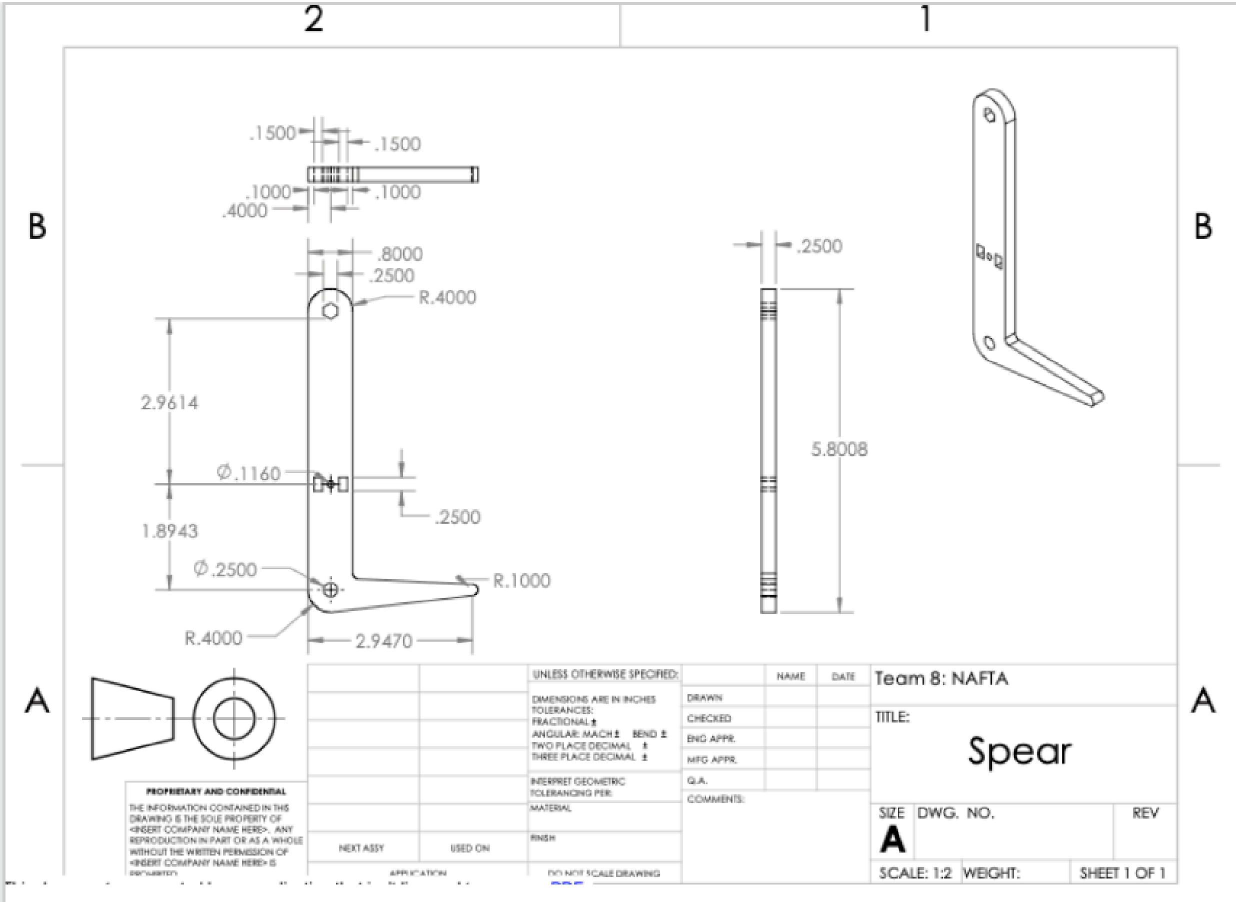
42	Passivated 18-8 Stainless Steel Phillips Flat Head Screw		Passivated 18-8 Stainless Steel	4
43	Planetary Gearbox	Planetary Gearbox from Screwdriver	Various metals	2
44	Pulley Tensioner	For timing belt subassembly	PLA	2
46	Right Chassis Wall	Lasercut	1/4" Acrylic Sheet	1
47	Servo	For spear and back door assemblies	Standard-size continuous rotation servo	2
48	Servo rod	For servo assmeblies - lathed	6061 Aluminum	2
49	Spear	Main feature of spear subassembly	1/4" Acrylic Sheet	1
50	Spear Supports	Used in spear subassembly	1/4" Acrylic Sheet	2
51	Spear Wings	Used in spear subassembly	PLA	2
52	Steel Pan Head Phillips Screw, 4-40 Thread, 2.5"	Long Tensioner for Drivetrain Belt	18-8 Stainless Steel	2
53	Trapezoidal Timing Belt, .200" Pitch, 6" Outer Circle, 1/4" Wide	For timing belt and pulley subassembly	Urethane	2
54	Unthreaded Spacers 3/16" OD 11/16" Length	For gearbox	Nylon	8
55	Velcro Patches, 1" by 5"	Secures battery to chassis	Velcro	1
56	Washer 0.39" ID, 0.77" OD from Screwdriver	For gearbox	18-8 Stainless steel	2
57	Washer 0.41" ID, 0.54" OD from Screwdriver	For gearbox	18-8 Stainless steel	2
58	Washer for Number 4 Screw Size, 0.125" ID, 0.312" OD	For gearbox	18-8 Stainless Steel	8
59	Wheel inserts	Lasercut - 2 per wheel	1/4" acrylic sheet	8
60	Wheels	Cast in milled max mold with acrylic insert	Ecoflex 30	4
61	External Retaining Ring for 10 mm Shaft Diameter	For gearbox	Steel	2
62	Motor receiver	Maintains line of communication between motor	Mixed materials	1

		and controller		

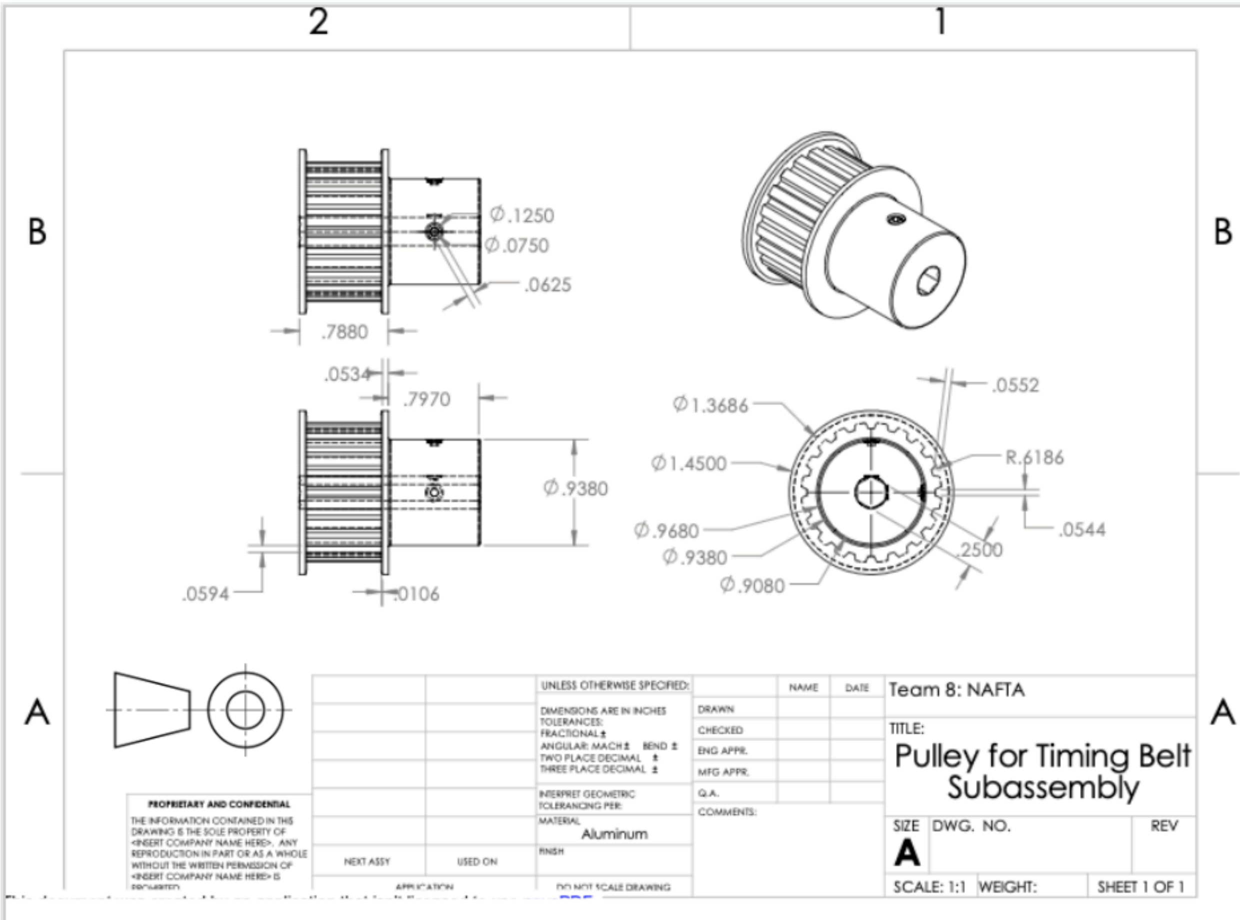
3rd Angle Projection of 3D Printed Axle Shaft Support



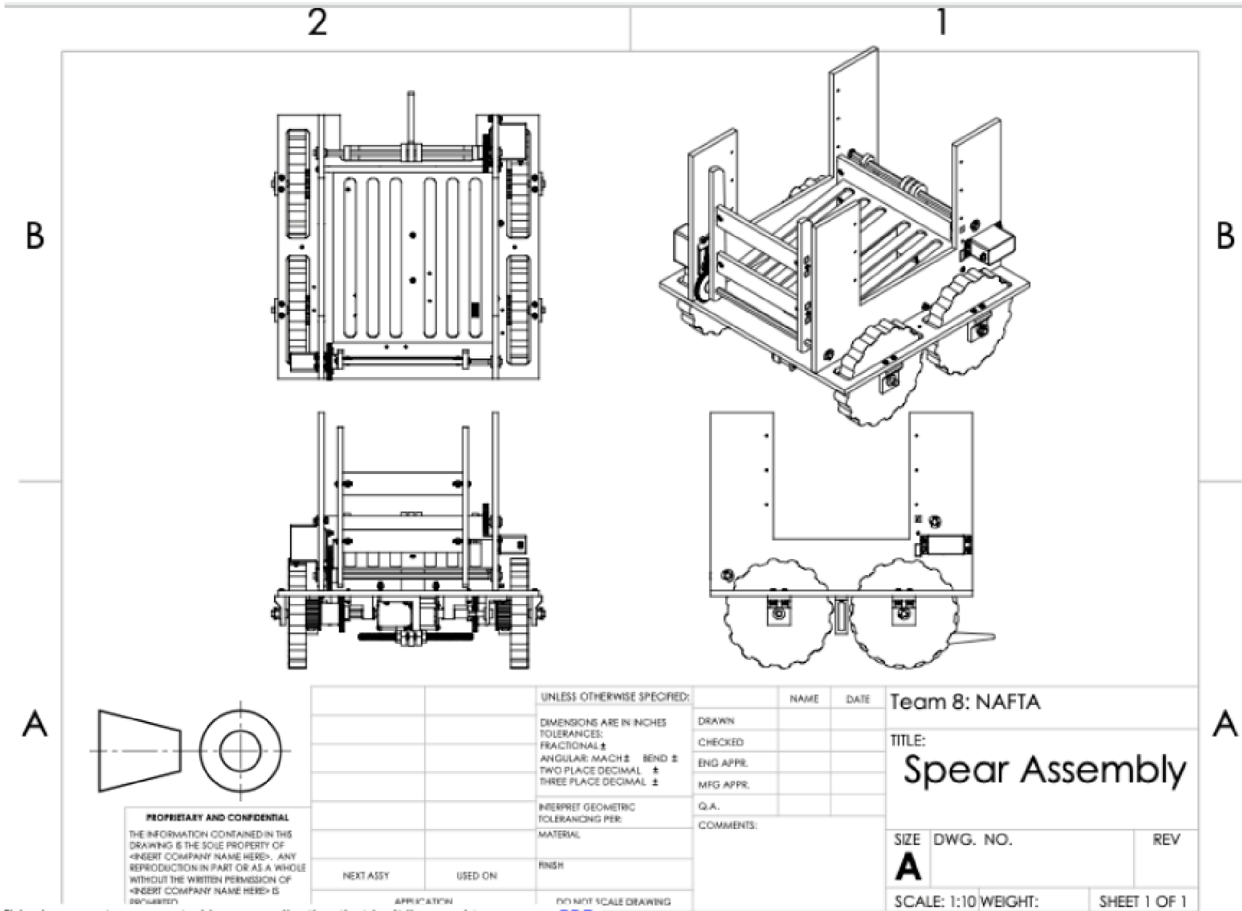
3rd Angle Projection of Spear



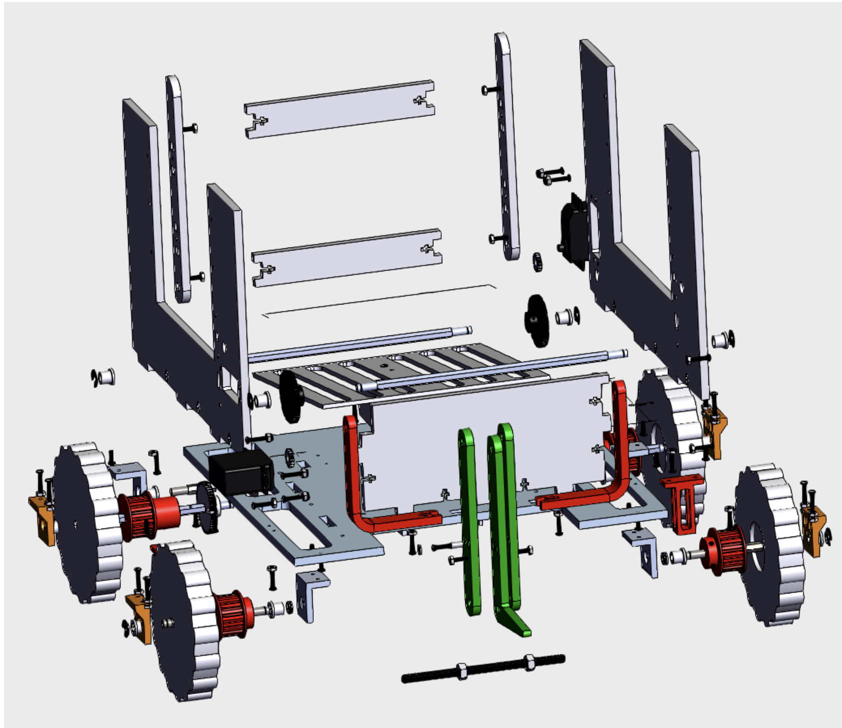
3rd Angle Projection of Pulley for Timing Belt Subassembly



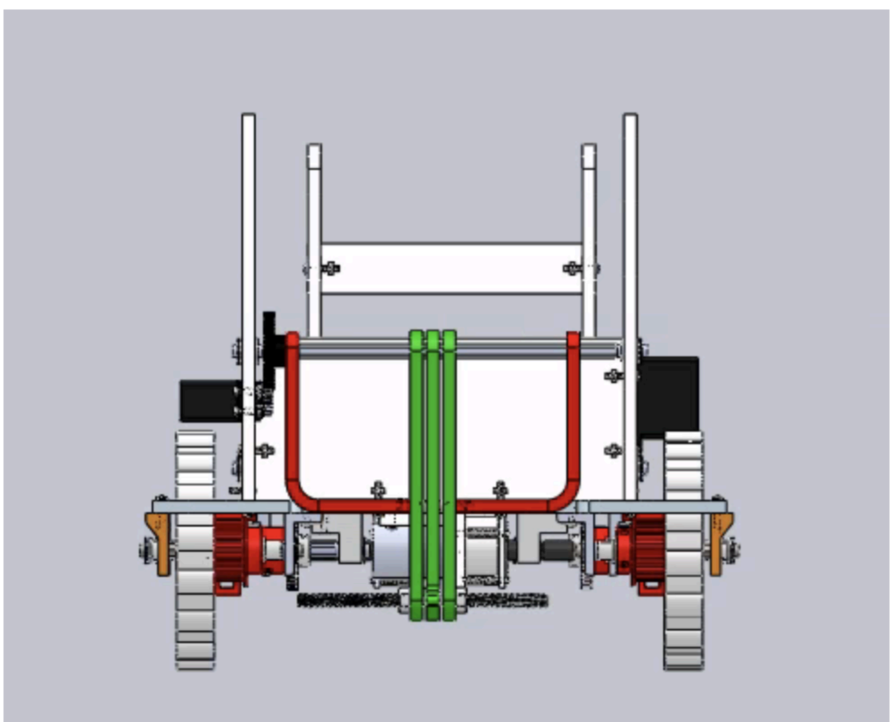
3rd Angle Projection of Final Robot



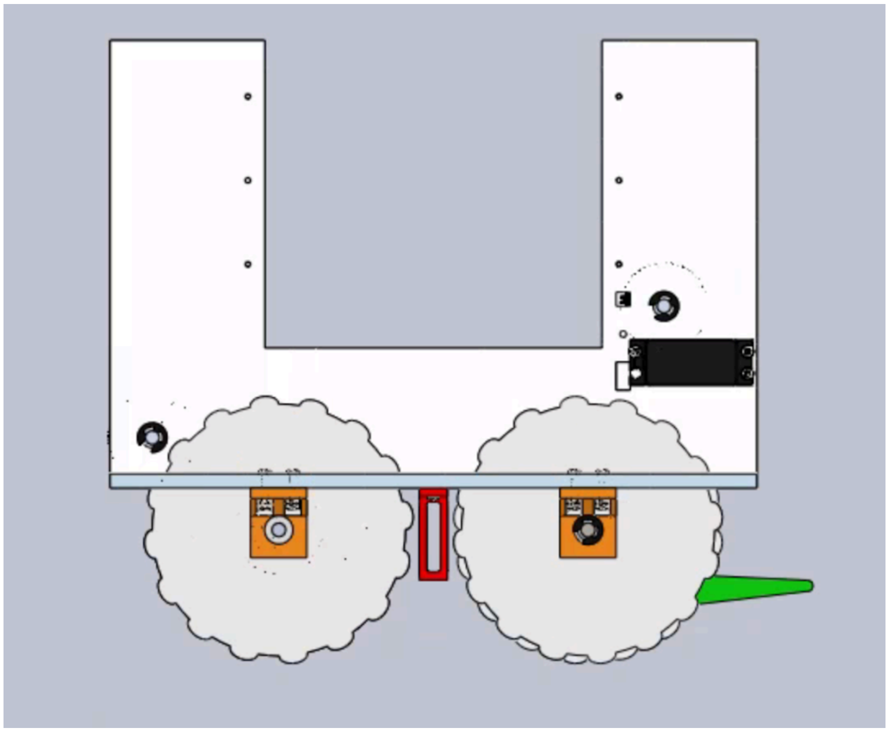
Robot Exploded View



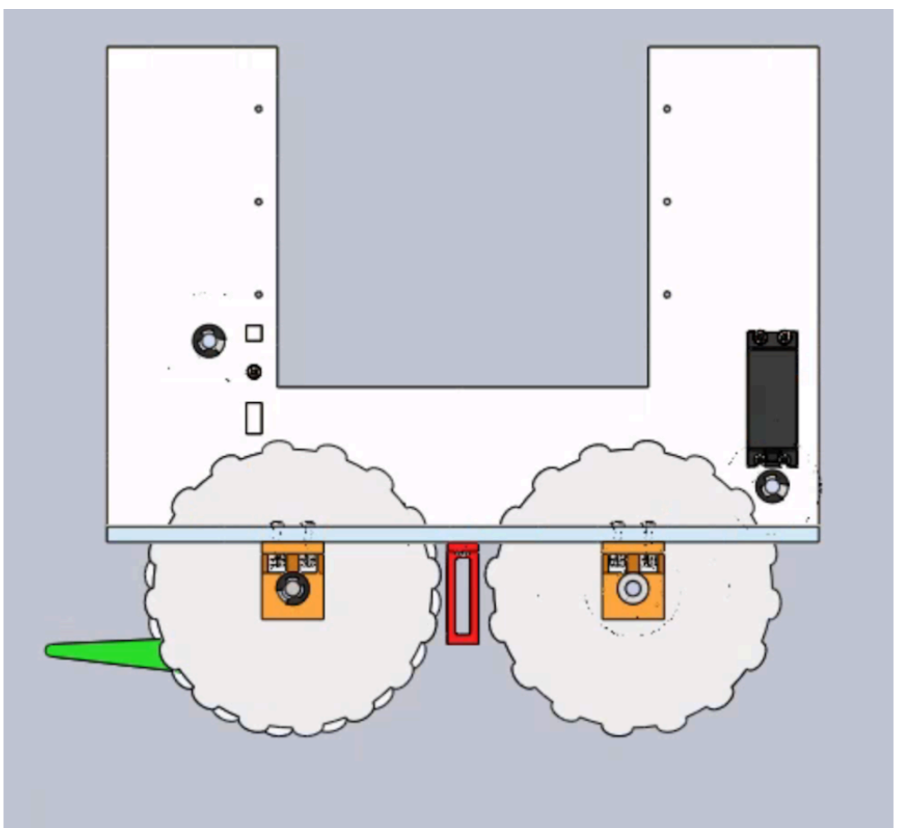
Robot Front View



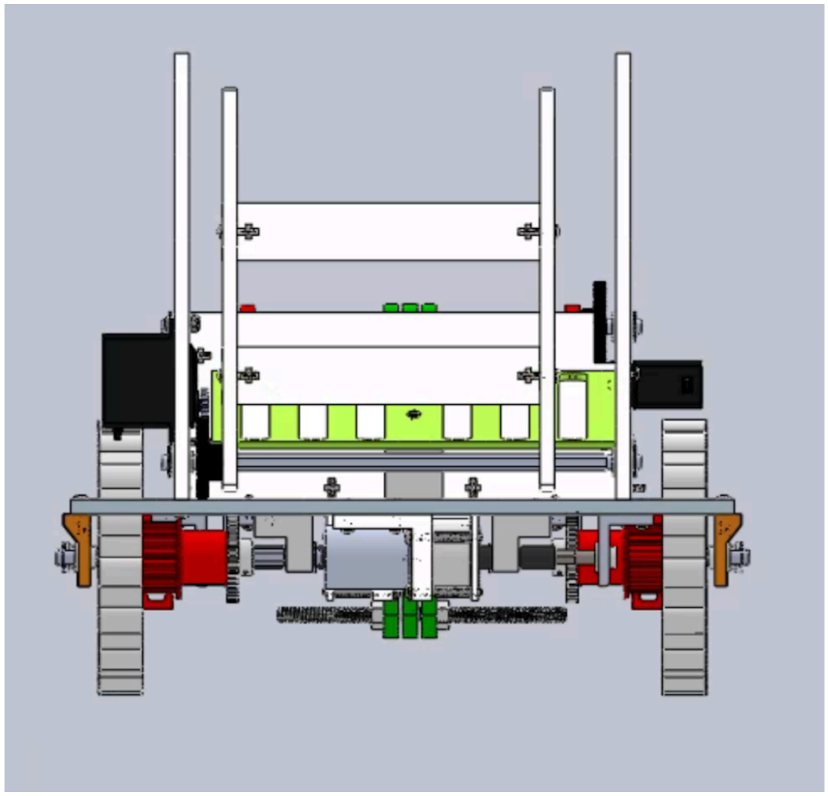
Robot Right View



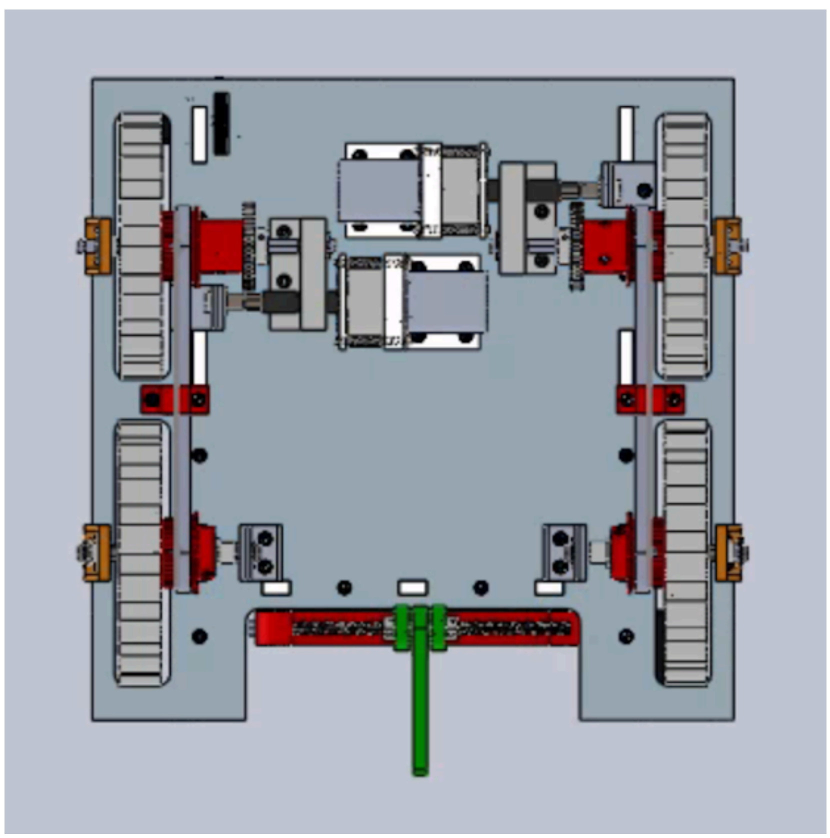
Robot Left View



Robot Back View



Robot Bottom View



Constructed Robot