ME2110 – Section A03

Final Report

Team 2:

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Submitted to: Dr. Richard S Cowan

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Abstract

This report details the design considerations and the final design for a robot that maximizes points attained in a forty-second head-to-head competition. The robot, constrained by size and budget, earns points by entering the competition field, dropping four ping pong balls (friends) through a minivan's sunroof, depositing a ping-pong ball (ghost) in each of the opponent's quadrants in the centerpiece, and completing a full egress. A house of quality and specifications sheet were developed to outline the team's goals and engineering requirements with target values. Afterward, a function tree and morphological chart indicate necessary operations to maximize points scored and identify potential solutions for each operation. Each team member developed a design to be ranked by the group using a level three evaluation matrix. The selected design was manufactured, programmed, and tested for the final competition. The robot completed three performance tests with perfect scores to win the competition.

I. Introduction

The objective of this project is to construct a robotic system that maximizes points scored during a forty-second autonomous competition. The robot must cost less than one-hundred dollars, operate autonomously for forty seconds or less, and fit within a 12” by 18” by 24” box. The robot maximizes points by dropping four ping-pong balls (friends) through the minivan’s sunroof above the revolving centerpiece, see Figure 1, and depositing one of three ping-pong balls (ghosts) into each enemy-colored quadrant in the centerpiece, seen in Figure 1. The design must optimize speed and precision to reliably score maximum points. Potential design tradeoffs include weight versus transit time, as heavier robots require greater torque to move. Similarly, greater speed conflicts with accuracy, as it can increase the effect of external force on position/path deviation.

II. Problem Understanding:

The ability to produce a successful robot stems from customer requirements (team goals) and engineering specifications. A house of quality (HOQ), shown in Table 1, categorizes the relationship between the established requirements and specifications. The most influential customer requirements are to meet size and movement requirements, score maximum points, operate autonomously, and have a low assembly time and cost. These categories rank highest because they correspond to rules or to scoring points. Areas that don’t affect the competition environment have lower scores because they don’t directly contribute to successful scoring.

A specification sheet, found in Table 2, was developed from the engineering requirements to provide benchmarks for evaluating the final design. The design requirements include size/weight, cost, cycle time, total points scored, ghost distribution accuracy, position accuracy, total ghosts/friends deposited, transit time, and max setup time. From the relationship matrix, it was found that cycle time, total points scored, and ghost distribution accuracy were the most critical. Less central requirements include build quality, extra parts, and weight.

Many engineering requirements correlated positively, such as cycle time, transit time, and deposit time. Moreover, position accuracy, max. score frequency, and ghost distribution accuracy all correlated with total points scored. Size and weight negatively correlated with transfer time due to the motor’s limited torque threshold. By prioritizing transfer time, the team’s robot completes tasks prior to its competitors, preventing risk of obstruction. Additionally, stability could be maximized with proper weight distribution.

III. Conceptual Design:

The five primary functions, shown in Figure 4, for the robot are to initialize, reach center, deposit ghosts, deposit friends, and egress. Using a morphological chart shown in Table 3, four to five potential solutions were developed for completing each function and sub-function. Mousetraps were eliminated as an energy source due to limited control and unreliable movement. To reach the centerpiece, rolling and sliding rails were considered. A rolling robot utilizes motorized wheels, tank treads, or rotating flaps to travel to the centerpiece, whereas a stationary robot with rails would have an end-effector travel to the centerpiece on gravity-powered drawer slides. Drawer slides would maximize deployment speed but may induce failures with vertical stability at the manipulator end – refer to Figure 3. However, a rolling robot was calculated to travel at an appropriate speed – refer to Figures 4 and 5.

A roller button, infrared (IR) sensor, ultrasonic sensor, or timing are methods for determining when the robot reaches the centerpiece. Timing would be simplest but may induce failure with a varying start position. For the ghosts, the balls could be stored in a slot and indexed by a solenoid-controlled latch, by a rotating wheel, or with a lever actuated by contacting the beacons. The passive lever is energy-efficient but introduces complex geometry. Therefore, the motor and solenoid would be functionally simplest, but the solenoid might be limited by the force it could apply against a rubber band or other elastic. Because the motor does not need significant torque to move the balls, it would not require a gear system and could drive the actuator directly, thus increasing simplicity.

To sort the balls into each low zone, a long-arm button could be used to detect the beacons or an IR sensor/ultrasonic sensor could detect the walls of each zone. The button is the most likely choice as it would require the least amount of calibration.

To deposit the balls in the minivan, the robot must reach the sunroof, sense the sunroof, and drop the balls. To reach the van, ideas include a motorized conveyor belt, motorized/pneumatic arm, and spring-loaded catapult. The catapult would have trouble with accuracy and the conveyor belt might have trouble reaching the opening. A pneumatic arm is preferred since the arm must travel between two discrete positions and will require less complex power transmission. Again, a button, ultrasonic sensor, or IR sensor could sense the sunroof. Sensing the beacons with a button or detecting the sunroof opening with the ultrasound were proven to be most reliable. The balls could be dropped using a pneumatic/solenoid-controlled latch, motorized flywheel, or a system that uses gravity to let the balls roll down. It would be advantageous to use a solenoid since it can retract quickly into an open state. Finally, the robot could simply roll backwards in the case of the rolling robot or could retract the sliders with a motorized rack and pinion or cable.

IV. Design Overview

The final design, see Figures 6, 7, 8, and 9, includes a rear-wheel-drive chassis powered by the large motor, a pneumatically actuated four-bar lift, a solenoid powered friend dropper, and a wheel-driven ghost sorter powered by the small motor. The robot features a roller button on the chassis to determine when the robot has contacted the centerpiece, as well as two vertically movable long-arm buttons mounted on the ghost sorter support to sense the beacons on the drum. Once the specified indicator is detected, the robot will use timing to determine when to drop the friends and when to deposit each ghost.

The chassis incorporates a top plate that features laser cut slots for the drive gears and to affix the subsystems using finger joints. The side plates attach to the top plate using glued finger joints and wood screws for additional strength. The threaded rod axles span the width of the robot, passing through designated holes in the side plates. Using lock nuts, laser cut medium density fiberboard (MDF) wheels are affixed to the outside of the chassis and an MDF driven gear is held in the center of the rear axle. The large motor fits into a 3D-printed motor mount on top of the chassis and drives an acrylic-MDF composite gear that meshes with the driven gear to provide power until a roller button on the front of the robot detects when the robot has contacted the centerpiece.

The four-bar lift has two triangular support towers that slot into the chassis, supported by finger joints and four steel corner brackets for added strength. It features four parallel MDF arms with laser-cut holes for bolts to act as joints. The pneumatic cylinder pivots around a threaded rod that passes through the bottom rear of the towers and attaches to the upper four-bar arms by using a T-shaped 3D-printed joint. A horizontal arm at the top of the lift keeps the four bars parallel and reaches across the top of the van when extended to place the dropper over the sunroof. When folded, the lift lies across the length of the robot and the upper arm sits on top of the arm bars.

The friend dropper features a vertical ball storage compartment constructed from U-shaped MDF pieces slotted together at a ninety-degree angle and supported by curved ribs to improve stiffness. In transit, the balls are held in place by a rubber band stretched across the bottom, restrained by the small solenoid. Before the match starts, the solenoid is held closed by a static lock gate on the lift. When power is provided to the robot, the solenoid activates and contains the balls until the drop zone is detected using the upper button. Once detected, the solenoid turns off and the rubber band removes the pin, allowing the balls to fall into the van.

The ghost sorter uses a similar structure to the dropper by incorporating slotted linear rails and curved ribs for stiffness. The sorter stands on an MDF tower angled towards the center of the centerpiece. After being loaded through the rear opening, the balls roll down a ten-degree angle until they meet the sorter wheel. The wheel is a curved five-pointed star cut from acrylic and powered by the small motor, which is held in a 3D-printed motor mount. When the home zone is detected using the lower button, the robot uses timing to drop a ball in each zone, where one fifth of a turn from the gear allows one ball to drop through.

The final code flowchart can be seen in Figure 10, detailing the robot actions during a match. The final cost of materials was $37.34, excluding the mechatronics components. A full breakdown can be seen in the Bill of Materials in Table 5.

V. Alternative Designs

Prior to selecting the final design, four design concepts were developed by the team. Each was scored using a level three evaluation matrix and ranked. The lowest scoring alternative is a box style design, seen in Table 4. The robot would approach the centerpiece using mousetrap powered wheels. After egress, adjustable switches would sense each zone, and a solenoid would control the release of ghosts down a ramp and into the enemy zones. For the release of friends, a motor-powered arm would reach the van and the balls would roll out into the sunroof. Finally, once all other tasks were complete, a pneumatic cotton ball launcher would fill the home zone to prevent other robots from scoring. The total weighted evaluation score for this design was 405; it lost points in some of the highest weighted categories, such as move, score max points and efficient functionality. A major disadvantage to this design is the mousetrap wheels because they could lead to unpredictable movement and are difficult to setup.

The second-best scoring alternative is an open frame structure, seen in Table 4. This robot would have no wheels and would reach the centerpiece using gravity powered rails. On the rail there would be a mousetrap-powered arm to reach the sunroof opening. A solenoid would release the friends when an ultrasonic sensor detects the sunroof. Ghosts would be sorted using a solenoid and rubber band, timed by a long arm button. The total weighted evaluation score for this design was 415. The design lost points for ghost distribution and maintainability.

The final alternative is an open frame design, seen in Table 4. This robot would use two motors to power the wheels. The friends would be deposited using a pneumatic launcher and timed with a button to detect the beacons. Ghosts would be released with a passive mechanical system, where adjustable tabs would pull open a door to release one ghost in each enemy zone and would close the door using a rubber band. The total weighted evaluation score for this design was 434. The design lost points due to the expected inaccuracy of the piston launcher.

VI. Performance Results

During initial testing, the robot launched every time except once when there was a power error as seen in Table 6. It also scored full egress points on 40 out of 43 tests. The data suggest that the lift design was reliable in clearing the mystery machine and allowed for successful deposit of friends into the sunroof. The ghost's depositor was consistent when properly set up. Throughout testing, the ghost depositor averaged 2.63 ghosts out of 3 ghosts.

From total testing as seen in Table 7, the robot achieved an average score of 143.56 as red, 145.33 as blue, 135.46 as white, and 153.14 as yellow. The average of every test was 136.58 and with the finalized code the average was 146.3.

During the final competition the robot successfully launched, deposited all the ghosts into enemy quadrants, deposited all friends into the mystery machine, and fully egressed every time as seen in Table 8. With the three perfect runs the robot scored a perfect score of 483 and won the competition.

VII. Conclusion

In the final competition, the robot performed as designed, winning the competition with three perfect scores. This indicates vast improvement from the interim competition, where the robot failed to score twice and damaged itself by latching on to the rotating centerpiece and shearing off the friend dropper. This necessitated a less rigid dropper door, stronger lift, and easier-to-load ghost sorter. The team selected improved designs that eliminated the cause of error and greatly improved operational efficiency. This was the biggest learning experience for the team and really drove home the cyclical nature of the design process. Overall, the team learned the importance of proper documentation, design development, and design evaluation from the project. Given the opportunity to improve further, we would focus on reducing the robot's cycle time.

Appendix

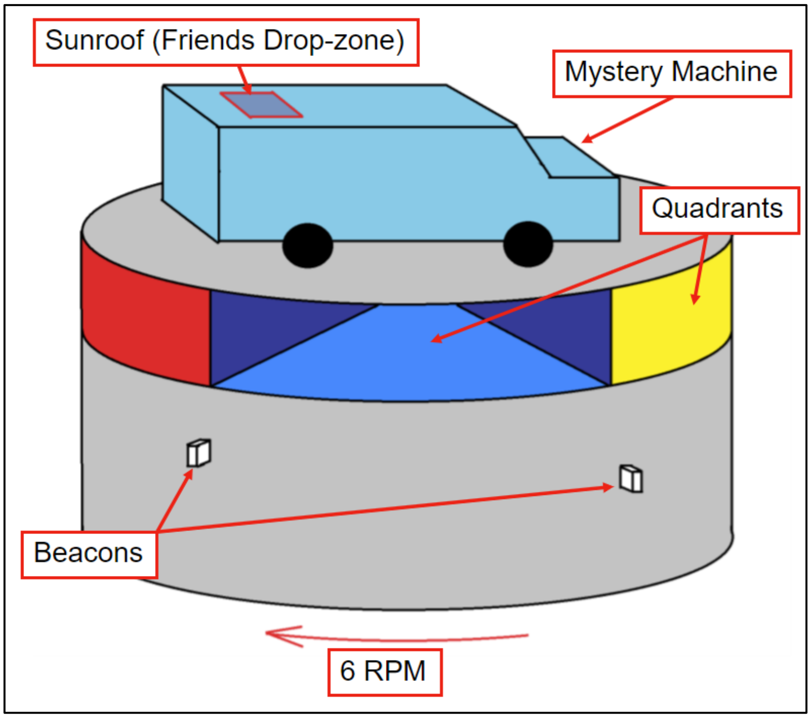


Figure 1: Centerpiece configuration with labels.

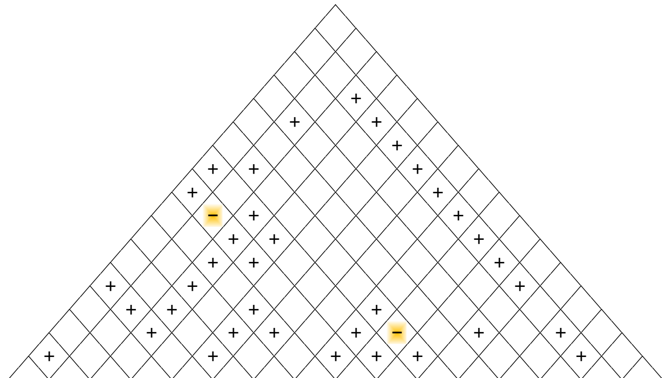
Table 1: House of Quality.

Date: 6/7/2022

Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



Category	Weight	Customer Requirements (Explicit and Implicit) / Engineering Requirements	Weight	Size	Total Points Scored	Cycle Time	Position Accuracy	Total Ghosts Deposited	Total Friends Deposited	Ghost Distribution Accuracy	Transit Time	Deposit Time	Cost	Build/Design Quality Jury	Extra Parts	Max. Setup Time	Maximum Score Freq.	
		Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
		Direction of Improvement	◇	◇	▲	▼	▲	▲	▲	▲	▼	▼	▼	▲	◇	▼	▲	
Safety	5	General Safety	○	○														
Geometry	4	Portable	●	●											○			
	10	Fit within Size		●														
Scoring	10	Move													▽			
	10	Score Max Points			●	●	●		●	●	●	●	●	●		○	○	
	10	Autonomous			▽	▽	▽	▽	▽	▽					▽			
	9	Deposit Ghosts			●	●	○	●		○			○					
	7	Deposit Friends			●	●	○		●				○					
	8	Ghosts in Each Quadrant			○	○	○	●		●			○					
	8	Efficient Functionality	▽		●	●			●	●	●	●	○					
Ergonomics	10	Affordable																
	6	Aesthetics		▽									○					
Ease of Operation	9	Maintainable		○											○	●		
	10	Assembly Time	○	○												●	●	
	7	Reliable				●	●			●	●	●	▽		▽		●	
		Target	Weigh 20-25 lbs	23" x 17" x 11"	At least 119 points	30 seconds	± 2 inch	3 Ghosts	At least 3 Friends	85%+	Max 10s	Max 20s	Less than $100	Team Rating of 8/10	1 for each critical	Max. 2:30 minutes	90%+	
		Max Relationship	9	9	9	9	9	9	9	9	9	9	9	9	3	9	9	
		Technical Importance Rating	73	148	204	239	167	95	135	202	125	125	171	50	66	125	115	
		Relative Weight	4%	7%	10%	12%	8%	5%	7%	10%	6%	6%	8%	2%	3%	6%	6%	
		Weight Chart																

Table 2: Specification sheet outlines demands and wishes for engineering specifications.

			Issue Date:	7-Jun-22
Changes	**D/W**	**Specification**	**Responsibility**	**Source**
		Geometry		
17-Jul	D	< 23" x < 17" x < 11" box	All	Rules [1]
17-Jul	D	22.5" - 24.0" vertical extension	Josh	Field Geometry
		Energy		
	D	Use only allowed power sources	All	Rules [1]
	W	< 30 sec cycle time	All	Team goal
	D	Operate on 110V standard	All	Rules [1]
	D	< 100 psi air tank	Setup crew	Mech. Manual [2]
		Ergonomics		
	W	> 8/10 aesthetic score	All	Team Jury
	W	< 25 lbs	All	Team goal
		Maintenance		
	W	< 2:30 minute setup time	Setup crew	Team goal
	D	1 Additional part for critical features	Vaughn	Team goal
		Costs		
	D	$100 max	All	Rules [1]
		Production/Operation		
	W	Reach the center in 10 seconds	Siva	Team goal
	D	Deposit 3 ghosts in 15 seconds	Josh/Drew	Team goal
	D	Deposit at least 3 friends in 10 seconds	Josh/Vaughn	Team goal
	D	Complete at least partial egress	Siva	Team goal
17-Jul	W	Account for starting position deviation of 2 inches	Siva/Drew	Team goal
17-Jul	W	90% perfect score rate	All	Team goal

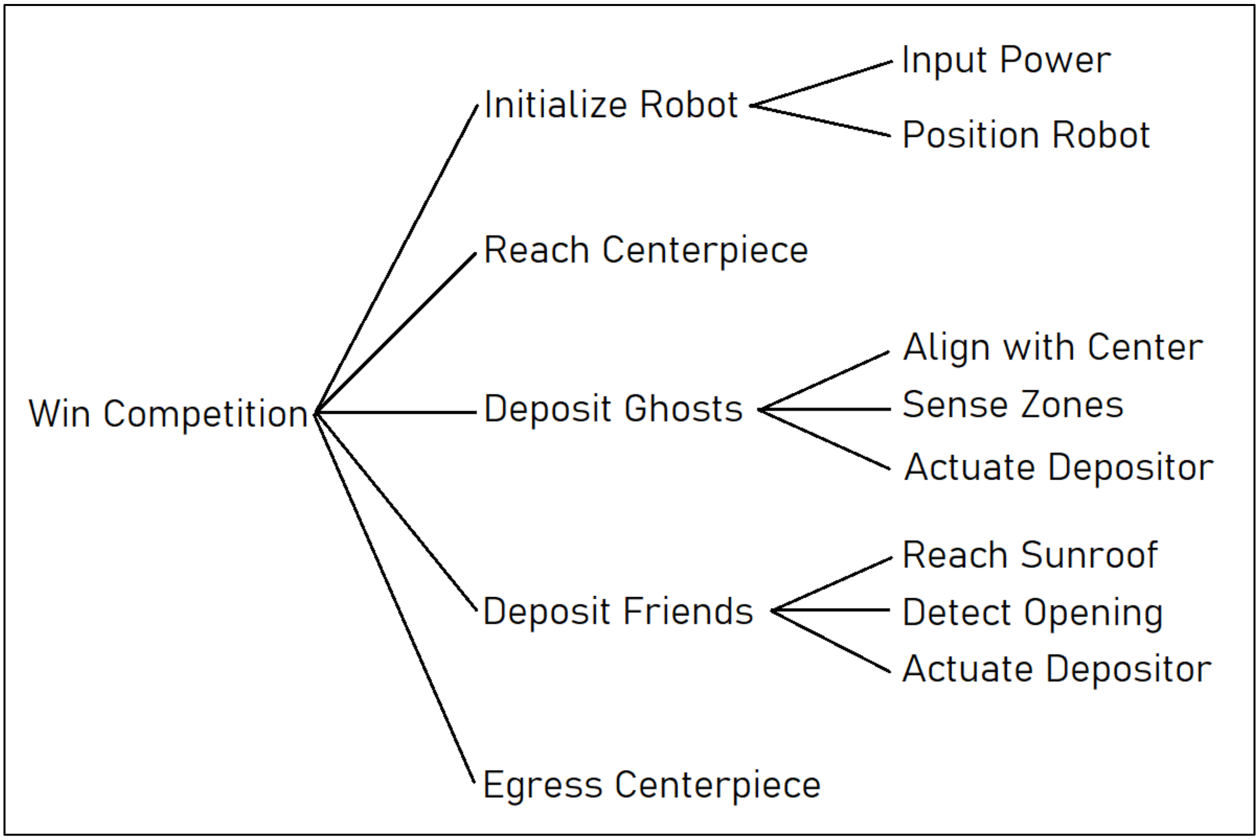
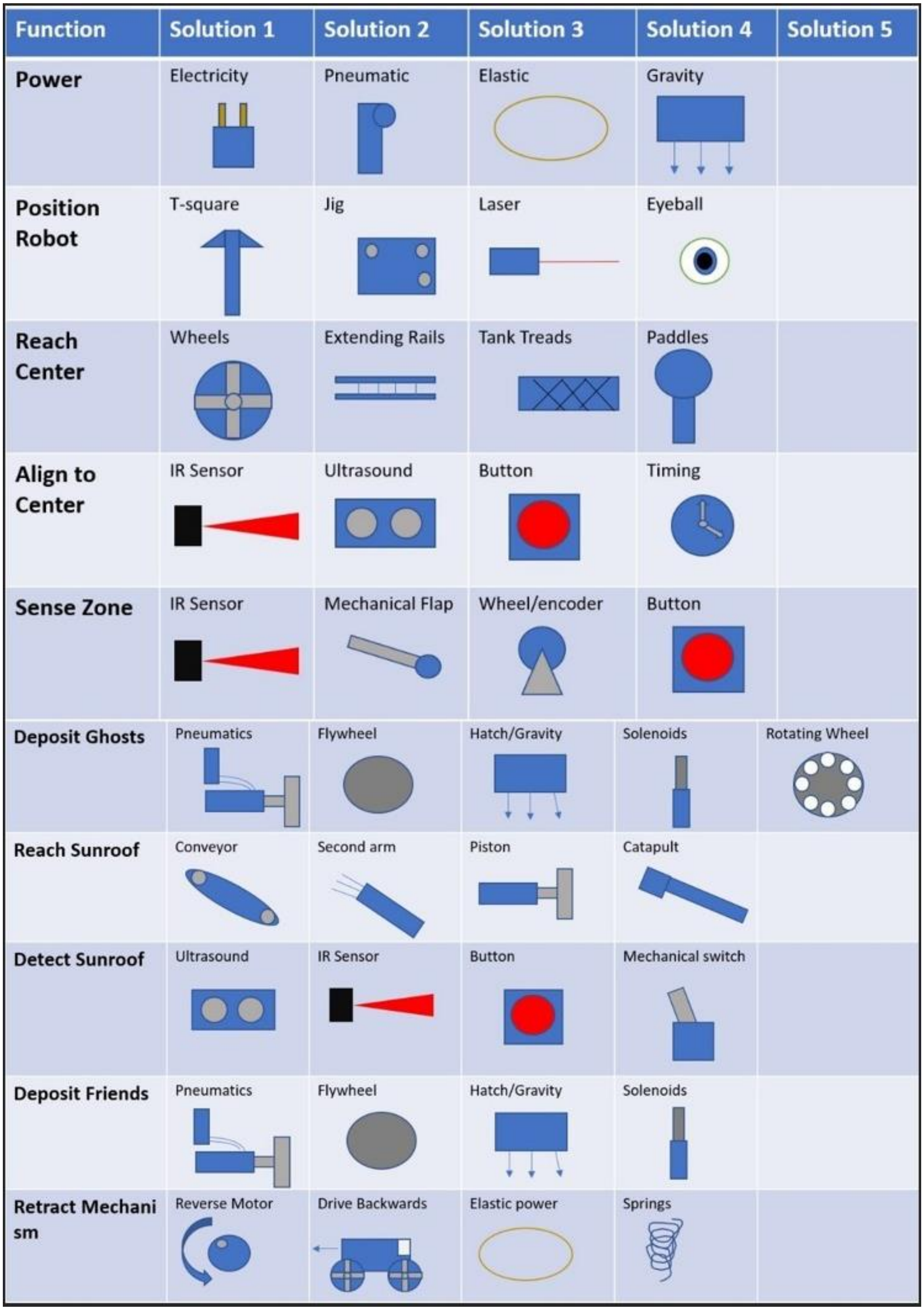


Figure 2: Function Tree.

Table 3: Morphological Chart presenting possible solutions for accomplishing given functions.

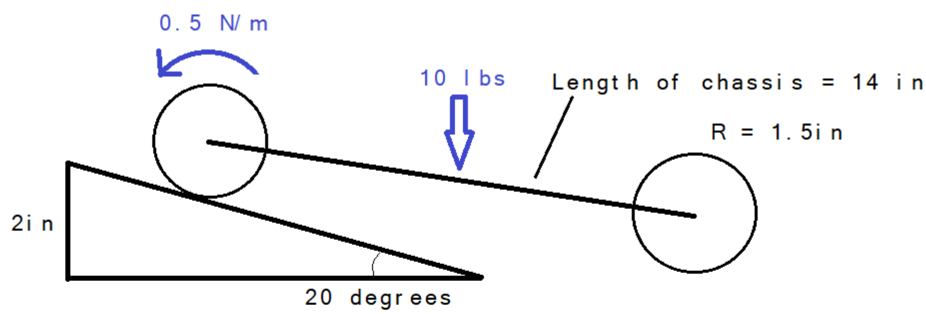


Function	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5
Power	Electricity	Pneumatic	Elastic	Gravity	
Position Robot	T-square	Jig	Laser	Eyeball	
Reach Center	Wheels	Extending Rails	Tank Treads	Paddles	
Align to Center	IR Sensor	Ultrasound	Button	Timing	
Sense Zone	IR Sensor	Mechanical Flap	Wheel/encoder	Button	
Deposit Ghosts	Pneumatics	Flywheel	Hatch/Gravity	Solenoids	Rotating Wheel
Reach Sunroof	Conveyor	Second arm	Piston	Catapult	
Detect Sunroof	Ultrasound	IR Sensor	Button	Mechanical switch	
Deposit Friends	Pneumatics	Flywheel	Hatch/Gravity	Solenoids	
Retract Mechanism	Reverse Motor	Drive Backwards	Elastic power	Springs	

A variation in the angle of a 3-foot slide by 1 degree causes a change in the location of the end effector by 0.63 inches:

$$\frac{\pi}{180} radians * 36\ inches = 0.63\ inches\ of\ arc$$

Figure 3: Deflection in linear sliders.



$$0.5\ N \cdot m = 4.426\ lb \cdot in$$

Maximum Slope: $\sin^{-1}\left(\frac{2\ in}{14\ in}\right) = 8.21°$

Maximum Force down the Ramp: $10 \sin(8.21) = 1.428\ lb$

Torque necessary to carry robot up the Ramp: $1.428\ lb \cdot 1.5\ in = 2.142\ lb \cdot in$

Since $2.142 < 4.426$, a 1:1 gear ratio with the motor will be sufficient assuming the center of mass is at the center of the beam, the load is 10 lbs., and the wheel does not slip.

Figure 4: Determining gear ratio for proper egression up the ramp.

Time Necessary to Reach Centerpiece or Return from Centerpiece

Angular Velocity of Wheel: $60\ RPM = 6.28 \frac{rad}{s}$

Velocity at Point P where wheel and ground contact: $\left(6.28 \frac{rad}{s}\right)(1.5\ in) = 9.42 \frac{in}{s}$

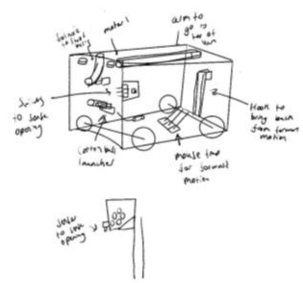
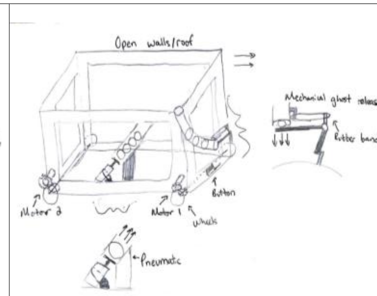
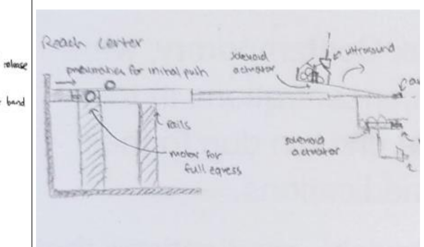
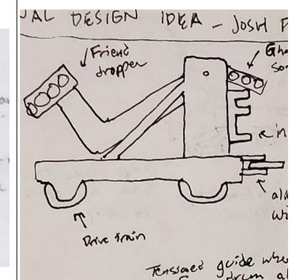
Time to reach centerpiece: $\frac{24\ in}{9.42\ in/s} = 2.55\ s$

Ideally, the robot should reach the centerpiece in 2.55 seconds.

Figure 5: Justification for using motors/wheels to approach centerpiece.

Table 4: Level-3 Evaluation matrix shows alternative designs and scores assigned.

Decision Matrix

Final Competition Design	WEIGHT								
Requirements Criteria/Constr.		**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
General Safety	5	3	15	4	20	3	15	4	20
Portable	4	4	16	4	16	4	16	4	16
Fit within size	10	4	40	4	40	4	40	4	40
Move	10	3	30	4	40	4	40	4	40
Score Max Points	10	3	30	3	30	3	30	3	30
Autonomous	10	4	40	4	40	4	40	4	40
Deposit Ghosts	9	4	36	2	18	4	36	4	36
Deposit Friends	7	4	28	3	21	3	21	4	28
Ghosts in Each	8	3	24	3	24	2	16	3	24
Efficient Functionality	8	3	24	3	24	3	24	4	32
Affordable	10	4	40	4	40	4	40	4	40
Aesthetics	6	4	24	4	24	3	18	3	18
Maintainable	9	3	27	4	36	2	18	3	27
Assembly Time	10	1	10	4	40	4	40	4	40
Reliable	7	3	21	3	21	3	21	4	28
Total		**50**	**405**	**53**	**434**	**50**	**415**	**56**	**459**
	Scoring Key: 0 = unsatisfactory, 1 = just tolerable, 2 = adequate, 3 = good, 4 = very good (ideal)								

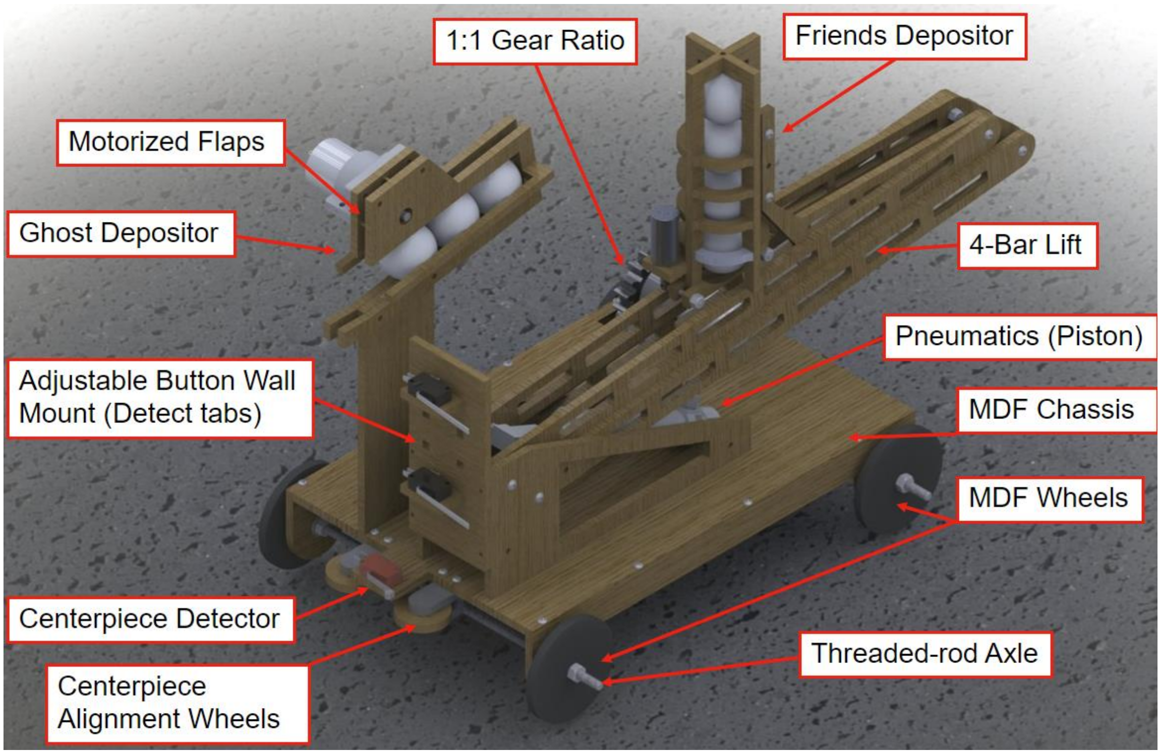


Figure 6: Full render of chosen alternative design.

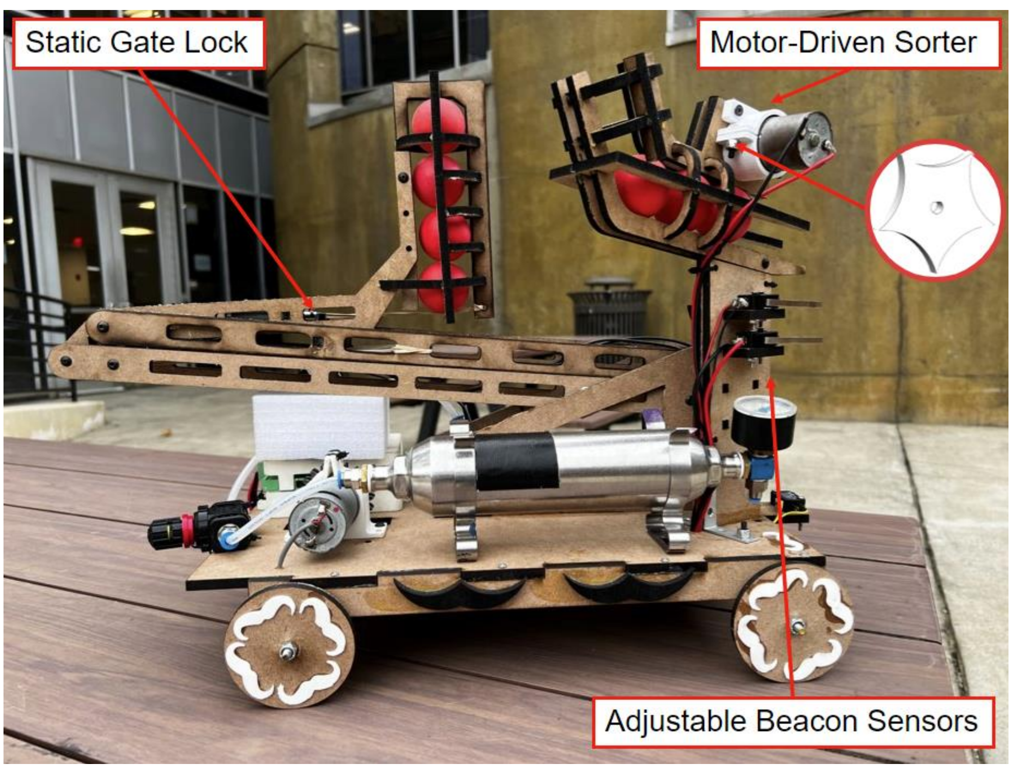


Figure 7: Side view of final robot in the starting configuration.

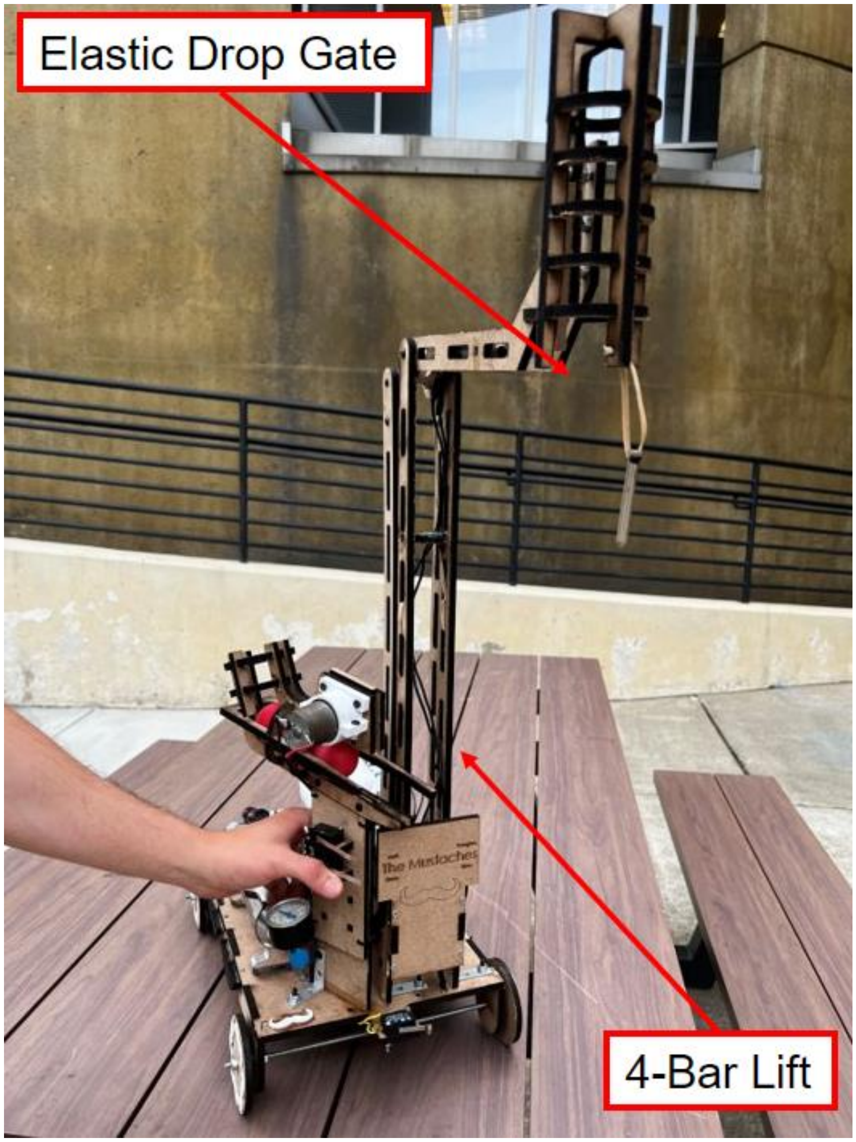


Figure 8: Front view of final robot in the "open" configuration.

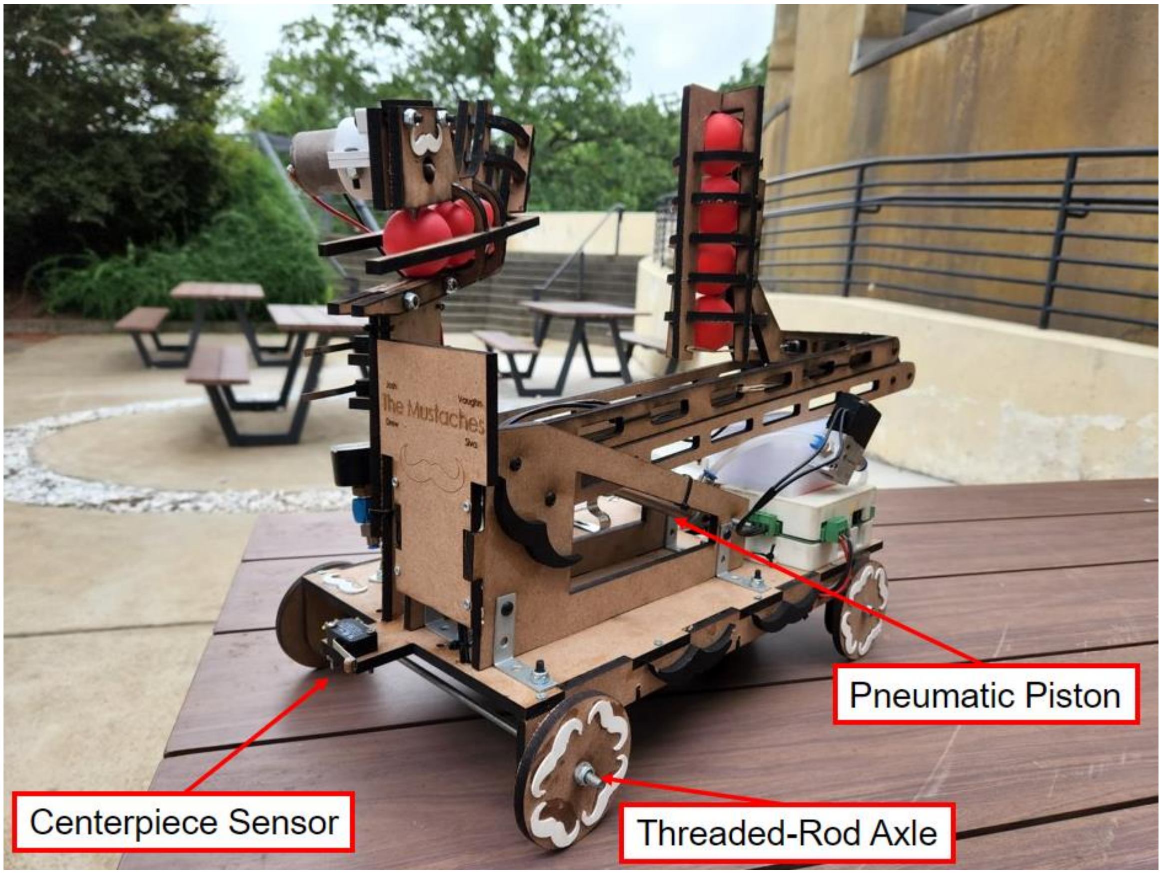


Figure 9: Right view of final robot in the starting configuration.

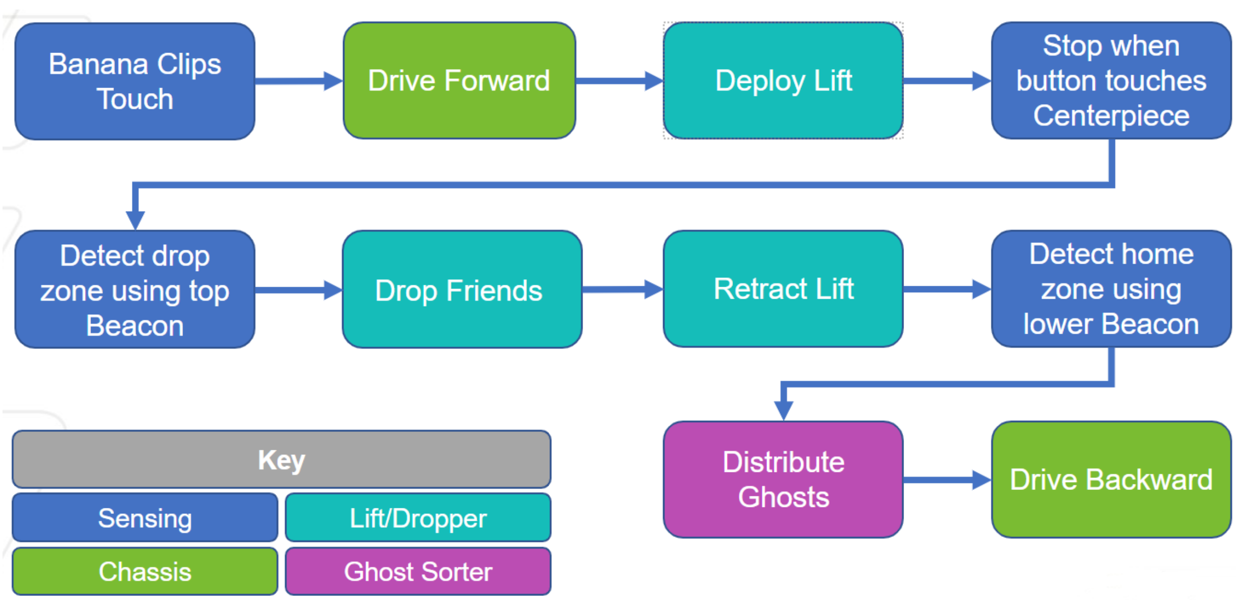


Figure 10: Code Flow indicates sequence of actions.

Table 5: Bill of materials excluding cost and mass of mechatronics components.

Bill of Materials: Project/Product Development									
Project:	***ME 2110 Autonomous System***								
Engineering Team:				*Siva Appana* *Vaughn Claussen* *Drew Malott* *Josh Perlmutter*					
Date:				*7/19/2022*					
				Functional Analysis	**Mfg. + Other Analysis**				
Module/ Part #	**Description/ Name**	**Qty**	**Unit Cost**	**Function**	**Mfg. Process**	**Dimensions**	**Mass (lb)**	**Material**	**Other Physical Properties**
A-1: Chassis									
A-1-1	Chassis Top Plate	1	$1.64	Placement for all subsystems	Laser-cut	Width: 9 in Depth: 16.9 in Thickness: 0.25 in	0.962	MDF	
A-1-2	Chassis Side Plate	2	$0.38	Positions wheel/axle systems	Laser-cut	Width: 14 in Depth: 2.5 in Thickness: 0.25 in	0.221	MDF	
A-2: Driving System									
A-2-1	#10-24 Threaded Rod Axle	2	$0.76	Holds gears and wheels for the drive	Extrusion and Thread-Rolling	Threads: #10-24 Length: 10.5 in	0.057	Stainless Steel	
A-2-2	Wheels	4	$0.30	Allows smooth translational movement with minimal energy input	Laser-cut	Radius: 1.5 in Thickness: 0.25 in	0.045	MDF	
A-2-3	26-tooth Driven Gear	2	$0.22	Transfers motor's energy	Laser-cut	Radius: 1.4 in Thickness: 0.25 in	0.032	MDF	
A-2-4	20-tooth MDF Driving Gear	1	$0.13	Drives driven gear	Laser-Cut	Radius: 1.1 in Thickness: 0.25 in	0.019	MDF	
A-2-5	20-tooth Acrylic Driving Gear	2	$0.13	Prevents motor to gear connection from stripping	Laser-cut	Radius: 1.1 in Thickness: 0.125 in	0.025	Acrylic (Plexiglass)	
A-2-6	#10-24 Nylon Lock Nuts	13	$0.07	Fastens components on threaded-rod axle	Cold-forming	Threads: #10-24	0.0001	Stainless Steel + Nylon	Vibration-resistant nuts
A-2-7	Motor Mount	1	$1.40	Secures motor and prevents its rotation	3D Printing	Radius: 0.73 in Width: 3.79 in Bolt Diam.: 0.2 in	0.062	PLA	
A-2-8	#4 Wood Screws	8	$0.16	Clamps puzzle-fitted chassis plates	Extrusion and Thread-Rolling	Threads: #4 Length: 5/8 in	0.0003	Steel with Zinc finish	
A-2-9	#8-32 Bolts	2	$0.40	Fastens motor mount to chassis	Extrusion and Thread-Rolling	Threads: #8-32 Length: 0.75 in	0.003	Steel	
A-2-10	#8-32 Nylon Lock Nuts	2	$0.06	Fastens motor mount to chassis	Cold-forming	Threads: #8-32	0.0001	Stainless Steel + Nylon	Vibration-resistant nuts
A-2-11	Large Motor	1	NA	Attaches to driving gear and fits inside motor mount	NA	Length: 2.7 in Diameter: 0.73 in	NA	Various	

A-3: Lift									
A-3-1	Lift Support	2	$1.15	Support Lift	Laser-cut	Width: 9.75 in Depth: 5.25 in Thickness: 0.25 in	0.17	MDF	
A-3-2	1.5" Corner Brace	4	$1.03	Support Lift Support to Chassis connection	Punch from sheet metal	Width: 1.5 in Height: 1.5 in Depth: 0.5 in Thickness: 0.125 in	0.033	Stainless Steel	
A-3-3	Parallel Arms	4	$0.66	Transfer power	Laser-cut	Width: 19 in Depth: 1 in Thickness: 0.25 in	0.097	MDF	
A-3-4	Horizontal Arm	2	$0.44	Transfer power, mounts Friends Dropper	Laser-cut	Width: 10.5 in Depth: 5.75 in Thickness: 0.25 in	0.064	MDF	
A-3-5	Pneumatics Assembly	1	NA	Provide power	NA	NA	NA	Various	
A-3-6	Transfer coupling	1	$0.12	Connect cylinder to arms	3D Printing	Width: 0.8 in Depth: 1.5 in Height: 0.5 in	0.009	PLA	
A-3-7	#8-32 Bolts	15	$0.40	Fastens motor mount to chassis	Extrusion and Thread-Rolling	Threads: #8-32 Length: 0.75 in	0.003	Steel	
A-3-8	#8-32 Nylon Lock Nuts	20	$0.06	Fastens motor mount to chassis	Cold-forming	Threads: #8-32	0.0001	Stainless Steel + Nylon	Vibration-resistant nuts
A-3-9	#10-32 Threaded Rod	1	$0.41	Anchors piston to lift support	Extrusion and Thread-Rolling	Threads: #10-32 Length: 4 in	0.098	Steel	
A-3-10	Decorative Front Plate	1	$0.73	Plate with names/team-name engraved	Laser-cut	Width: 5.5 in Depth: 3.75 in Thickness: 0.25 in	0.107	MDF	
A-3-11	Rubber Bands	3	NA	Assists pneumatics with lift	Rubber Extrusion	Size: #64	0.003	Rubber	
A-4: Friends Dropper									
A-4-1	U Mount Front	1	$0.20	Hold Balls and Mount to Lift	Laser-cut	Width: 6.9 in Depth: 2.7 in Thickness: 0.25 in	0.045	MDF	
A-4-2	U Mount Side	1	$0.19	Hold Balls	Laser-cut	Width: 6.9 in Depth: 2.5 in Thickness: 0.25 in	0.039	MDF	
A-4-3	Dropper Ribs Short	12	$0.02	Add support to Dropper	Laser-cut	Width: 1.23 in Depth:1.23 in Thickness: 0.25 in	0.003	MDF	
A-4-4	Dropper Ribs Long	2	$0.02	Add Lower supprt to Dropper	Laser-cut	Width: 0.84 in Depth:2.01 in Thickness: 0.25 in	0.004	MDF	
A-5-5	Small Solenoid	1	NA	Holds Balls in Place	NA	NA	NA	Various	
A-5-6	Rubber Bands	1	NA	Pulls solenoid plunger	Rubber Extrusion	Size: #64	0.003	Rubber	

A-5: Ghost Sorter									
A-5-1	Ghost Tower	1	$0.85	Elevates ramp to necessary height	Laser-cut	Width: 2.5 in Depth: 8.18 in Thickness: 0.25 in	0.125	MDF	
A-5-2	Ghost Ramp	2	$0.21	Gravitational energy for balls to roll	Laser-cut	Width: 9.75 in Depth: 4.53 in Thickness: 0.25 in	0.031	MDF	
A-5-3	Ramp Ceiling	2	$0.29	Prevent ball's vertical movement	Laser-cut	Width: 5.21 in Depth: 2.4 in Thickness: 0.25 in	0.042	MDF	
A-5-4	Side-rails	1	$0.26	Prevent ball's lateral movement	Laser-cut	Width: 2.47 in Depth: 8 in Thickness: 0.25 in	0.039	MDF	
A-5-5	Funnel Rails	2	$0.05	Side rails for the funnel	Laser-cut	Width: 0.45 in Depth: 2.75 in Thickness: 0.25 in	0.007	MDF	
A-5-6	Ribs	16	$0.02	Connect ramp to the side-rails	Laser-cut	Width: 1.23 in Depth: 1.23 in Thickness: 0.25 in	0.003	MDF	
A-5-7	Top Motor Mount	1	$0.30	Mounts motor to ghost sorter assembly	3D Printing	Width: 2.32 in Height: 0.96 in Depth: 1 in	0.013	PLA	
A-5-8	Bottom Motor Mount	1	$0.25	Clamps motor	3D Printing	Width: 2.32 in Height: 0.85 in Depth: 1 in	0.011	PLA	
A-5-9	Ghost Indexer	1	$0.09	5-sided indexer fit for ping-pong balls	Laser-cut	Outer Rad.: 1.15 in Thickness: 0.125 in	0.017	Acrylic	
A-5-10	#8-32 Bolts	4	$0.40	Fastens motor mount to chassis	Extrusion and Thread-Rolling	Threads: #8-32 Length: 0.75 in	0.003	Steel	
A-5-11	#8-32 Nylon Lock Nuts	4	$0.06	Fastens motor mount to chassis	Cold-forming	Threads: #8-32	0.0001	Stainless Steel + Nylon	Vibration-resistant nuts
A-5-12	Button Mount	1	$0.54	Wall with slots for moveable button holder	Laser-cut	Width: 2.5 in Depth: 5.45 in Thickness: 0.25 in	0.080	MDF	
A-5-13	Button Holder	2	$0.06	Holds button	Laser-cut	Width: 1.5 in Depth: 1.08 in Thickness: 0.25 in	0.008	MDF	
A-5-14	Long-arm Button	2	NA	Senses beacons	NA	NA	NA	Various	
A-5-15	Zip Ties	4	$0.02	Fastens Button Mount to Ghost Tower	Molding	NA	0	Nylon	
A-5-16	1.5" Corner Brace	2	$1.03	Support Lift Support to Chassis connection	Punch from sheet metal	Width: 1.5 in Height: 1.5 in Depth: 0.5 in Thickness: 0.125 in	0.033	Stainless Steel	
A-5-17	Small Motor	1	NA	Indexes Ghosts (ping-pong balls)	NA	NA	NA	Various	
TOTAL			**$37.34**				**3.879**		

Table 6: Testing Data

Key		Launch	Deposit Ghosts	Escape	Home zone points	Egress		
Shop	Color	0 For No 1 For Yes	Number Plus 1 if in each 0-4	Friends in Mystery Machine 0-4	Balls in Home Zone	0 For No 1 For Partial 2 For Full	Total	Notes
Classroom								
7/11/2022								
Test 1	Red	1	3	4	0	2	140	Error: Played as Blue(Human Error)
Test 2	Red	1	3	4	0	2	140	Error: Played as Blue(Code Error?)
Test 3	Red	1	3	4	0	2	140	Error: Played as Blue(Def Code Error)
Test 4	Red	1	4	4	0	2	161	Perfect
Test 5	Red	1	4	0	0	2	109	Error: Lift didn't activate (Code error)
Test 6	Yellow	1	2	4	0	2	119	Error: Ghost Deposit Error
Test 7	Yellow	1	4	4	0	2	161	Perfect
Test 8	White	0	0	0	0	0	0	Error: No power(Fixed)
Test 9	White	1	4	0	0	2	109	Only testing Ghost
Test 10	White	1	2	4	0	2	119	Ghost Depositer Slip
7/12/2022								
Classroom								
Test 1	Blue	1	4	4	0	2	161	Perfect
Test 2	Blue	1	4	4	0	2	161	Perfect
Test 3	White	1	0	4	0	2	77	Code Error
Test 4	White	1	0	4	0	1	67	Code Error
Test 5	White	1	4	4	0	2	161	Perfect
Test 6	Red	1	4	4	0	2	161	Perfect
Test 7	Yellow	1	4	4	0	2	161	Perfect
Test 8.1	Blue	1	0	3	1	1	57	Code Change for 8.2
Test 8.2	Blue	1	4	4	0	2	161	Perfect
7/13/2022								
Classroom								
Test 1	Blue	1	3	4	0	2	140	Placed Two in Red
Test 2	Yellow	1	4	4	0	2	161	Ghost Depositer Slip
Studio								
Test 1	Red	1	4	4	0	2	161	Perfect
Test 2	Yellow	1	4	3	0	2	148	Ball Hit by Pin to hard
Test 3	Yellow	1	4	4	0	2	161	Perfect
Test 4	Yellow	1	4	4	0	2	161	Perfect
Test 5	Red	1	4	4	0	2	161	Perfect
Test 6	Blue	1	4	4	0	2	161	Perfect
Test 7	White	1	3	4	0	2	140	Doubled Up
Test 8	White	1	4	4	0	2	161	Perfect
Classroom								
Test 1	Red	1	3	4	0	2	140	Doubled Up
Test 2	Red	1	3	4	0	2	140	Doubled Up
7/14/2022								
Test 1	White	1	4	4	0	2	161	Perfect
Test 2	White	1	4	4	0	2	161	Perfect
Test 3	White	1	4	4	0	2	161	Perfect
Test 4	White	1	2	4	1	2	122	Missed last ghost backed up to soon
Test 5	White	1	4	4	0	2	161	Perfect
Test 6	White	1	4	4	0	2	161	Perfect
Test 7	Blue	1	4	4	0	2	161	Perfect
Test 8	Blue	1	3	4	0	2	140	Perfect run as red(Siva didn't do his job)
Test 9	Blue	1	4	4	0	2	161	Perfect
Test 10	Blue	1	4	4	0	2	161	Perfect
Test 11	Blue	1	2	4	0	2	119	Tooth allignment
Test 12	Blue	1	4	4	0	2	161	Perfect

Table 7: Data Averages

Average Red	Average Blue	Average White	Average Yellow	Average Overal All Testing	Average Overal With Final Code
143.555556	145.3333333	135.4615385	153.1428571	136.5754462	146.2608696

Table 8: Final Competition Data

Final Competion	Team A3-3					
	Launch	Deposit Ghosts	Escape	Home zone points	Egress	
Color	0 For No 1 For Yes	Number Plus 1 if 1 in each 0-4	Friends in Mystery	Balls in Home Zone	0 For No 1 For Partial 2 For Full	Total
White	1	4	4	0	2	161
Black	1	4	4	0	2	161
Blue	1	4	4	0	2	161

References

[1] ME 2110 TA/Instructors, “Final Design Project: Scooby Doo,” Georgia Institute of Technology, Atlanta, Georgia, USA, Engineering. 2022.

[2] ME 2110 TA/Instructors, “Arduino Mechatronics Manual,” Georgia Institute of Technology, Atlanta, Georgia, USA, Electronics. [Accessed July 22, 2022]

Contributions Statement

1. Siva Appana: Contributed toward figure/table generation, bill of materials, and final editing.
2. Vaughn Claussen: Contributed toward writing the performance review and final editing.
3. Drew Malott: Contributed toward writing the alternative design and final editing.
4. Josh Perlmutter: Contributed towards abstract, conceptual design, design overview, and final editing.