University of North Carolina Asheville
Journal of Undergraduate Research
Asheville, North Carolina
May 2015

Application of the Engineering Design Process: A Fully Autonomous Line Following Robotic Platform Tasked With Completing Specified Tasks Using the Games Simon, Etch a Sketch, Rubik's Cube and Playing Cards

Sean Finnigan, Casey Murphey, Stephen Moyer, Max Kern, Paul Guennette, Benjamin Wagner, Benjamin Brewer Bowman, Eli Buckner, Gabriel Early, Guerin Williams, Alex Stevens
Mechatronics Engineering
The University of North Carolina Asheville
One University Heights Asheville, North Carolina 28804 USA

Faculty Advisor: Dr. Rebecca Bruce

Abstract

The 2015 IEEE Southeast Conference Hardware Competition is designed to bring together universities in IEEE's (Institute of Electronic and Electrical Engineers) region 3 in a friendly intercollegiate robotics competition. This year, the competition involves a white line on a black background that leads to four traditional road trip games. The games, and how they are played, include playing Simon for 15 seconds, writing IEEE on an Etch a Sketch, turning the top row of a Rubik's cube 180 degrees and picking up a playing card off the top of the deck and bringing it to the finish line. These tasks are to be completed autonomously by a robot, with no input, during a competition run that has to fit within a 1-ft x 1-ft x 1-ft cube. The judges must be able to see the games being played [1]. Research went into completing and integrating these tasks together onto a single platform, along with the design and organization process the team would use to complete each task.

1. Introduction

The 2015 IEEE Southeast Conference Hardware Competition is designed to bring together universities in IEEE's region 3. This distinguished competition allows students to test their engineering abilities in a competitive environment while working on a team. This year, the competition requires that a robot autonomously play four traditional road-trip games while following a white line that has been painted on a black piece of plywood. The games are to be played under certain conditions for points. To accomplish each task, the team set out with a categorical design approach to gain the maximum allotted points and win the competition. The team was given a set of guidelines including a max time for an entire round. The team also had to work within the boundaries of a budget, dimension of the robot, and power restraints. A traditional engineering design process was followed to assure that not only would the team successfully accomplish the task, but allow the team members to experience how projects of this nature will be organized and implemented in future professional settings.

The first step in the process involved brainstorming how the robot would complete these tasks and how the team would be organized so that everyone involved had an important and engaging task aligned with their personal interests. After several brainstorming meetings, involving the entire team, overall decisions were made as to the current work breakdown structure and some key elements of the robot design. It was decided that each game would have a specific apparatus, designed and managed by a 3-4 person team. Another task was created for the purposes of navigation and chassis design. These teams would then report to a team of project managers and lead engineers who had final say on organizational and technical criteria.

It was decided by the team that the robot would follow the white line to the games by using an infrared light sensor that would report different values based on a difference in shading (in this case, white or black). This would allow the robot to follow the white line to the games. The team also decided that an Arduino Mega microcontroller would be the best choice for the control apparatus of the robot, as the team members have extensive experience with its implementation and coding language, and an abundance of resources for componentry. Finally the group as a whole decided on a “U”shaped chassis design so as to contain the games within the bounds of the chassis, allowing for a simplified method of retrieving the games for play.

Each team, coinciding with each task, was broken up into a task leader, coder, modeler and mechanical expert for building the apparatus and researching components and materials. Because the team wanted this project to be enjoyable and beneficial to their education, each person on the team was tasked with jobs that best fitted their ability as well as interest.

Team would not only design the apparatus that would accomplish their task, but they would also be responsible for staying within an allotted budget, space within the chassis, and time limit to play their assigned game. The overall budget for the robot was set at $2000 by Dr. Rebecca Bruce, the project supervisor, and it was decided by the project management team that each task be given an equal amount of this budget as a spending ceiling. Therefore each task group was allotted a budget of $400 in materials to complete their task.

The competition rules state that the robot must complete the entire course within five minutes to achieve full points. Therefore, it was decided by project management that navigation would be allotted 3 minutes while each game would have 30 seconds in which to accomplish their goal. The power requirements of the robot, based on traditional componentry, were set at a 12 Volt power source requiring an output of at least 5000 mAh. The rules of the competition state that the robot must fit within a 1x1x1 ft cube, therefore each game task was allotted a cube of 6 in. x 6 in. x 10 in. within which their apparatus and all accompanying hardware should fit.

The project management team maintained a detailed Gantt chart [2], detailing the work breakdown structure of the team as a whole, each individual, each subset of disciplines, i.e. coders, modelers, and also providing team approved deadlines. It was then asked of each task leader to maintain a more detailed breakdown of the progress of each group, including their success and issues. The teams were then asked to provide research for their conclusions including testing based off of accepted engineering criteria. The teams were asked to present ideas and models to the team as a whole within a deadline, to allow for the greatest exposure of an idea or concept to critique thus allowing for the best possible outcome.

2. Cards

The objective of this team was to design and implement a mechanism to pick up a single card from a deck and carry the card for the remainder of the game. In addition to reliably picking up the card, this team had to minimize space and power consumed.

Parameters were developed for the complete bot team that also applied to the Cards team. In addition to fitting on the chassis we sought for each task apparatus to occupy the smallest footprint possible. This allowed us to allocate more room on the chassis for batteries and provided more options for optimizing weight distribution. We were not certain of the best arrangement of the devices so we decided that we wanted them to be modular. This enabled us to vary the size of each task device and to alter and replace them without having to alter other apparatus.

The above stipulations served as our starting point. We needed to calculate torque, speed, power, and percent error to find specifications for the motor and system setup. After making a final decision as to what apparatus was to be used to implement this task (Figure 2), the amount of torque and speed required for the design turned out to be relatively minimal. The motor simply needed to apply enough force on a card to slide it off a deck. The reliability of our design mainly depended upon dimensions and lengths to work consistently.

Power was the main requirement for the particular motor we chose. The motor used for testing was tested and consistently picked up a card thirty times in a row. The motor pulls 0.37 amps at 7.2 Volts without load. The load is small enough to be considered negligible with the design equation (1). Given the maximum run time of 30seconds, it was calculated that the total power consumption would not exceed 79.92 Joules equation (2). The team estimated that the actual time to complete the task would only take roughly 2 seconds, therefore the power consumed over this period would be 5.328 Joules.

$$P = IV \quad (1)$$
$$P = (.37Amps)(7.2Volts) = 2.664\,Watts$$
$$W = Pt \quad (2)$$
$$W(30s) = (2.664\,W)(30s) = 79.92\,Joules$$
$$W(2s) = (2.664\,W)(2s) = 5.328\,Joules\ [3]$$

The team proposed five "card pick-up" design concepts likely to meet our requirements and implemented a decision matrix to decide between them (figure 3).

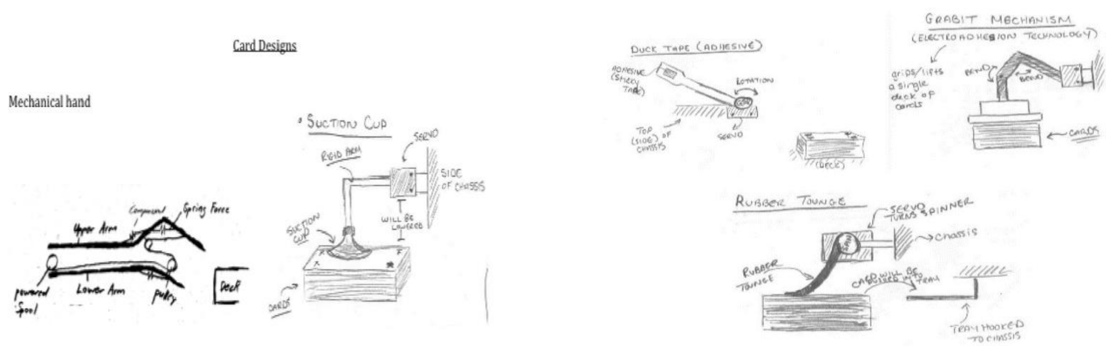


Figure 2. Cards Group Initial Brainstorming Drawings

Design Label	1	2	3	4	5
Name	Adhesive Arm	Suction Cup	"Grabbit" Mechanism	Rubber Tongue	Mechanical Hand
Effectiveness	9	3	8	8	7
Cost (Low)	9	7	1	10	7
Easiness	10	6	9	9	5
Size (Small)	8	7	3	7	6
Hardware Simplicity	9	3	2	8	5
Software Simplicity	9	7	8	10	8
Fabrication Intensity (Low)	9	7	8	8	6
Total	63	40	39	60	44

Figure 3. Cards Group Apparatus Decision Matrix

The entire cost of the test apparatus was mitigated by the fact that all the materials required for initial testing were on hand and made available by the engineering department (figure 4).

Item	Cost	Shipping	Quantity	Total
Vex 3-wire motor	$19.99	$3.99	1	$23.98
Sheet Metal	$1.50	$0	1	$1.50
Scews	$0.99	$0	5	$0.99
Aluminum Rod	$5	$0	1	$5.00
Rubber Tongue	$2	$0.00	1	$2.00
			Net Worth:	$33.47
			Actual Cost:	$0

Figure 4. Cards Group Annotated Budget

After making this decision materials were acquired, dimensions were tested (figure 5), the design was modeled using Solidworks Cad software (figure 6), and code was written to implement the chosen design. A functional proof of concept was completed and presented by the course completion date.

Location of the shaft from front of card (cm)	Height from gnd to shaft (cm)	Length of tongue from center of shaft (cm)	# of times top card fell off 0-10	# of times bottom card fell off 0-10	Total times worked 0-10
center	6.25	6.25	10	2	8
2	6.25	6.25	10	0	10

Figure 5. Card Group Testing Data

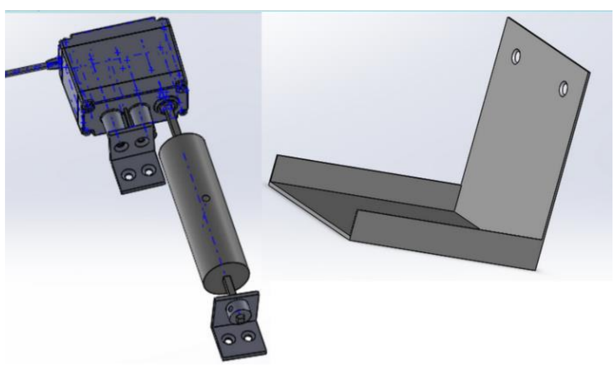


Figure 6. Final Cad Model of Card Pick Up Mechanism

3. Simon Says

The objective for the Simon Says portion of the IEEE competition robot is to play the handheld game “Simon says” for 15 seconds without error. Multiple methods for tackling this problem were investigated and evaluated using the decision matrix method prescribed by team management (figure 7). These solutions were drawn out and presented to the entire robot design team with this decision matrix in an effort to justify what this group thought was the best course of action (figure 8).

Simon Says Button Pushing Mechanism Decision Matrix						SCALE: 1-10
Model:	I	II	III	IV	V	
Easiness	7	8	9	3	2	
Amount Of Hardware Used (Less)	4	6	8	5	2	
Simplicity	9	7	8	4	4	
Hardware Building Easiness	7	8	9	4	4	
Software Building Easiness	8	7	6	2	8	
Reliability	8	6	4	4	2	
Total:	43	42	44	22	22	

Figure 7. Simon Group Apparatus Decision Matrix

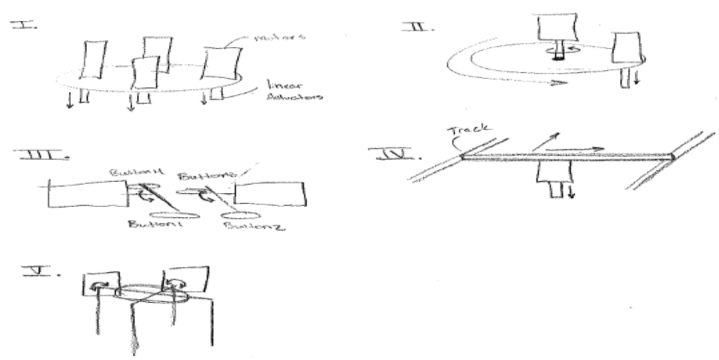


Figure 8. Card Group Design Drawings

Upon approval by the greater team and management this team designed a module for the robot that consisted of a bracket to hold the module, linear actuators to press the buttons, and LUX (luminosity) sensors to detect the Simon Says sequence (figure 9,10). This design can be moved anywhere on the bot, depending on the needs of the others groups and overall space requirements.

Simon Says Motor/Servo/Actuator Decision Matrix					SCALE: 1-10
Model Name:	Commercial Linear Actuator	Chapstick Servo LA	Solenoid	Step Motor	Motor W/Worm Gear
Picture:					
Size (Small)	2	8	6	8	1
Cost (Low)	1	10	8	8	5
Weight	2	9	8	7	3
Resources	4	9	5	4	6
Software Simplicity	4	9	6	7	8
Hardware Integration	2	8	3	7	4
Total:	15	53	36	41	27

Figure 9. Linear Actuator Decision Matrix

Simon Says Sensor Decision Matrix					SCALE: 1-10
Sensor Name:	QTI	RGB Sensor	Lux Sensor	Parallax ColorPal	Vishay Semiconductor
Picture:					
Effectiveness	2	1	9	1	3
Cost (Low)	6	6	8	3	10
Easiness	7	2	9	8	8
Size (Small)	8	7	7	5	10
Hardware Simplicity	8	2	8	6	5
Software Simplicity	7	2	8	4	8
Resources	8	6	7	9	4
Total:	46	26	56	36	48

Figure 10. Simon Button Detection Sensor Decision Matrix

The size restraint that each group received was 6 in; X 6 in.; however, our model only requires 3.89 in. by 3.89 in. This gave extra room for any other group that could possibly need more room than the set restraints. The buttons of the Simon Says can be read by the sensors at variable distances so this gave us some room for error vertically and horizontally; however, the farther the sensors are away from the buttons, the less accurate they become.

The power required to push a button on the Simon Says game is small. The linear actuators we decided to use are homemade, using every day common objects [4]. We looked up the documentations of these actuators and found that given a power of 1.2 Watts (200mA * 6.0V) the actuator can provide 10 N of force (figure 11). We found that 10 N was plenty of force to push the buttons on the Simon game.

POWER REQUIREMENTS AND POWER SPECS							
Servo	Current(A)	Voltage(V)	Power(W)	Torque(kg*cm)	Force(N)	Time(s)	Work(J)
SPRINGRC SM23/33	0.2	4.8	0.96	2.8	~10	15	14.4
	0.2	6	1.2	3	~10	15	18

Figure 11. Actuator Power Analysis

When the items were evaluated for this design it was found that the required cost was $127 which exceeded the requested $100; however, since many teams found that they would not need the full $100 this was acceptable (figure 12). Once the mechanism had been designed a Solidworks model was created and code written to begin testing the mechanism that would later be placed on the competition robot (figure 13).

BUDGET			
Item	Price	Quantity	Subtotal
Servo	$11.95	4	47.8
Chapstick Tubes	$1.37	4	5.48
Metal Tube	$6.67	1	6.67
Lux Sensor	$3.95	4	15.8
Proximity Sensor	$5.95	8	47.6
Magnet	$0.95	4	3.8
		Total	127.15

Figure 12. Simon Group Total Budget

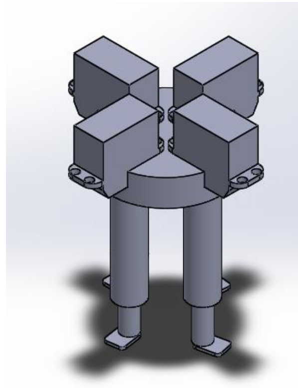


Figure 13. Solidworks model of the Simon Group Mechanism

4. Etch A' Sketch

This team was responsible for designing and implementing an apparatus to write 'IEEE' on an Etch A Sketch. The apparatus needed to function so as to enhance and not interfere with the performance of the total bot. This required that the device fit on the line following chassis, drain as little power as possible, and perform the Etch A' Sketch task.

In addition to the constraints imposed by the IEEE rules [1], the design parameters for the complete bot team also applied to the Etch A' Sketch team. It was decided that each task was required to take less than thirty seconds to complete. To be competitive, it needed to be fast. In addition to fitting on the chassis each task apparatus had to conform to the smallest footprint possible. This allowed for the allocation for more room on the chassis for batteries and provided more options for optimizing weight distribution. The final orientation of the devices was undecided so the tasks were designed to be modular. This also allowed a variety of sizes for each apparatus and to alter and replace them without affecting other task teams. With a total budget of $500, each task had a budget of $100. We successfully spent less than this amount (figure 14).

Etch A Sketch Parts

	Stepper Motor	Motor Controller	Motor w Acme Screw	Linear Bearing	Bearing Rod
Cost	15.95	5.95	32.95	43.95	12.98
Quantity	2	3	1	2	4
TOTAL:	**$31.90**	**$17.85**	**$32.95**	**$87.90**	**$51.92**
Final Total:					**$222.52**

Figure 14. Etch A' Sketch Budget

The above stipulations served as a starting point. The initial questions that needed to be answered were, what torque was needed, how accurately the game could be located, and how much power would be required to complete the task. A method had to be devised to test the amount of torque necessary to turn the knobs on the Etch A' Sketch. Weights were affixed by a string to the knobs and it was found that .06 Nm was adequate to turn each knob thus a motor needed to be selected capable of delivering 6.5 N-cm of torque, using a factor of safety of 100, for safety. The second question was not answered by the work thus far. Options were chosen that required as little accuracy as possible and attempted to reinforce this laxity with physical guides for positioning the Etch A' Sketch. The required power was largely a function of which motors were chosen. In light of this, the smallest motors were chosen that were certain to meet the torque requirements. The chosen motors pull .5 amps at 7 volts when not under load and the motor drivers can output up to 2 amps. The chassis team was informed of this apparatuses total power requirement and testing was completed with bench top power sources (figure 15).

	Current (A)	Voltage (V)	Power (W)	Torque (N*cm)	Time (s)	Work (J)
Needed	--------------	--------------	--------------	6.0	30	--------------
Pololu1207	.5	7	3.5	6.5	30	105

Figure 15 Etch A' Sketch Testing Data

The team proposed five Etch A' Sketch design concepts likely to meet our requirements and implemented a decision matrix to decide between them (figure 16, 17). After making an educated and fully vetted decision, modeling the design and writing code to implement the chosen design began. A functional proof of concept was completed by the course completion date (figure 18).

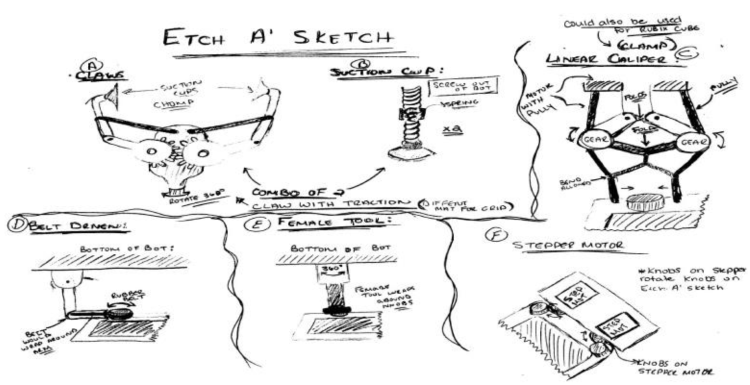


Figure 16. Etch A' Sketch Brainstorming Pictures

	A Claws	B Suction Cup	C Caliper	D Belt Drive	E Female Tool	F Capstans
Footprint	6	5	6	4	4	4
Power Req	7	6	8	5	5	5
Game Holding	6	5	5	6	5	5
Weight Disttibution	7	6	7	3	3	3
Knob Turning	8	1	4	3	6	2
Knob Holding	7	3	3	5	7	0
Part Availability	3	2	4	3	4	2
Cost	7	3	5	3	5	3
Time	6	5	7	5	4	4
Coding Complexity	7	4	4	4	3	3
Required Accuracy	8	8	9	5	2	5
Sensor Feedback	1	1	1	0	0	0
Analyzability	6	3	7	5	5	3
Fabrication	7	6	6	4	3	3
Total	86	58	76	55	56	42

A-F coorespond to letters assigned on brainstorming drawing
0 =Best / 10=worst

Figure 17. Etch A' Sketch Apparatus Decision Matrix

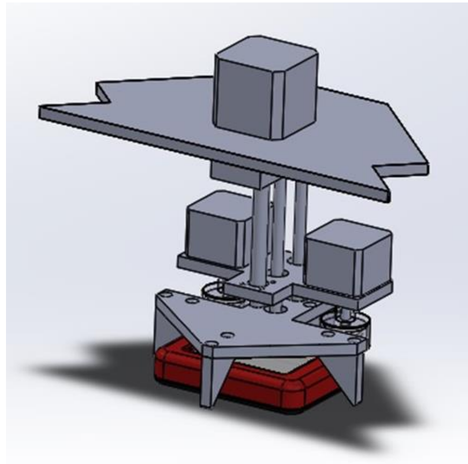


Figure 18. Etch A' Sketch Final Design Model

5. Rubik's Cube

The Rubik's Cube task required rotating one row of the cube 180 degrees. The mechanism to complete this task needed to be designed according to several criteria including budget, power requirements, complexity of design and implementation, weight, speed, and accuracy.

The first step to every design process is assessing team members' strengths and weaknesses, distributing tasks, and scheduling and planning.

The brainstorming process produced many ideas and sketches (figure 19). These ideas were tested against a decision matrix that made it possible to quantify the relative effectiveness and feasibility of each design proposal. Each proposal was rated on a scale of 1-10 according to each of the aforementioned criteria (figure 20). This made it possible to come to a distinct decision on what design proposal to execute.

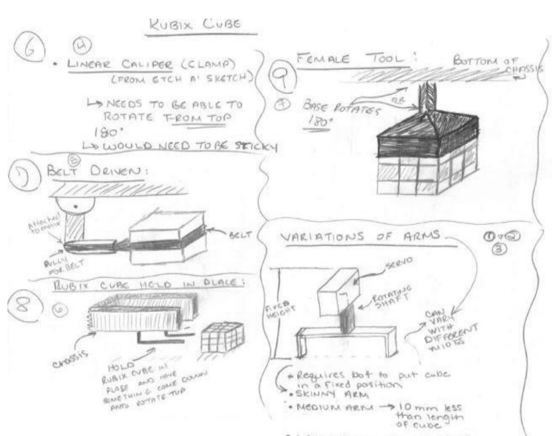


Figure 19. Rubik's Cube Apparatus Brainstorming Pictures

	1	2	3	4	5	6	7	8	9
	Skinny-Arm 1 servo	Medium-Arm 1 Servo	Big-Arm 1 Servo	Linear Acuator with Servo	Worm Gear	Linear Caliper	Belt Driven	Rubix Cube Held in Place	Female Tool
Effectiveness	6	9	7	6	4	6	3	5	6
Cost	9	9	9	5	8	7	2	8	7
Easiness	9	9	9	3	6	7	2	4	4
Size	8	8	7	7	7	6	5	2	5
Hardware Simplicity	9	9	9	3	6	7	2	4	4
Software Simplicity	10	10	10	4	9	5	3	5	8
Resources	8	8	8	5	6	7	4	5	6
Total	59	62	59	33	46	45	21	33	40

Figure 20. Rubik's Cube Apparatus Decision Matrix

This led to some experimental testing to determine several parameters needed for the parts sourcing/building process. A fixture was built to measure the amount of torque that was needed to turn one row of a Rubik's cube. This value was found to be (2.1x10^-6) N-m; the value was then multiplied by 10 to account for binding in the cube. This led to the decision to use a 3-wire Vex motor module used in conjunction with a 7:1 ratio under drive gear system using vex gears. There was then testing to determine how much wider the rotating tool could be to grasp the Rubik's cube. This was done to account for alignment error. The value was found to be 10mm. This data allowed us to design and build our proof of concept model with a tool interface of 65mm as opposed to the 55mm width of the Rubik's cube.

It is designed to complete the task in 15 seconds measured from the time the interface contacts the cube to the completion of the 180 degree rotation. This model is controlled by an Arduino Uno and requires a calculated maximum of 60 mA-h (2.664 watts/7.4V*0.37A (free speed)) (figure 21). The footprint of the model is much smaller than the 6"x6" allotted space and is also modular for easy interface with the final chassis. All of the components for the model were on hand except for the ¼" aluminum plate (onlinemetals.com: Aluminum 6061-T651 12"x12" plate. Price: $30.88) needed to fabricate the final holding fixture (figure 22, 23).

Component		Current(A)	Voltage(V)	Power(W)	Torque(Free)	Torque(Bind)	Time(s)	Work(J)
Vex motor module		0.37	7.4	2.74	2.1g*mm	36g*mm	15	41.1

Figure 21. Rubik's Cube Group Calculated Power Requirements

Rubik's Cube Budget Components		Quantity	Shipping	Price	Total	Source		
6061-T651 Aluminum Plate								
12"x12"x0.25"		1	$9.35	$30.88	$40.23	www.onlinemetals.com		

Figure 22. Rubik's Cube Group Budget Estimate

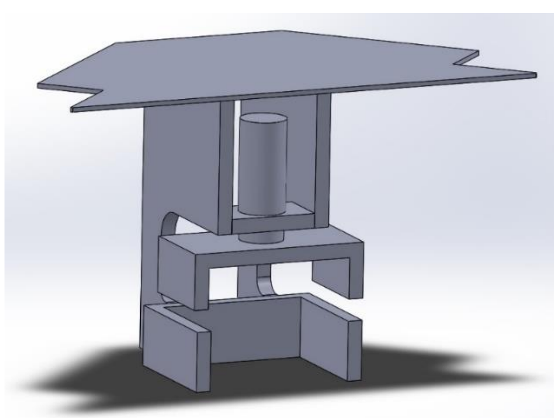


Figure 23. Rubik's Cube Solidworks Model

6. Navigation and Drive System

The goal of the Navigation t [5]eam is to create an algorithm that controls the line following, time keeping, and structure of game play; as well as design and model the chassis and drive system. These are both critical to the success of the robot as the games cannot be played if the Bot cannot not successfully reach them. These must also be accomplished under budgetary, size and power constrictions.

Many factors must be considered to accomplish both these tasks. A line following code must be written with the goal of being both efficient in size and highly accurate. The rules of the competition also include the possibility of 90^0 and curved turns to navigate toward 3 way intersections that lead to a 1X1 ft box containing the games, this must also be included in the overall line following code. The chassis must be designed to fit in a 1x1x1 ft square, including all drive components. These tasks were approached through the prescribed design method and achieved both navigation team and robot team approval.

In order for the line following to work, the code must keep track of the Bot's current position on the line, correcting when necessary (as to follow any given line), all while searching for 90 degree turns and intersection with task lines). Once a task line is found, the Bot must follow it to the corresponding task box, U-turn and enter to play, U-turn and exit back to the intersection to continue game play.

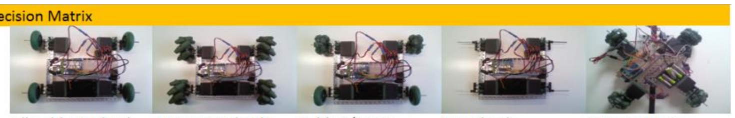
Actual implementation includes PID control to follow the line (self-tuning after the sensor calibration stage), and interrupts to determine elbows, intersections, and task boxes [6].

In order to prevent a task from being performed too long, global time keeping using Arduino's embedded millis() timer is used. This allows the Bot to break free from any task game play, when the set time is exceeded, in order to continue to the next task.

For clocking the gameplay, three methods were considered. The methods consisted of using an RTC Module, an external library called Timer3, and using the millis function to keep track of the time since activation [7]. It was decided not to use RTC early on and primarily tested the Timer3 and millis() methods, as these would allow time to be recorded without having to use the money, space, or power required from an RTC. The Timer3 library would perform a specified function after a certain period without a need for polling, while just using millis() over and over again would be a less efficient. However, because the Timer3 library was limited to only calling a function after the specified period ends and not actually being able to stop the function it stared in, it still returned to the task it was supposed to exit once the function was called. Ultimately it was decided to use millis(), as it returned a simple value that could be used in about any way we need to, making it more versatile.

A U shaped chassis design was chosen in the initial team brainstorming sessions therefore it was the navigation team's goal to integrate this with the drive and individual task components and model these components in Solidworks. There were many options that were tested for the drive system. The team built several test chassis to try out different wheels and movement patterns that were opened by a few of these wheels (figure 24).

Drive System Decision Matrix



Criteria	All Rubber Wheels	Mcanum Wheels	Rubber/Omni	No Wheels	OMNI X Wing
Building	6	6	6	10	4
Modeling	7	4	5	10	4
Codeing	5	4	6	0	5
Speed	7	6	7	0	7
Accuracy	3	5	6	0	10
90 Turns	4	6	7	0	10
Curve Turns	5	7	6	0	10
Power required	7	6	7	10	6
Cost	7	5	6	10	5
Total:	**51**	**49**	**56**	**40**	**61**

Figure 24. Prototype Chassis and Wheel Orientations for Drive and Navigation

Omni wheels were patented in 1919 [8]. For the purposes of this project, they are 2.75 in plastic bodies with rubber wheels along the outside allowing for forward and sideways travel. They also allow for Holonomic movement of the robot, which allows this chassis to travel at any angle from a single orientation, as well as fully controlled turning. Another wheel that was tested that could be considered Holonomic is the Mcanum wheel setup a set of 4x2 in wheels This wheel has a similar setup as the Omni but the rubber rollers along the outside are at a 45^0.angle. The Mcanum wheel setup allows the wheels to allow forward motion while all wheels are moving forward, and sideways movement when the left and right are run opposite in direction relative to each other. The Omni wheel setup has the wheels oriented 45^0 away from forward travel, but allows the chassis to spin in one spot and make unencumbered 45^0 turns. The Omni wheels were tested to run parallel to forward travel but soon realized that with the slightest push it would roll uncontrollably sideways.

A combination of normal 3in rubber wheels was tested as well as a pair of these wheels with the Omni wheels. These were tested with the Omni wheels in the front with the thought that these would allow the front end of the robot to make a 90^0 turn with less friction in the front due to the rubber rollers, while running the rear wheels opposed to each other. Also, the Omni wheels were placed diagonally on the chassis with respect to forward motion in the hope that this might reduce 90^0 turn friction as well.

After testing all these platforms it was decided that the Omni wheel setup would work the best for this application. Its combination of the ability to move in any desired direction from any orientation, and that line following in forward motion could be simplified purely by changing motor speeds instead of having to over correct, were the deciding factor. Choosing this type of wheel and drive orientation necessitated a change in the original chassis design from the original U shaped design to a belt driven overhead plat design. This would allow the games and motors to reside independently of each other, alleviating any worry of running out of room (figure 25).

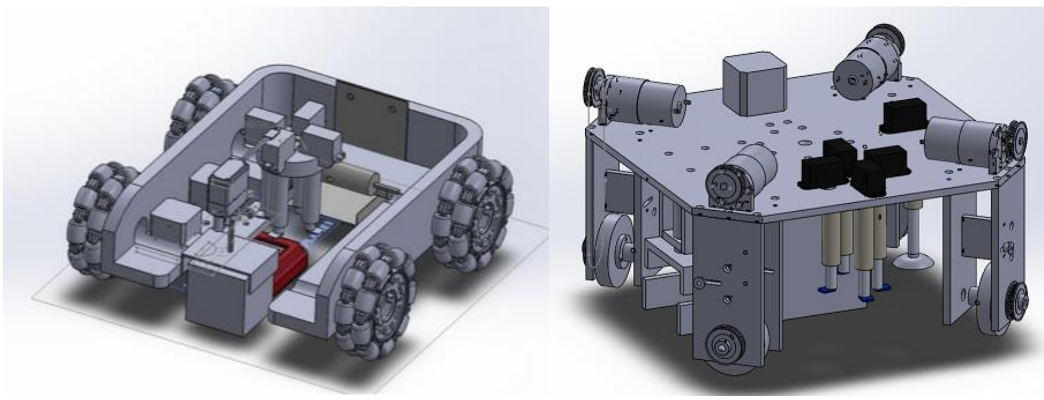
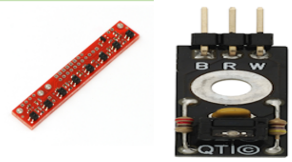


Figure 25. U Shaped Chassis vs. Overhead Plate Chassis

To get to the games, the robot must follow the white line to gain the maximum allowable points. There are several sensors available that would allow for the platform to detect the change from the white line and the larger black surface. The Pololu QTR sensor emits an infrared light and allows a signal to be transmitted based on the contrast of the light received by the sensor. This signal can then be interpreted by the microcontroller and used to control the path of the robot on the course. This is similar to other types of sensor but its cost and performance far outweighed the other options (figure 26). The sensors then had to be oriented in such a way as to optimize the information being sent to the microcontroller. The team decided that all commercially available platforms would not be sufficient to achieve the accuracy that was wanted. Therefore, the team decided to design a custom line following sensor array on a printed circuit board (figure 27). This sensor had independent micro controllers that would process the line following information into packets that would then be sent to the main microcontroller for control interpretation using the spi protocol.

Line Following Hardware Decision Matrix SCALE 1-10



	Pololu QTR-8RC	Paralax QTI Sensor
Effectiveness	10	6
Cost (Low)	10	5
Ease of Apllication	8	6
Size (Small)	7	8
Hardware Simplicity	9	9
Coding Simplicity	5	4
Resources	8	9
TOTAL	57	47

Figure 26. Line Following Sensor Decision Matrix

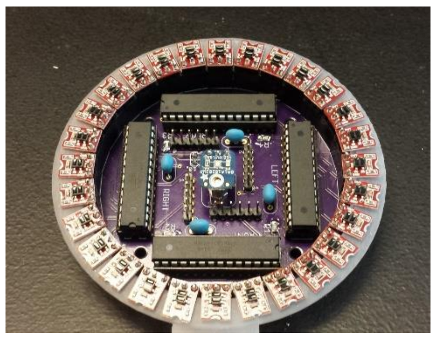


Figure 27. Custom Line Following Sensor

Drive motors are essential to getting the robot to the games. Details such as size, cost, voltage requirement, torque and speed had to be taken into consideration in the pursuit of the right dynamic output device. The team decided on a 12 volt, high torque drive system which would allow for all the power needed to move to a robot made entirely of aluminum. It was also decided that the motors would need to have encoders. Encoders create a Gray code digital signal that gives a measurement of where the axle of the motor is relative to a set point. This allowed the team to calculate, using the microcontroller, to have an exact idea how far the robot would move on the course and in the task boxes and use that information in the control algorithm for optimum navigational accuracy. The team scoured through motor spec sheets to find motors that met these specifications, then compiled several choices into a decision matrix to be vetted by the group as a whole (figure 28).

Motor Decision Matrix

Model	131:1 Gear Motor	131:1 Gear Motor	30:1 Gear Motor	24 V Brushless	Vex 2 wire
Cost	5	7	7	4	10
Speed Control	9	9	4	6	2
Reliabillity	9	7	8	7	1
Size	7	7	7	5	8
Weight	7	7	7	5	8
Accuracy	9	5	5	6	3
Power Consumption	7	8	6	3	8
Rated Torque	9	9	5	9	4
TOTAL:	62	59	49	45	44
Actual Cost (1)	$40.00	$25.00	$22.00	$56.00	$0.00
Actual Cost (5)	$200.00	$125.00	$110.00	$280.00	$0.00
Encoded	Yes	No	Yes	Yes	No
Vendor	robotshop.com	robotshop.com	robotshop.com	robotshop.com	robotshop.com

Figure 28. Drive System Decision Matrix

Once the motors had been chosen, the next step was to estimate how much power the motors would need in real time and over the course of several runs. This involved using the voltage and amperage provided in the spec sheet to calculate the steady state power requirement and then the work required to maintain this power output over an estimated run on the course also calculate the amount of overall energy that would be taken from a battery in Ampere hours (3) (4) (5).

$$P = (4000\ mA)(12V) = 48\ Watts \tag{3}$$
$$W = (48\ W)(180\ \text{sec}) = 8640\ Joules \tag{4}$$
$$Ah = (4000\ mA)\left(\frac{180\ s}{3600\ s}\right) = 200\ mAh \tag{5}$$

The team also had to calculate the power used by the sensors (6) (7) (8).

$$P = (160\ mA)(12V) = 1.92\ W \tag{6}$$
$$W = (1.92\ W)(180\ s) = 345.6\ J \tag{7}$$
$$Ah = (160\ mA)\left(\frac{180}{3600}\right) = 8\ mAh \tag{8}$$

Now that the navigation components had been chosen it was time to add up the total cost for budget purposes (figure 29).

Navigation Budget

Item	Price	Shipping	Quantity	Total	Source
QTR Sensor	$9.95	3.95	4	$43.75	www.pololu.com/product/961
Omni Wheels	$19.99	6	4	$85.96	www.robotmesh.com
QTI Sensor	$9.99	6	1	$15.99	www.robotmesh.com
Arduino Mega	$14.33	0	2	$28.66	www.gearbest.com
Motors	$40.00	15	5	$215.00	
			Net Total:	$389.36	

Figure 29. Navigation Budget

7. Power

Once each individual task group has created a power profile for their device, the Power group could begin to select the components necessary to power the robot through testing and competition runs. The power team took each group power requirements and created a power profile that included an estimate of each group's effect on a battery then adding these up to get an estimate of the requirements for a power storage system. Each group was asked to create a "maximum" power profile, therefore the power team would be able to select a battery that would be more than sufficient for the task. Each team was also asked to include the voltages needed as well as the number of powers, grounds and signal lines they would need to accomplish their task. This information was then put into a total power profile to aid in the choice of batteries and also check the number of required lines going to the microcontroller (figure 30).

Task	Etch-A-Sketch	Card Pickup	Simon Says	Rubik's Cube	Line Following	Arduino Mega	Total
Completion time (seconds)	15 - 30	10	15	10	180 (3 min)	300 (5 min)	300 (5 min)
Current (mA)	7400 (max)	250	1000	?1000?	motors: 4000 sensor:160 Total: 4160	(max): 200	max possible draw: (8160)
mAh	30.8	0.7	4.2	2.8	208	16.7	? 275 ?
Voltage (Volts)	?3.6?	5 and 6	5 and 6	? 7.2 ?	5 and 12	input: 7 - 12 output: 5, 3.3	3.6: 1 5: 3 6: 4 7.2: 1 12: 4
Pins	9 digital	2 digital 1 PWM	10 digital 5 PWM 4 analog	5	12 digital 4 PWM 1 SDA 1 SCL	Provided: 39 digital 16 analog 15 PWM 1 SDA 1 SCL	Used: 33 digital 4 analog 10 PWM 1 SDA 1 SCL
# of wires	11	6	22	7	6 x4 (Motors) 5 (sensors)		9 wire buses

Figure 30. Total Power Profile

The power team then chose batteries that would supply above all the requirements deduced from the power profile. The team chose rechargeable, 14.4 volt, 5000 mAh batteries. This would allow the robot the necessary voltage required as well as enough energy in the battery to last for multiple runs during testing. In order to get the required voltages to the different subsystems, the power design group chose linear voltage regulators that would display the power into the regulator, the power output of the regulator, the real time amperage used and the real time power output. This allowed the team to have a better idea of how the robot was performing compared to the estimated power usage. To simplify the power distribution, the team chose to use Molex^{TM} connectors. Molex^{TM} connectors affix the input and output wires of each subsystem to a plastic housing that clips into an adjacent housing on the power distribution system. The team chose to create a custom printed circuit board that would fit into the Arduino, thus eliminating the need to track each individual wire. These systems were then put into a budget document to check against the total budget (figure31).

	Quantity	Price	Shipping	Total
Tenergy Rechargeable Batteries	2	59.99	14.99	134.97
Battery Charger	1	18.99	Free	18.99
Linear Voltage regulators	4	27.80	xx	27.80
Molex Connectors	36	0.50	xx	18.00
Molex Leads	200	0.04	xx	8.00
Miscellaneous	--	--	xx	42.24
Shipping	--	--	20.00	20.00
				270.00

Figure 31. Power Team Budget

8. Construction

Once all subsystems had been planned and documented, the construction of the robot could take place. The creation of Solidworks models for all the individual tasks allowed for the creation of blue prints that could be used in machining the parts for the robot. Raw materials needed to be purchased for this process, therefore a materials budget had to be created (figure 32).

	Belt Drive Parts		
			
	Flanged Bearings	125 Tooth x 4mm Timing Belt	30 Tooth Cog
Cost	$59.77	$3.81	$7.62
Quantity	1	6	10
Total:	$59.77	$22.86	$76.20
Final Total:			$158.83

Building Materials			
Item Description	**Proposed Vendor**	**Quantity**	**Cost**
3 " x .25" x 72" aluminum plate	Misc.	1	$32.87
12" x 12" x .25" aluminum plate	Misc.	1	$28.03
100 PACK 3mm x .5 x 12mm flat bolts	Misc.	1	$19.26
Motor Mount 1995	pololu.com	5	$7.95
.25" x 12" x 12" UHMWPE sheet (black)	Misc.	1	$14.57
.25" x 6" x 6" aluminum plate	Misc.	1	$19.53
.48" x 3" spring (06812077)	Misc.	2	$4.15
.48" x 3" spring (06811996)	Misc.	2	$4.15
.48" x 3" spring (06812150)	Misc.	2	$4.30
	Total:		**$179.21**

Figure 32. Chassis Materials List

9. Conclusion

The engineering design process was essential in accomplishing our goal of creating proof of concepts for all the tasks required by our robot. This goal was also reached with all teams meeting all deadlines, size requirements and overall budget. A commitment to proper scheduling and team communication aided in reaching this goal. The extensive brainstorming and testing process allowed the team to explore many options to accomplish the tasks and revealed solutions that all team members were happy with. The creation of a full design document and presentation gave the team a chance to present these findings in a way that allies with what will be required in a professional setting.

It was decided in the initial team brainstorming sessions that the requirements of each group would be decided by the project management team. These included size, time and budget requirements. All groups came in under the allotted size requirement, as well as meeting all prescribed deadlines. Due to the complex nature of these tasks, many sensors and actuators are required. After a review of the cost of each of the other tasks, it was found that there would be more than enough capital to offset the cost of all tasks. Therefore, all teams are currently within the design parameters prescribed (figure 33).

	Total Budget
Group	Cost
Cards	0
Etch A Sketch	222.52
Rubik"s Cube	40.23
Simon	127.15
Navigation and Drive	389.36
Chassis	338.04
Power	270
Circuit Boards	100
TOTAL	1487.3

Figure 33. Total Robot Budget

The team used different scheduling and communication techniques to ensure the completion of the project and keep the team well informed. It was decided in the initial brainstorming session that Gantt charts would be used for both the team as a whole and for each task group. These Gantt charts were kept up to date weekly and uploaded to a team Google Drive account. The Drive account was used for all information regarding the project and was shared with all team members. This resource allowed all team members access to documentation, guidelines, and models.

The brainstorming and testing process was essential to creating successful proof of concepts. Formal brainstorming sessions required each group to present to the team at least 3 ideas, drawn and rated on effectiveness with decision matrices. Testing was performed using the engineering theory team members have developed and applying it to real world situations. Techniques such as testing the torque required to turn an Etch a Sketch knob or

Rubik’s Cube or reading serial information to improve the light sensing abilities playing Simon, required use of the knowledge all team members have gained in their studies. This testing was essential in purchasing the correct materials to accomplish the task.

10. References

[1] IEEE, "Overview of rules for 2015 IEEE Southeast Coference Hardware Competition," Ft. Lauderdale Fl, 2014.

[2] ""What is a Gannt Chart"," 2012. [Online]. Available: http://www.gantt.com/.

[3] W. H. Hayt and J. E. Kemmerly, "Power," in *Fundamentals of electric circuits 5th edition*, New York, McGraw Hill, 2013, p. 150.

[4] M. Peick, "Makezine," [Online]. [Accessed August 2015].

[5] "What is PID Control?," [Online]. Available: http://www.facstaff.bucknell.edu/mastascu/econtrolhtml/PID/PID3.html. [Accessed 21 April 2015].

[6] [Online]. [Accessed December 2014].

[7] Arduino, "Millis()," [Online]. Available: http://www.arduino.cc/en/reference/millis. [Accessed 15 April 2015].

[8] J. Grabowiecki, "wikipedia". USA Patent 1303535, 1919.