Product Design Report

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Executive Summary

Within this report, the generic design and iteration process as applied to the goal of constructing a mechatronics system with the ability to collect a tesseract cube power source from a power plant wall, and placing it under a power pyramid with no human interaction is detailed. Through the implementation of innovative techniques, a problem definition, objectives and constraints were developed and highlighted. At this point, creativity and brainstorming was done to come up with multiple solutions to solve the problem with the maximum effectiveness and by making use of GO NO-GO charts and decision matrices, the most feasible of the design ideas was chosen which featured a battle tank drive system with a rotating magnetic arm and a forklift mechanism. As a whole, the team developed multiple iteration ideas and implemented them into the design to get the best and most consistent results. Various tests were conducted for the sensors using Arduino's serial monitor to figure out which placement and coverings would be best suited for the final design. A detailed description of the showcase performance and its analysis is also provided within this report. By working on this project, the team developed a better understanding of the process of iteration and its importance to every engineering project as a whole. In the end, despite having troubles finishing the assigned task in the three trials provided, the design came very close to a perfect run on the fourth bonus round. The design performed effectively as a whole and also had its own essence of being aesthetically appealing.

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Introduction

The idea of design and iteration is implemented into all projects in the engineering profession. Through this process, engineers are able to take their ideas and construct working models and novel solutions through step by step improvements and adjustments to obtain the best possible working design. The team was presented with a problem and tasked with designing and building a mechatronic system that would aid in solving the issue at hand with minimal human contact.

The problem is presented to the team by Tesseract Power Co. which has developed a potent new power source that comes in the form of a cube-like tesseract. These power packs are located at the edge of the power plant and must be placed within a Power Pyramid that converts the energy of the tesseract into electricity. Due to the dangers associated with handling the power source and pyramid, it is not safe for humans to handle the tesseracts directly and thus must make use of the aforementioned mechatronic device to collect the tesseract and place it into the appropriate position under the Power Pyramid.

The dimensions and the approximate shape of the power plant was provided to the team, from here on out the enclosed power plant area will be referred to as the 'arena'. The arena floor is approximately square with the length of each side ranging anywhere between 6-10 feet. The arena walls are 3.5 inches in height and are sturdy enough to handle small scale collisions. There are also power conduits lying around the arena floor acting as speed bumps that need to be maneuvered over, the placement of these conduits is random throughout the arena and an approximation is given by *Figure 1.*

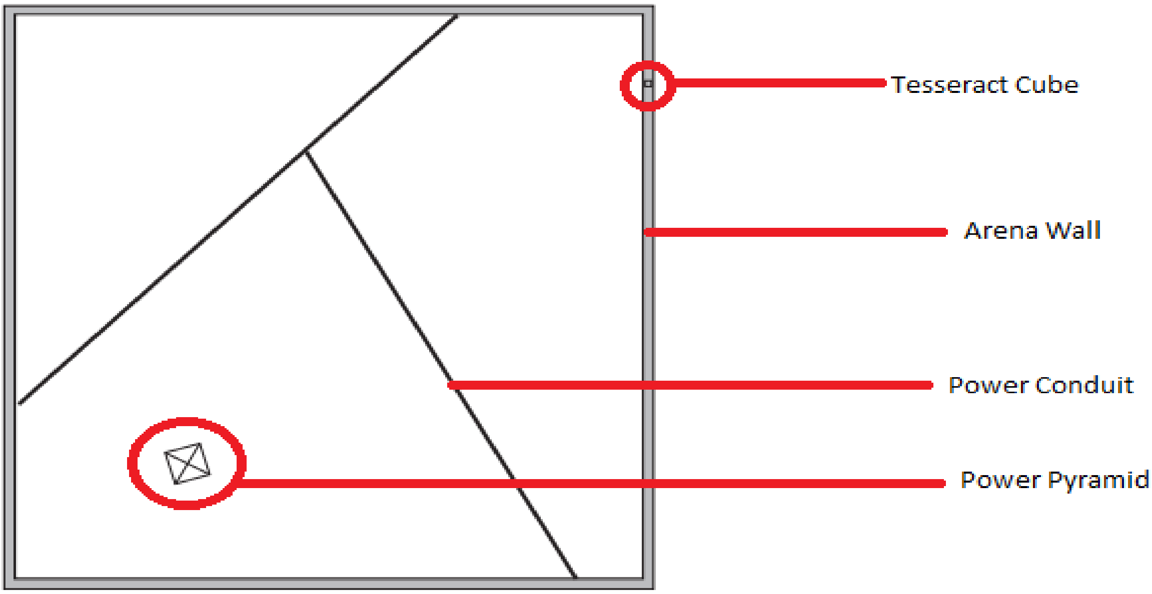


Figure 1: Depiction of arena setup

Dimensions for the tesseract power source are given as a 0.75 inch cube with a permanent magnet enclosed inside it. The magnet can be used as an advantage by the team if required but it is not a requirement. The Power Pyramid base is approximately 4 inches with a 1.5 inch square opening in the base to accommodate the tesseract cube and the pyramid itself is about 3 inches tall.

Due to the nature of the power conversion process, the Power Pyramid's position moves throughout the power plant. To assist in localizing the pyramid, it emits a modulated infrared signal with a carrier frequency of 38 kHz which is modulated at either 170 or 340 Hz.

The team was given approximately seven weeks to plan out a strategy and come up with several different methods of accomplishing this task. It was required that the team select the most suitable design out of the proposed ideas and build a functional prototype alongside with providing valid documentation and reasoning for the design process.

This report provides an insight to the initial ideas that the team brainstormed along with detailed visuals to further enhance the readers understanding of each design concept. Requirements such as the problem definition, objectives and constraints are also highlighted and built upon throughout the design process. Two design review meetings were also conducted throughout the project timeline, one on March 9th, 2017 and the other on March 23rd, 2017. These meetings featured discussion of how the project was coming along, as well as how the team was allocating and diving time for each major task. The entire timeline for the project has been summarized in **APPENDIX A** the form of a Gantt chart.

Development of Specifications

In consideration of the open ended problem stated earlier, the team began with the identification and formulation of a problem definition to aid in the structuring of potential solutions. The finalised problem definition is as follows:

Design and create a mechatronic system that can autonomously maneuver through the terrain of the power plant and the power conduits to locate, retrieve and place the pyramid power pack under the power pyramid.

As the above stated problem definition is still fairly open ended, it was essential to produce several objectives and constraints to further limit the potential solutions and be more concise about the generation of concepts. The implementation of objectives and constraints also helped the team's understanding towards the overall goal of the project. Of the highlighted requirements, some were very general to allow the team to establish a starting point while others were based more specifically towards the problem defined. Over the course of two meetings, the team came up with the following design requirements for the final product:

- Fit into MSE locker (1' x 1.5' x 1.5')
- Operate autonomously
- Operate on provided MSE battery (max 7.4 V)
- Operate by use of microcontrollers
- Code must fit within memory capacity of the microcontroller
- Function with variations in environmental conditions

- Locate, retrieve and hold the cube

  -> Strong enough to overcome magnetic force between wall and cube
- Precisely locate, retrieve and hold the pyramid
- Place pyramid over the cube while it is on the ground
- Light enough to move under its own weight while holding cube and pyramid
- Circuiting must not inhibit possible range of motion due to tangling
- Come to a stop once the design objectives are completed
- The robot must exhibit controlled motion in at least the X-Y plane
- Chassis must be stable enough to maneuver over the power conduits
- Have enough speed to complete the designated tasks in under 3 minutes
- Pick up the cube and or pyramid off of uneven surfaces
- Be aesthetically appealing

Conceptual Design

Based on the problem defined, several concepts were generated through the use of collaborative brainstorming techniques in order to provide a plausible solution for the situation. For optimizing proficiency, the overall mechanism was divided into three categories: drive system, cube retrieval and pyramid retrieval. Different concepts were generated for each of these categories based on the objectives and constraints.

Drive system

A total of four different concepts were formulated for the drive system based on movement systems that are commonly used in rough terrain situations. These systems are solely land based on the fact that there is not a significantly large water body in the power plant and approaching the problem from an air borne robot is too complex for the purposes of this task.

Three of the four ideas involved the use of various orientations of wheels as a driving force. The four wheel drive system would have two wheels powered while the other two merely provided balance and support. The three wheel drive system would incorporate the triangular base shape like that of an auto rickshaw and have the two back wheels powered and the front wheel follow. The two wheel drive system would incorporate two powered wheels at the centre of the chassis and have two coasters on the front and back end to provide support. The last concept used two parallel tank treads on opposite ends of the chassis being rotated by gear assemblies as the driving force for the robot.

Cube retrieval

Six concepts were generated for the process of retrieving the cube from the walls of the arena. All six ideas are based on the initial condition that the robot will be placed parallel next to the wall that has the cube on it. Each of the ideas also has its own proposed design and sensors for the rotating arm assembly running along the top of the wall that will be used to collect the cube.

Concept 1 makes use of the fact that the cube has a permanent magnet inside and so a Hall Effect sensor placed on the arm will alert the system that the cube has been located. The arm will then rotate in the X-Y plane and knock the cube off into a pocket on the robot.

Concept 2 has a piston assembly mounted on its arm along with a stopper at the bottom and a permanent magnet on the edge of the piston, facing the wall. As the arm is running along the wall, the permanent magnet will be in the extended piston position and hence when the arm is above the cube, the magnet will attract and pick it up.

Concept 3 proposed multiple hinge like apparatuses which would enclose over the cube once it came into contact with one of the faces. The overall structure looks like the letter ‘L’ and has three flanges, two of which fix onto the side and top face, and one flange that rotates 90° downwards to fix onto the face opposite to the first.

Concept 4 makes use of an extendible claw assembly that is able to retrieve the cube off the wall once an ultrasonic sensor alerts the system of its presence. The claw can then be reopened when required to drop the cube anywhere in the arena.

Concept 5 was generated by visualizing a construction crane assembly. An ultrasonic sensor would signal when the cube was in proximity of the arm and a vice grip would vertically descend and latch on to the cube and be able to displace it to other locations in the arena.

Concept 6 makes use of two suction cups on the tips of the arm facing the cube. Employing a strategy similar to the piston idea, the cube will be sucked onto the arm and stay there until the piston is reset to its initial position, consequently letting go of the cube and dropping it in the desired position.

Pyramid retrieval

Six concepts were generated for the manipulation and placement of the pyramid as well. All concepts alluded to assume that the cube has been retrieved and is attached to the cube retrieval arm, and that pyramid has already been located in the arena and that the robot is standing in front of the structure. The process for locating the pyramid after retrieving the cube will be highlighted in subsequent sections.

Concept 1 employs a rotating platform mounted on top of the chassis base which is able to rotate itself 180° in the X-Y plane parallel to the ground, and also raise and lower itself in the Z direction perpendicular to the ground. The front of the platform has a cut-out with a width that matches the width of the pyramid and so when the robot drives forward, the pyramid will slide into position. The rotating platform will then lift the pyramid off the ground and rotate 180° which would ideally place the pyramid exactly behind the robot. So if the cube is first placed right behind the robot, then the pyramid can be placed on top of it with ease.

Concept 2 uses the idea of a conveyer belt to retrieve the pyramid. Once the robot makes contact with a face of the pyramid, two parallel gears will rotate to move the belt inwards towards the base of the robot therefore bringing the cube towards a pocket where it will stay until instructed to do otherwise.

Concept 3 takes heritage from the others and uses a shovel to retrieve the pyramid. The shovel's edges are angled and its width matches that of the pyramid and a force sensor will be used to check when the pyramid is in the desired position. The pyramid can then be lifted off the ground using a gear assembly to a height just enough to clear the bumps and cube. The whole robot can then reverse over the cube and place the pyramid on top of it.

Concept 4 uses a force sensor to acknowledge making contact with pyramid and then have two appendages come down and engulf the sides of the pyramid, mimicking a claw formation perpendicular to the ground. The claws of the arm may be opened or closed by will and place the pyramid on top of the cube at any location in the arena.

Concept 5 is essentially the same idea as the suction cups concept generated to pick up the cube from the wall and it can be applied to picking up the pyramid in the same manner as described earlier.

Concept 6 extends from the construction crane idea used to pick up the cube, however due to the shape of the pyramid, a minimum of three appendages would be used and each appendage has notches which are able to slide underneath the base of the pyramid and then lift it off the ground in the same manner as a crane.

Concept Selection

After multiple concept generations through regular meetings and implementations of creativity techniques such as brainstorming and mind mapping, the team had to decide on one concept to build on through the rest of the work term.

To help in making the decision for which concept to work on, both GO-NO GO tables and decision matrices were used for all three phases of the project. Various conditions were used to evaluate the generated concepts, including but not limited to, degrees of freedom in motion, minimal number of motor requirement, complexity, feasibility, and power efficiency to name a few. The tables can be found in **APPENDIX B.**

There were three concepts left in each category after the implementation of the GO-NO GO tables and so a decision matrix was used to decide on the final product. The constraints used were similar to the ones used in the GO-NO GO tables, but the constraints were weighed with respect to each other in terms of importance to the overall project. The concepts were then analyzed on how well they performed each of the weighted constraints and the overall result was computed. The matrices can be seen in **APPENDIX C.**

After using the decision matrix to weigh the feasibility and efficiency of the concepts in all three categories, it was decided that tank treads would be used for the drive system, the magnetic piston arm assembly (Concept 2) would be used for the cube retrieval, and the shovel elevator (Concept 3) would be used for the pyramid retrieval. Together these choices paired together would provide the most efficient and effective solution for the project.

As outlined in the previous section, various concepts were generated for the three different stages of the project and a final product was decided on through the use of multiple concept selection techniques. The selected concept specifications are highlighted below:

Drive System

The robot's drive system is a continuous track similar to that of a battle tank's treads, consisting of 60 pieces linked together in a circular chain. The treads are on either side of the chassis and are being powered by two conventional VEX motors, one for each tread. The left tread has two ultrasonic sensors attached to it as well, the purpose of these sensors is to ensure that the robot is always driving parallel to the wall in a straight path. The robot is able to execute turns by adjusting the speed of the motors powering each tread, for example, if a right turn is required then the right motor will slow down while the left maintains its speed, consequently making the robot execute a right turn.

Chassis and frame

The robot base has an approximate square shape and is the hub of five different operations being executed through the entirety of the robot's runtime in the arena:

- It holds the two motors used to drive the entire system around the arena
- It is the base upon which the cube retrieval arm is resting and rotating about
- It provides support for the shovel used to retrieve and lift the pyramid

- It holds the Arduino board, which is the brain of the project
- It also holds the battery pack which powers the whole robot

Cube retrieval

Once the robot has been placed inside the arena and parallel to the right wall, the cube retrieving arm will initially make a 90° angle with respect to the arena walls. The height of the arm will just be above the surface of the walls and as the robot drives down the arena, the arm will be running along the top of the wall. The arm itself is composed of a piston gear mechanism that is able to extend and retract a permanent magnet on the top face of the arm. The bottom face of the arm has a stopper attached to it. The magnet on the is initially extended while the robot is travelling parallel to the arena wall, once the arm passes over the cube, the magnet on the arm and the magnet inside the cube will attract, bringing the cube to stick to the bottom face of the arm. A force sensor placed at this location will be used to detect if the cube has been retrieved and the whole arm will then rotate 90° back toward the rear of the robot. For the releasing of the cube, the piston will simply retract the magnet and consequently, the cube stuck to the bottom face will want to move along with it. However, with the placement of the stopper on the bottom face, the cube will be held back while the magnet continues to be taken further away and eventually the magnetic force between the two will be too weak for the cube to hold on and thus it will fall to the ground as desired.

Pyramid retrieval

Once the cube has been collected from the wall, the robot will turn away towards the arena and an infrared (IR) sensor will be placed at the front of the chassis to read the pings sent out by the pyramid. The IR sensor will be encased in a covering in order to minimize the amount of rays coming into contact with it from every direction and focus more on receiving rays from a particular direction. As the robot scans and locates the direction of the pyramid, it will start driving towards the structure. An ultrasonic sensor is placed above the body, facing downwards that detects and lowers the shovel when the pyramid is within range. The shovel has a base cut-out with the same dimensions as the pocket underneath the pyramid and has angled edges to optimize its performance. The robot will drive the shovel underneath the base of the pyramid and keep driving until it approaches either a power conduit or the arena wall, approaching one or both of these will push the pyramid further into the shovel. A force sensor will be placed into the shovel to check when the pyramid has slid into the proper position and once it does, the robot will stop driving forward and the shovel will be raised off the ground. To complete the final task, the cube will be dropped directly behind the robot and the robot will then reverse straight over the cube until the pyramid is directly overhead. The shovel will then be lowered onto the cube, and since there is a cut-out with the same dimensions as the pyramid pocket, the pyramid will be placed directly on top of the cube and then released from the shovel.

Material Selection

To produce the optimal mechatronic system for Tesseract Power, it was necessary to undergo a material selection process. Through identifying the proper material to use for the various components of the mechatronic system, the group would effectively minimize costs while still maintaining product performance goals.

Based on design specifications developed during quality function deployment, the fundamental criteria for the material to build the mechatronic system was developed. Three requirements were considered, as follows:

1) **Light Weight**: The mechatronic system is required to function off the energy budget permitted by a single MSE battery pack. By minimizing weight, current required to run the motors will be reduced, and therefore the battery lifetime will be increased. Additionally, the maneuverability of the arm and shovel of the robot will be made easier by reducing the weight of the components themselves.

2) **Strong/Rigid**: Although the weight requirement for the chassis to support is not excessive, it was still important to ensure that the chassis had the strength to support the load that it carried. Furthermore, the geometry of the arm used to pick up the cube

was such that it experienced a large bending moment. As a result, the material used for the final design would also require rigidity.

3) **Safe to Handle**: Based on information provided by the customer, the robot will be operating in an environment that is inaccessible to humans. However, in the event of damage or malfunction, maintenance will be required on the mechatronic system. To ensure technician safety, the material used must be safe to work with.

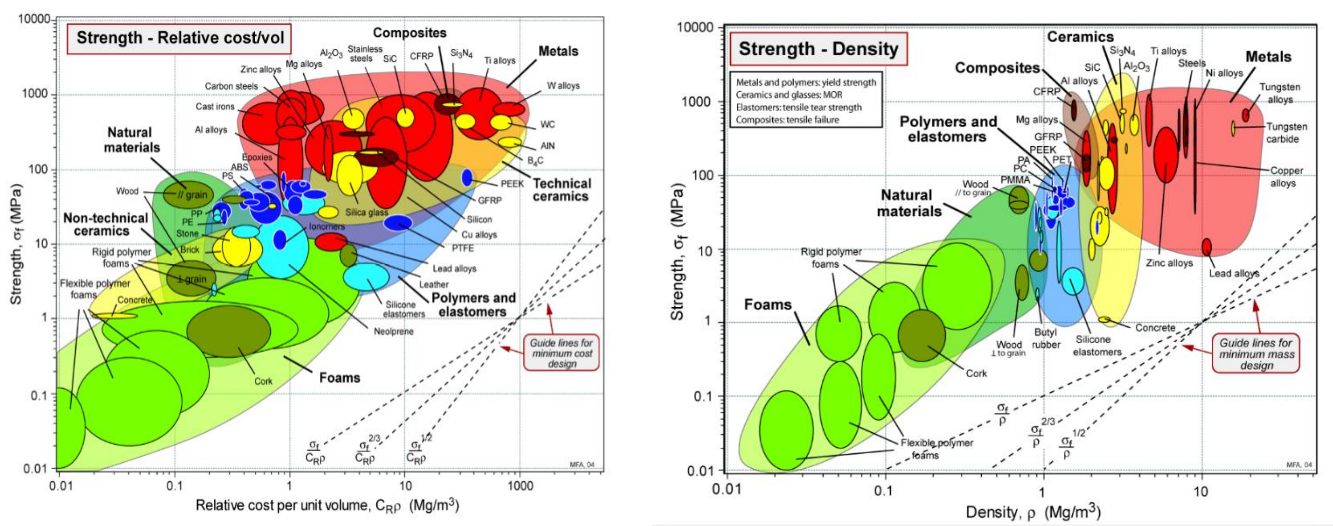


Figure 2 – Material Selection Charts for Strength versus Cost and Strength versus Density

Due to the desire to minimize the cost of the final design, a material selection charts in *Figure 2* were analyzed. When considering the chassis and main body of the mechatronic system, the most inexpensive materials that satisfied the strength criteria were ceramic-based materials. However, due to the brittle nature of ceramic, the material was avoided.

Polyvinyl Chloride (PVC) provided the most suitable option due to its strength, low cost, and ease to work with. From the material selection chart above, PVC was considered as the best potential candidate for the final design.

The cantilever arm used to pick-up the cube required a material that was capable of handling greater stress than the chassis. Although, wood was suitable for the final design of the arm, it tended to warp and undergo partial fracturing. As a result, it was avoided in the design of the rotating arm.

The next material under consideration was polycarbonate due to its ability to satisfy the strength criteria and relative inexpensiveness. Additionally, it was more effective than wood due to the strength and toughness it provided. In turn, it was considered the best material for the design of the final mechatronic system.

A summary of the material selection data can be found below in Table 1:

Part	**Material**	**Description**
Chassis/Main Body	PVC	Provides required strength, durability, and handling at a low cost and density
Rotating Arm	Polycarbonate	Provides required toughness and strength at a relatively low cost and density
Tracks	Rubberized Polyvinyl Chloride	Provides high coefficient of friction, maneuverability, and durability
Miscellaneous	Polyvinyl Chloride	Light-weight, strong material that is relatively inexpensive

Table 1: Summary of proposed materials for certain parts of the final design

Use of CAD in Design Process

As the concept was finalized and a good understanding of its functioning was established, the team needed a visual representation for the building of the prototype and thus CAD modelling had to be employed into the design process. Solidworks was the simulator used to create 3D representations for the parts to be used in building the prototype and also how each part should come together to form the final assembly.

In order to help in modelling the design, documents and drawings made in the design notebooks were expanded and built on in Solidworks. Parts like the gears that would drive the tank treads, shafts powered by the motors, crossbars to support the chassis, and a multitude of sensors were modelled and analysed to determine if a specific orientation would work and what the optimal position to place each component should be.

Solidworks was also incorporated to model parts like the shovel assembly and the IR sensor covering, these individual parts were then laser-cut in order to have precise measurements for the prototype build. This also proved to be more efficient for the design and iterations of irregular shapes that could not be built by VEX parts, once the approximate dimensions were calculated it was easier to have the parts laser-cut precisely instead of having to make handmade incisions and holes on materials like acrylic, plastic and wood.

Finally, by incorporating the use of CAD models into the design process, the team was able to have an effective system of resource management and bookkeeping for the number and types of parts used for building the prototype. It serves as an electronic copy of the design blueprints along with all of its physical attributes and dimensions. Examples of the CAD models can be seen in **APPENDIX D.**

Prototype Design

After the completion of the Solidworks drawings and assemblies, the team started building the final prototype which consisted of the selected mechanisms highlighted in earlier sections. This model was designed and built using accessible VEX robotics parts along with some components being manufactured out of 16th inch acrylic. The design features a battle tank like robot with two treads on either side along with a separate arm, and shovel assemblies for the retrieval of the cube and pyramid respectively.

The prototype functions by making use of a 7.4 V battery provided to the team by the project supervisors. This battery is used to power the MSEduino board fitted onto the chassis, which is essentially the brain of the robot. The drive system consists of two 24-tooth VEX sprockets clamped in between a 60 piece chain link of treads on either side of the robot. One of the sprockets is being rotated by a VEX motor in each tread while the other sprocket serves as a support and provides more torque to the chain. Hockey tape was applied to further improve the traction between the ground and treads, hereby giving a better performance in turning and going over bumps.

The left tread of the robot has been fitted with two HC-SR04 ultrasonic sensors separated by a distance of 3 inches. These sensors are in place to ensure that the robot drives along a straight path by making use of the adjacent arena wall as a guide. If both the sensors receive readings that are either higher or lower than the optimal range then the robot will adjust accordingly by either turning left or right to realign itself in the proper position to continue moving straight. A VEX ultrasonic sensor is also attached to the front of the robot in order to detect if it is about to run into a wall.

The arm designed for retrieving the cube is constructed out of acrylic slabs hot glued together and supported by electrical wires and threads. The mechanism consists of a 60-tooth VEX gear extending and retracting a sort of gear rack piston with a permanent neodymium magnet taped to its end. A VEX servo motor is used to power the 60-tooth gear, while another servo motor is attached to the base of the arm which allows the appendage to rotate 90° in the X-Y plane. A 1.5 inch outer diameter PVC pipe with a length of 2 inches is placed vertically on the chassis to act as a support column for the arm.

Instead of using a force sensor, a mechanical switch was placed near the edge of the bottom face of the arm. This is a more efficient way of knowing when the cube has been picked up from the wall because once the cube attaches to the bottom face of the arm, it will press down on the switch and signal the system that the task has been completed. Duct tape is used to hold the switch and magnet in place.

As alluded to earlier, the pyramid retrieval assembly consists of two main components, the shovel, and the lift. The shovel was created in Solidworks and then the model was laser-cut to the specified dimensions and finally superglued into the proper alignment. The front edges of the shovel were sanded in the woodshop in order to get angled notches that are able to get under the base of the pyramid. Additional hockey tape was applied to the faces of the shovel in order to ensure that the pyramid doesn't slide off after it has been picked up. The force sensor was replaced by a mechanical switch to detect when the pyramid is in place for the same reasons as stated before for the cube retrieval.

The lift mechanism makes use of gear racks, brackets, crossbars, a 12-tooth gear and a VEX servo motor. The servo is used to turn the gear, which is connected to the gear racks and thus the crossbar is able to move up and down as required. The height that the pyramid is raised to is just enough for the robot to be able to clear any bumps and for the chassis to reverse over the cube in the final stage of the task. The ultrasonic sensor used to detect the presence of the pyramid is mounted on a cantilevered crossbar perpendicular to the crossbar of the lift, making an 'L' shape. The IR receiver is placed right in the centre of the lift assembly so that the shovel is facing towards the pyramid once the signal is detected.

Various extension cables and wires are incorporated into the prototype in order to connect each of the sensors and motors to the MSEduino board in the centre of the body. Zip ties, packing wires and duct tape were used to avoid tangling and damage to these wires. As there are a multitude of motors and sensors that need to be operated, both microcontrollers on the board were used. For the ease of functionality, a VEX bumper switch was connected and placed near the top of the chassis. The following section highlights the number and types of functional sensors and motors.

Sensors and Motors

As previously stated, there are a multitude of sensors and motors that were placed into the final prototype. A summary of the number and type of each component is given below:

- Two VEX 2-Wire 393 motors
- Three VEX 3-Wire Servos
- Two HC-SR04 ultrasonic sensors
- Two VEX Ultrasonic Range Finders
- Two Subminiature Basic Switches
- One TSOP32338 IR Receiver

- One VEX Bumper Switch
- One Tower Pro Micro Servo 9g

All the parts mentioned above were readily available in the VEX kits provided to the team with the exception of the HC-SR04 ultrasonic sensors which were purchased separately. Apart from the sensors and motors, all other parts and pieces used in building the prototype were easily accessible VEX parts provided. Further modifications brought materials such as acrylic boards and PVC pipes being purchased for better performance in specific tasks.

Circuitry

Due to the simplicity of interfacing, maintaining, and using the MSEduino board, it was selected for use in the final design of the mechatronic system. Additionally, the MSEduino provided all necessary pinouts for the servos, motors, and sensor involved in the design.

The second microcontroller was used as the main microcontroller for developing the code for the final design. In order to accommodate the servos, drive motors, and sensors used, all digital pinouts were used on the second microcontroller, as shown in **APPENDIX E.**

All servos and motors were connected to digital pins D8 to D13 since it allowed for ease of cable maintenance. Pins D2 to D7 were occupied by ultrasonic sensors, which required the use of two digital ports for both input and output. Jumpers were used on the Arduino to provide all components except the drive motors with a source voltage of 5V. The drive motors, on the other hand, had a jumper connected such that they received a source voltage of 12V.

The infrared sensor was connected through the leads to a 5V source, ground, and the RX pin (D0). Since the infrared signal emitted by the pyramid was easily read through the serial receiving ports of the Arduino, the infrared sensor was connected to the D0 pinout.

Both mechanical lever switches used in the design were connected to analog pinouts. A pull-up resistor was used for the switches to prevent shorting and potentially damaging the analog ports of the Arduino. Furthermore, the mechanical switches were used as analog inputs as opposed to digital inputs because all digital ports on the second microcontroller were in use and the analog port provided analog values in a range that were easy to code.

Finally, the A4 and A5 analog pins of the second microcontroller were connected to the A4 and A5 pins of the first microcontroller, respectively. The purpose of connecting the SDA (A4) and SCL (A5) ports of the Arduinos was to allow for communication via Inter-Integrated Circuit (I2C) Protocol. As a result, data could be transmitted from the first microcontroller (the slave) to the second (the master) via the “wire” library in Arduino, providing more pinouts for use in the design of the mechatronic system.

By using the two microcontrollers via internal communication, an opportunity was provided to make use of the second microcontroller. Because data could only be sent one byte at a time, a single ultrasonic sensor was connected to digital pins 6 and 7 of the first microcontroller to simplify data transfer, as shown in **APPENDIX E**

Software Design

Within the final design of the mechatronic system, it was imperative to develop a robust code that would allow the system to operate both efficiently and effectively. In order to ensure the completion of these goals, in-depth planning, testing, and analysis was completed on the code of the robot. Furthermore, to maintain optimal organization for the code, GitHub was used a repository for the code being developed.

The code for the final design of the robot was split into three main sections: obtaining the cube, obtaining the pyramid, and placing the cube beneath the pyramid. A more thorough description of these three sections follows:

Cube Retrieval

In order to successfully obtain the cube, the mechatronic system developed required the ability to drive straight along the wall while maintaining a specific distance for it. By maintaining the specified distance, the rotating arm of the robot would be capable of reliably picking up the cube while navigating over conduits.

The code for this section of picking up the cube involved an initial function for calibrating the two ultrasonic sensors located on the side of the robot. When the system was placed in the starting position and supplied with power, it initially calibrated the ultrasonic sensors to identify the proper distance from the side wall. When travelling along the wall, the ultrasonic sensors constantly read values, and the position of the robot was adjusted accordingly to maintain proper orientation. However, since the ultrasonic sensor were volatile, forty readings were taken, then averaged in order to achieve more stable values for reading.

When the robot reached the end wall, and therefore the corner, an ultrasonic sensor was attached to the robot in a manner that allowed it to read the end wall. If the value reached a certain threshold, the robot swung its arm in a 90 degree arc in order to pick up the cube with the permanent magnet used. The ultrasonic sensor was configured through the slave microcontroller, and as a result, data was sent from it using the "Wire" library in Arduino. Once the cube was obtained, the second stage began.

Pyramid Retrieval

To obtain the pyramid, the mechatronic system slowly moved over to the pyramid over multiple iterations.

The code for obtaining the pyramid involved rotating the robot counterclockwise while it scanned for an incoming infrared signal. The infrared signal was read as an integer through the serial port, and when read, the robot drove in the direction of the signal for two seconds. While driving in the given direction, readings were taken from an ultrasonic sensor pointing down in front of the robot. If the readings taken were random values that were high or low, then the pyramid was in front of the robot, due to the sloped surface of the pyramid. If the pyramid was not found, then the robot rotated clockwise and counter clockwise to reposition itself while looking for the pyramid. Again, if the pyramid was not found, then the sequence for scanning for the infrared signal of the pyramid was replayed.

Once the pyramid had been found, the robot was coded to drive forward for two seconds the quickly shake. This process was repeated until the pyramid contacted a conduit or wall and then began to scoop up the pyramid with the shovel. Once the pyramid successfully made it onto the shovel, it activated a lever switch to commence the third stage of the process.

Cube under Pyramid

To place the cube beneath the pyramid, the mechatronic system was programmed to raise the pyramid, drop off the cube, and then lower the pyramid onto the cube.

One the pyramid was on the shovel, a stopper arm was programmed to lower and hold the pyramid in place. The pyramid was then raised with the use of the shovel, and the entire robot reversed away from the wall or conduit. The robot was then programmed to stop, rotate the arm holding the cube until the arm was facing the back of the robot, and rotate the rack and pinion with the magnet so that the cube would drop of behind the robot. When the cube was dropped off, the robot was programmed to reverse over the cube for a length of time during which the cube got stuck on the front edge of the pyramid. Finally, the robot would quickly move forward to centre the cube under the pyramid, lower the pyramid onto the cube, and the quickly drive backward to drop off the pyramid.

All in all, this provides a summary of the software design used for the mechatronic system.

Prototype Testing

The drive system testing was done at first in order to ensure that the robot was able to drive along a straight path and pick up the cube from the arena wall. Two ultrasonic sensors are placed on the side of the left tank tread. Two sensors were employed instead of one because if only one sensor is used then the only measurable characteristic that can be obtained is the distance from the wall. However, if two sensors are used then the distances of both sensors can be obtained and by applying simple trigonometry, the angle that the robot is making with the wall can be calculated. This way if the angle is less than 90° then it is interpreted as the robot facing away from the wall and if the angle is greater than 90° then it is interpreted as the robot facing towards the wall and from there the motor turning speeds can be adjusted in order to make the robot turn either left or right based on what will get it back to 90°.

The retrieval testing was done in three separate stages, one for the cube retrieval, one for location of the pyramid with the use of the IR sensor and one for the pyramid retrieval,. For testing the cube retrieval process, the readings obtained on the serial monitor for the force sensor placed at the edge of the arm were analysed. The force sensor acts like a variable resistor so its values can change depending on how much stress is applied to it. When the cube is not attached to the arm, the force sensor reads a value of 400 with an error range of 50. Once the magnet pulls the cube off the wall, it attaches to the arm and covers the force sensor which in turn gives a spike in the readings on the serial monitor. Hence when the cube was attached to the arm, the serial monitor read a spike value of 1023. Therefore the robot was initially programed to exit the cube retrieval mode once the sensor read a value around 1023, however this wasn't the best approach to take because the sensor covered a very small surface area. This sometimes led to the robot continuing to look for the cube even when it had already received it because the cube wasn't pressing down properly on the force sensor.

Testing for picking up the pyramid required two stages, one for testing how far away the pyramid is from the robot's current location and another for lowering the shovel underneath the pyramid to pick it up. Two potential sensors were considered for testing the distance, namely an infrared proximity sensor and an ultrasonic sensor. The latter of the two was implemented because of three reasons. The IR sensor returned inconclusive data which could not be used effectively and there also weren't enough ports left on the

MSEduino to connect the IR sensor. It was also simpler to code for an ultrasonic sensor instead of an IR sensor.

The first set of tests involved recording the ideal values read by the serial monitor for three different situations, one for when there is nothing in between the sensor and the ground, one for when there is a power conduit in between the sensor and the ground, and lastly, one for when the pyramid is in between the sensor and the ground. The results obtained from the ground, conduit, and wall were expected but the ones from reading the pyramid were highly spiked with returned values around 4000. This number can be explained by the fact that the angled faces of the pyramid are not reflecting the waves directly back at the receiver and so the values tend to convey that the pyramid is really far when in reality it is right underneath the sensor.

Lastly, to test the direction of the pyramid, the IR receiver had to be tested for various different situations. To start the process, the receiver was tested to check if it was able to catch signals sent its way. This was done by making use of remote controls and mobile phones, once the functionality of the receiver was confirmed to be accurate, methods of creating a covering were proposed. This is because locating the direction of the pyramid can greatly be simplified if the receiver is only able to get a signal when it is directly facing the source. Since the signal sent out by the pyramid is so strong the receiver is able to pick it up from anywhere in the arena and hence the need of a decent covering is essential.

Iterations

After the team took advantage of a meeting to analyze the downfalls of the initial prototype, the specifications of the first design iteration were developed. The consolidation of these ideas led to the development of the consecutive prototype models until a final prototype design was obtained as mentioned in the earlier section. The various iterations implemented for the major tasks in the project are highlighted below:

Sensors & Chassis

The initial prototype featured force sensors placed in order to register when the cube and pyramid has been picked up, but in order to maximize the efficiency of the response, mechanical switches were implemented instead. These switches are activated by contact and hence are a better option as both the cube, and the pyramid will have to be attached on the body of the robot in order to register a signal from the switches. Hockey tape was applied to the treads and shovel to provide better traction between the two surfaces as opposed to just bare acrylic on acrylic.

The first design featured only one ultrasonic sensor placed on the side of the tank treads but this proved to be an ineffective means of aligning the robot and thus two HC-SR04 ultrasonic sensors were used instead for this purpose.

As the number of wires increased throughout the design process it became necessary to relocate the MSEduino board a couple of times. To prevent the issue of wire entanglement and damage, several zip ties and twist ties were added alongside with duct tape to provide rigidity and support.

Cube Retrieval

In order to test which magnet was strong enough to attract the cube off the wall a sort of trial and error was conducted. At first an array of cylindrical ceramic magnets were used but they weren't strong enough. Next was a slab of a stronger ceramic magnet but the results were still not satisfactory. It was decided that a neodymium magnet would be needed to accomplish the task at hand and this proved to be effective.

The arm was initially fixed to the base but after running a couple of tests it was decided that a rotating arm would prove to be much more beneficial than having the entire robot turn around to drop the cube off at a certain location. The length of the arm itself and the gear size used to extend and retract the piston was also subjected to change and decreased over the course of the testing period.

Pyramid Retrieval

To pinpoint the location of the pyramid, it was essential to make a covering for the IR sensor and this design saw a couple of iterations. The first covering designed was made out of incisions from regular business cards hot glued together. An additional layer of vertical duct tape was applied around the outside to act as a slit to prevent even more infrared rays from hitting the sensor. The design was satisfactory, however it would fail to block the rays for an angle beyond approximately 30° and the duct tape wasn't the most reliable material as some rays could still pass through to the sensor. The next iteration involved having two slits instead of just one, one would be horizontal and the other would be vertical like before which would ideally further reduce the randomness of rays being received by the sensor. This model saw issues as well because every time the robot would go over a bump, the horizontal slit would be displaced and the sensor would essentially be blinded by the obstruction, hereby causing defective data to be calculated. The third iteration to the covering was a laser-cut model crafted in Solidworks which featured just the vertical slits but this design was much worse than the previous two iterations so it was scraped. The final iteration saw the use of a plastic straw as a covering for the sensor and this apparatus was covered by duct tape to prevent the rays from bleeding in from every direction. Two vertical aluminum blinders were added to the sides to further block unwanted rays from hitting the sensor and giving unwanted results.

The process of lifting the pyramid was redesigned a couple of times as well. Initially the shovel was simply driven into the pyramid after being lowered in order to pick it up, however this proved to be ineffective as sometimes the pyramid may not properly slide all the way into the shovel and hence not activate the force sensor properly. To account for this flaw, a shimmy function was added to the code in order to properly hold on to the pyramid and activate the force sensor placed at the edge of the shovel.

After the first iteration the pyramid was still unable to slide on to the shovel smoothly due to obstructions caused by a hot glue bead and an offset bump of a screw. To accommodate for this deficiency, the screw was removed and replaced in a different orientation, while the entire shovel base was coated with aluminum foil to provide a smoother surface to slide upon.

The third and final iteration aimed to fix the problem of having a corner of the pyramid caught in the flat edge in the centre of the shovel. At times the pyramid would get stuck in the spacing cut out in the base of the shovel, and to fix this problem the shovel was sanded in the woodshop to give it a finer and smoother finish.

Showcase Performance

Once the prototype building and testing was completed, the team was ready to present the product in a performance showcase where the robot would have to complete the assigned tasks stated in the problem definition. The showcase allowed the team to demonstrate the robot's applications and also be able to witness other teams with their proposed mechatronic systems.

The showcase consisted of a total of three rounds per team. Each round lasted roughly three minutes and each team's design had to locate and grab the tesseract cube off the arena wall and then place it under the Power Pyramid in under three minutes. The power conduits were placed in a similar manner as to the one predicted and the cube was placed on top of the wall adjacent to the starting position of the robot. The team was provided a custom battery for powering the robot, the results of the three rounds are given below.

Round 1

The robot was able to maneuver over the power conduit placed at the very start of the course and followed the wall in straight path as planned. The cube retrieval arm was running along the top of the wall and picked up the tesseract effortlessly, turned away from the wall and started driving into the arena scanning for the pyramid. The IR sensor was able to identify the source and direction of the pyramid so the robot was driving towards the pyramid. However, once it attempted to pass over the power conduit again, the shovel ultrasonic sensor mistook the bump as the pyramid and thus the robot lowered the shovel to the ground and started shimmying around trying to fit in a pyramid that wasn't anywhere close.

While getting ready for the second round, an unforeseen circumstance led to the accidental breakage of the mechanical switch on the cube retrieval arm by a person walking by. Although this issue was fixed as best as possible, the performance of the robot in subsequent rounds was affected.

Round 2

The drive system and cube retrieval operations ran as smooth as they did the last round and the robot turned towards the arena once again scanning for the pyramid. The power conduit didn't throw off the ultrasonic sensor this time, however the IR sensor was unable to accurately detect the pyramid and just drove right past it. The robot attempted to turn a whole 360° and try again but the same issue persisted which eventually ended when the time limit was up.

Round 3

Just like the two previous rounds, the drive system and cube retrieval operations went off without a hitch. The robot turned to look for the pyramid but wasn't able to pick up a reading for the location at all. This happened because the pyramid had turned off and thus wasn't emitting any frequencies for the IR sensor to pick up. The team was allowed to start again but the same problem that happened in the first round returned and the shovel was lowered onto the conduit. The robot continued to shimmy over the conduit until the time limit was up.

Bonus Round

The team was allowed an additional round to complete the tasks in the allotted time. As usual, the cube was picked up and the robot was heading towards the pyramid, but this time both the IR and ultrasonic sensors cooperated and the pyramid was within the shovel and then lifted off the ground. The cube arm rotated 90° towards the rear end of the robot as required and dropped the cube in position. The robot starts reversing over the cube but falls just about an inch or so short and places the pyramid in a slanted manner on top of one of the faces of the cube and drives away. The total time taken to complete this entire run was one minute and thirty-four seconds.

Conclusion

Throughout the design process, the main objective of the team was to design and build a working model of a mechatronic system that is able to manipulate a tesseract cube and place it under a power pyramid with no human contact. From day one the team started brainstorming various different ideas and concepts for different tasks of the project that could work and implemented these into sketches, CAD models, and drawings. A Gantt chart displaying the tasks that needed to be completed over the project timeline was implemented in order to stay on schedule.

Once the team chose the best possible design for all three categories, the modelling and building of the very first prototype began. Successful completion of the wood and metal shop training allowed the team to use tools such as the vertical band saw and sanding machine amongst others to construct the prototype and the Solidworks associate certification enabled the team to model 3D drawings for the prototype.

Making use of the Arduino serial monitor, all the sensors involved in the prototype were tested and coded to perform the tasks assigned to the robot. Based on these tests, various iterations were made to each of the major components of the design. These featured changing lengths, sizes, amount, and overall designs in order to make the best mechatronic system through the process of iterations and calculations.

As the prototype was being built, several other documentations such as the design notebook and product development file were being created and edited for a more saturated form of information about the robot. These documentations are provided alongside with this report for anyone who's interested in learning more about the product.

The final showcase featured the final prototype being graded on its ability to complete the assigned tasks in the allotted time. The overall performance wasn't the best but it was still quite satisfactory compared to the rival engineering companies who were trying to model a solution for the same problem. The team was able to get to the final stage of the tasks but just barely missed placing the pyramid on top of the cube.

There are several possible explanation as to why the robot was unable to complete the assigned tasks accurately. The team used a 9 volt, 1.5 amp wall adapter to power the robot for all the testing conducted, but the battery provided to the team during the showcase was a less powerful one and hence the functioning and turning speeds of the robot were severely hindered. For example, the turning speeds were slower which led to the robot being unable to register the pyramid. The actual movement speed of the robot was slower as well, which led to the pyramid not being backed up enough in the allotted time and being placed at an awkward angle on top of the cube.

Another issue faced during the showcase was the accidental damage sustained to the mechanical switch of the cube retrieval arm and damage to the arm itself. The system had to be fixed on the spot and even though it managed to get the cube off the wall on all four trails, the arm was still in a fairly bad shape during the performance which led to plausible associated uncertainties and errors.

While the sensors were tested and proved to be functional, there are still instrumental errors associated with them and the lack of a decent IR covering coupled with this fact is a major reason why the second trial wasn't successful in obtaining the cube. The covering may also hinder the performance of the sensor instead of optimizing it, this happens when the robot goes over the bumps and due to the instability of channel, the slit and duct tape may actually block the sensor from receiving any signals at all and have the robot running blind through the arena.

Recommendations

Based on the results observed and recorded during the final showcase, the team generated a number of recommendations for future prototype iterations to maximize the efficiency of the robot. These include ideas pertaining to fixing flaws encountered by the robot in the arena, and also useful techniques observed from the other robots at the showcase that could be incorporated into our design.

The location of the MSEduino board should be relocated based on two reasons, it is currently located in a space where it is very difficult to access for troubleshooting the circuitry, and the cube retrieval arm tends to hit the wires when it is rotating, therefore risking the damage and entanglement of the wires.

The shovel slide is offset to the right in the current prototype and this causes an uneven application of force on the shovel when the pyramid comes into contact with it. It would therefore be better to have the slide be connected to the centre of the shovel as this would provide an even distribution of the load brought on by the pyramid.

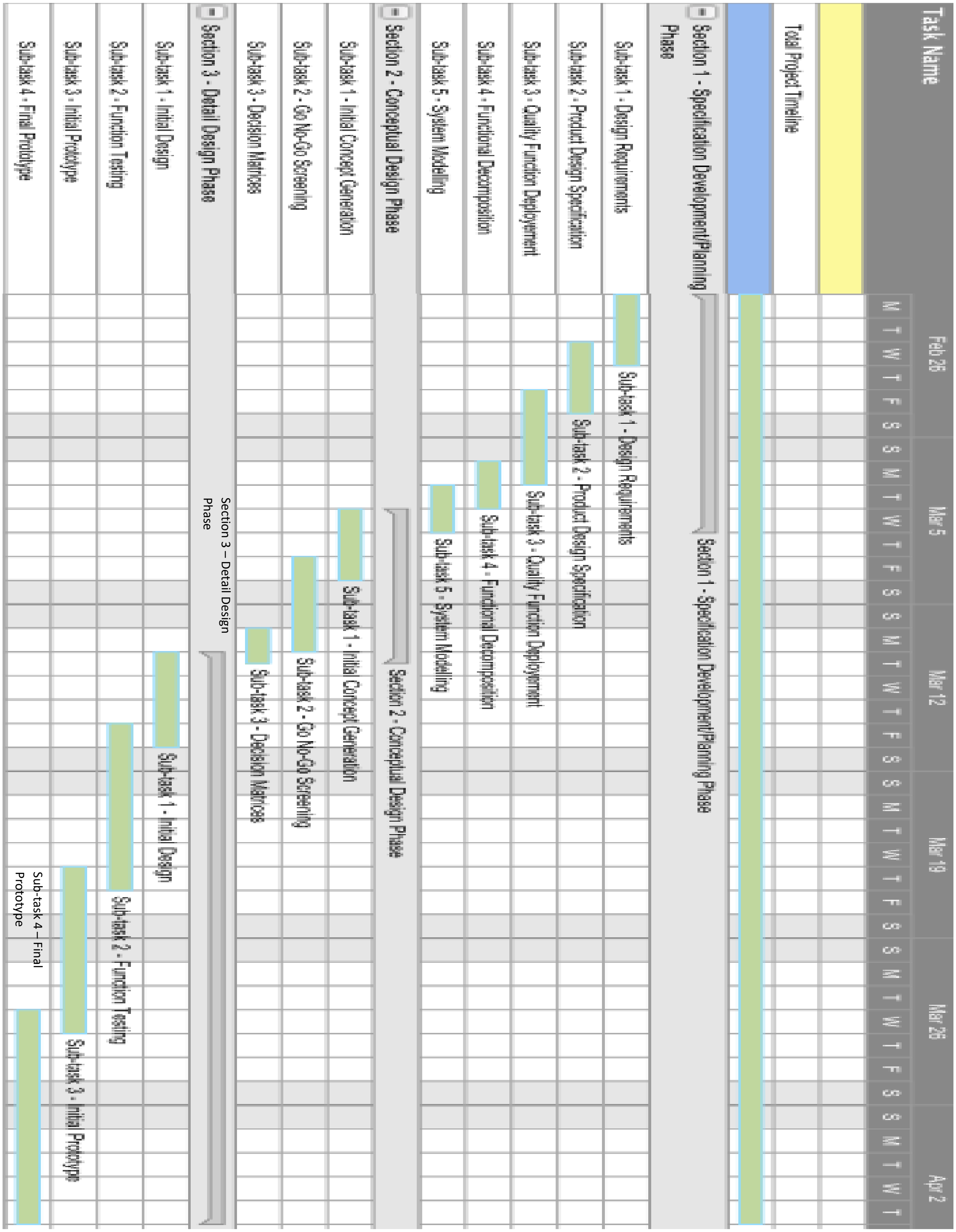
Instead of simply driving and relying on an object such as the arena walls to aid in picking up the pyramid, an assembly can be constructed that allows for a flange like structure to drop down from the top and scoop the pyramid into the shovel. This idea will also prevent failures in the functioning of the robot due to collisions with the arena walls and power conduits.

Stabilize the joint connecting the IR sensor to the IR covering so that the sensor is always perpendicular and able to receive the signals being emitted by the pyramid. Also have the cover incorporate the two vertical slits idea in order to maximize the functionality of the IR sensor

Lastly, instead of the idea of having the robot reverse over the cube and place it based on hard coding, there should either be a function or a sensor used to determine the location of the cube after it has been dropped off from the arm. A Hall Effect sensor that identifies the presence of the permanent magnet inside the cube would be an ideal candidate for this operation.

Overall this project looked at the essentials needed for iteration and its importance in the applications of engineering. If more time had been allotted for this project then the final outcome of the design would have been much greater with each iteration applied. Considering where the project ended, the next step could have made the design perform better in the next set of trials. Otherwise the team performed well collectively and stayed on track with the proposed Gantt chart.

Appendix A: Gantt Chart



Appendix B: GO- NO GO TABLES

Picking up cube:

Constraint(→) Concept (↓)	Optimal degrees of freedom	Minimum motors required	Complexity	Volume occupied	Power efficient	Feasibility	Overall
Hall effect sensor arm assembly	GO	NO GO	NO GO	GO	NO GO	NO GO	NO GO
Magnetic arm assembly	GO	GO	GO	GO	GO	GO	GO
L-shaped arm assembly	NO GO	NO GO	NO GO	NO GO	NO GO	NO GO	NO GO
Extendible claw arm assembly	NO GO	GO	GO	NO GO	GO	GO	GO
Vertical crane arm assembly	NO GO	NO GO	NO GO	GO	GO	NO GO	NO GO
Vacuum suction arm assembly	GO	GO	NO GO	GO	GO	NO GO	GO

Picking up pyramid:

Constraint (→) Concept (↓)	Optimal degrees of freedom	Weight	Complexity	Minimum motors required	Volume occupied	Power required	Feasibility	Handling precision	Overall
Rotating base/pick up	NO GO	GO	GO	NO GO	GO	NO GO	GO	GO	GO
Conveyer belt	GO	NO GO	NO GO	NO GO	NO GO	NO GO	GO	NO GO	NO GO
Shovel / Elevator	GO	GO	GO	GO	NO GO	GO	GO	NO GO	GO
Enclosing parallel claws	NO GO	NO GO	NO GO	NO GO	NO GO	GO	GO	GO	NO GO
Vacuum suction	GO	GO	NO GO	GO	NO GO	NO GO	NO GO	GO	GO
Overhead crane	NO GO	GO	NO GO	NO GO	GO	GO	NO GO	NO GO	NO GO

Drive System:

Constraint (→) Concept (↓)	Ability to go over bumps	Turning radius	Min number of motors	Stability	Minimum Volume consumed	Overall
Tracks	GO	GO	GO	GO	NO GO	GO
4 powered wheels	GO	GO	NO GO	GO	NO GO	GO
2 powered wheels + coasters	NO GO	GO	GO	NO GO	GO	GO
3 powered wheels	GO	NO GO	NO GO	GO	NO GO	NO GO

Appendix C: Decision Matrices

Cube Retrieval:

										Magnetic Arm	Extendible Claw	Vacuum Suction
	Degrees of freedom	Mass	Complexity	Number of motors	Power	Feasibility	Precision	Total	Weight			Datum
Degrees of freedom	1	3	0.2	5	3	0.14	5	17.34	0.154	1	0	0
Mass	0.33	1	0.2	0.2	0.33	0.14	0.2	2.4	0.021	0	0	0
Complexity	5	5	1	5	5	0.33	5	26.33	0.233	1	1	0
Number of motors	0.2	5	0.2	1	0.33	0.14	0.2	7.07	0.063	1	0	0
Power	0.33	3	0.2	3	1	0.14	0.2	7.87	0.07	1	1	0
Feasibility	7	7	3	7	7	1	3	35	0.31	1	1	0
Precision	0.2	5	0.2	5	5	0.33	1	16.73	0.15	0	1	0
Total								112.74	1	0.83	0.763	0

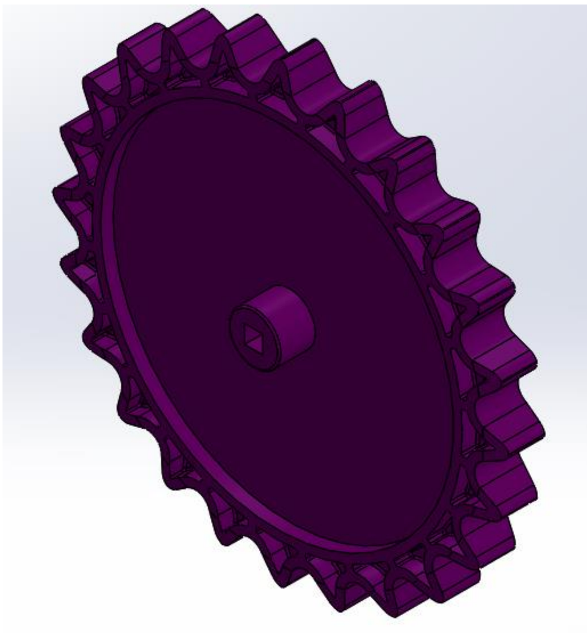
Pyramid Retrieval:

										Rotating Base	Shovel Elevator	Vacuum Suction
	Degrees of freedom	Mass	Complexity	Number of motors	Power	Feasibility	Precision	Total	Weight			Datum
Degrees of freedom	1	3	0.2	5	3	0.14	5	17.34	0.154	0	0	0
Mass	0.33	1	0.2	0.2	0.33	0.14	0.2	2.4	0.021	1	-1	0
Complexity	5	5	1	5	5	0.33	5	26.33	0.233	1	1	0
Number of motors	0.2	5	0.2	1	0.33	0.14	0.2	7.07	0.063	0	0	0
Power	0.33	3	0.2	3	1	0.14	0.2	7.87	0.07	1	1	0
Feasibility	7	7	3	7	7	1	3	35	0.31	1	1	0
Precision	0.2	5	0.2	5	5	0.33	1	16.73	0.15	0	1	0
Total								112.74	1	0.634	0.742	0

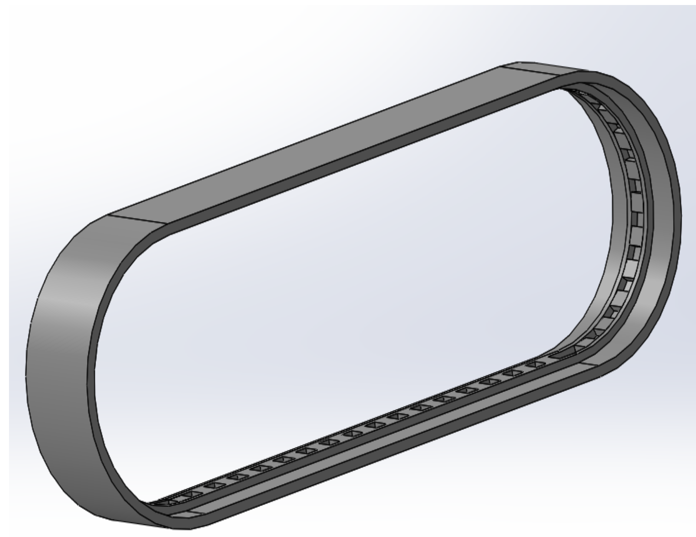
Drive System:

								Tank Tracks	Four Wheel Drive	Two Wheel Drive
	Clear bumps	Turning radius	Number of motors	Stability	Volume occupied	Total	Weight		Datum	
Clear bumps	1	5	7	0.2	7	20.2	0.346	1	0	0
Turning radius	0.2	1	5	0.2	5	11.4	0.193	1	0	1
Number of motors	0.14	0.2	1	0.2	3	4.54	0.077	1	0	1
Stability	5	5	5	1	0.2	16.2	0.274	0	0	-1
Volume occupied	0.14	0.2	0.33	5	1	6.67	0.113	-1	0	1
Total						59.01	1	0.503	0	0.109

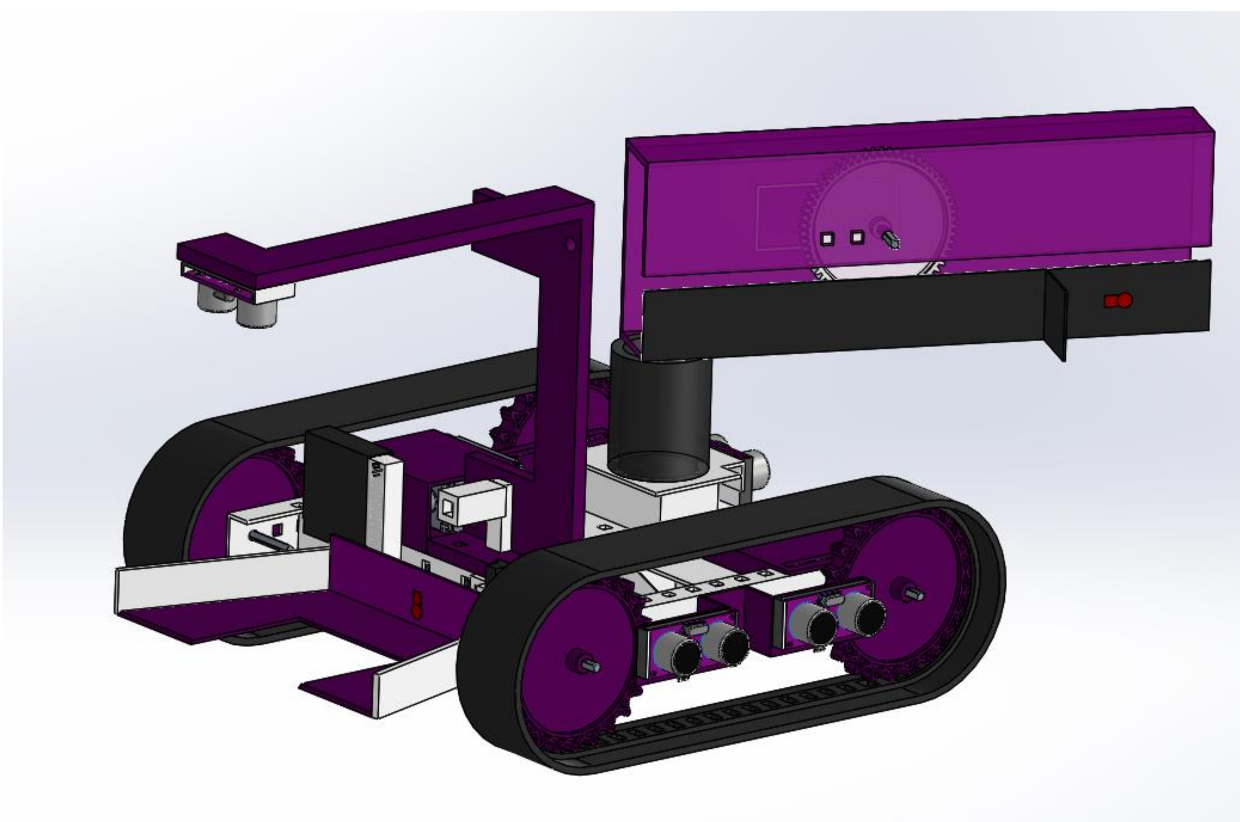
Appendix D: Sample CAD Usage



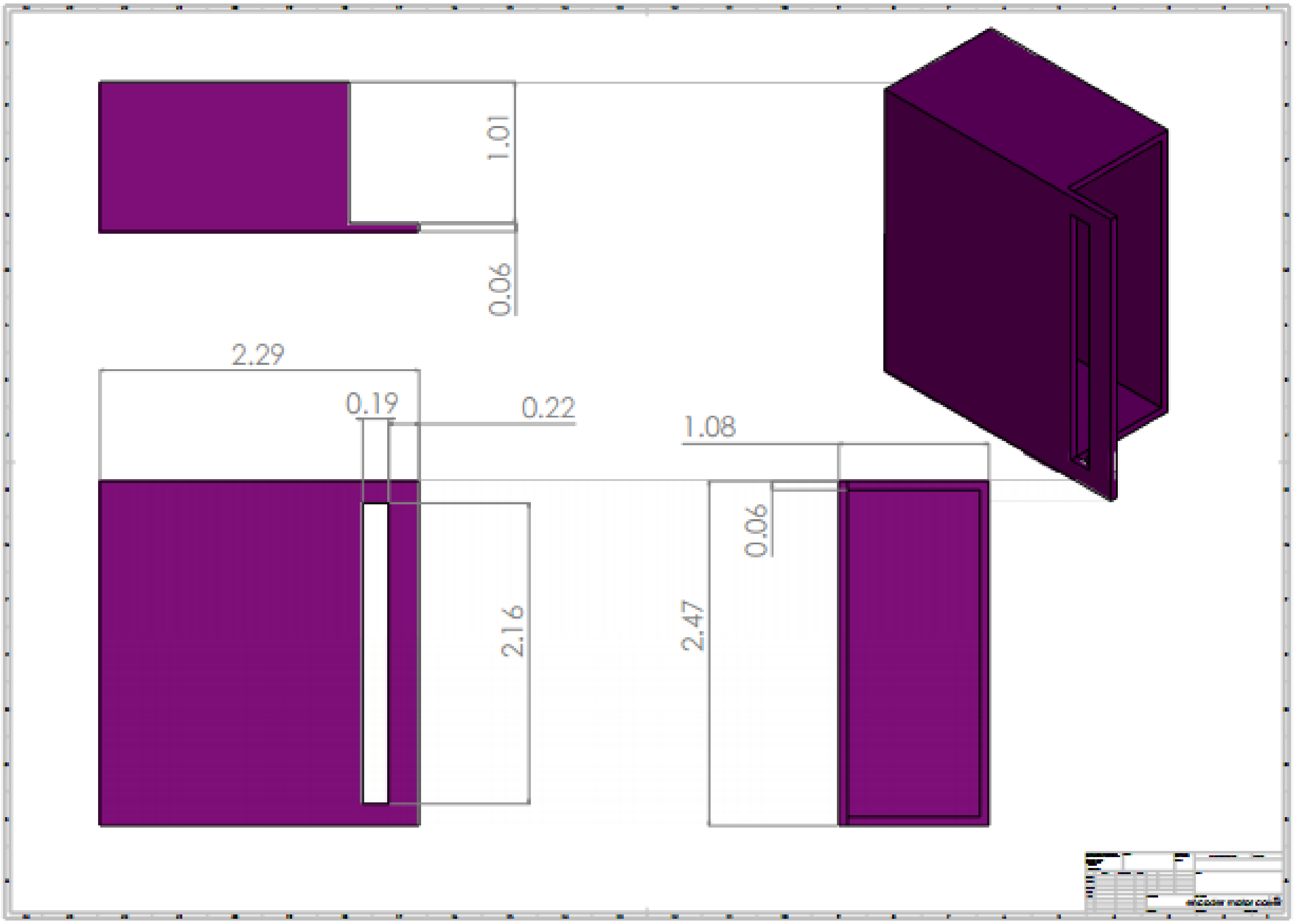
Sprocket used in tank treads



Tank tread assembly

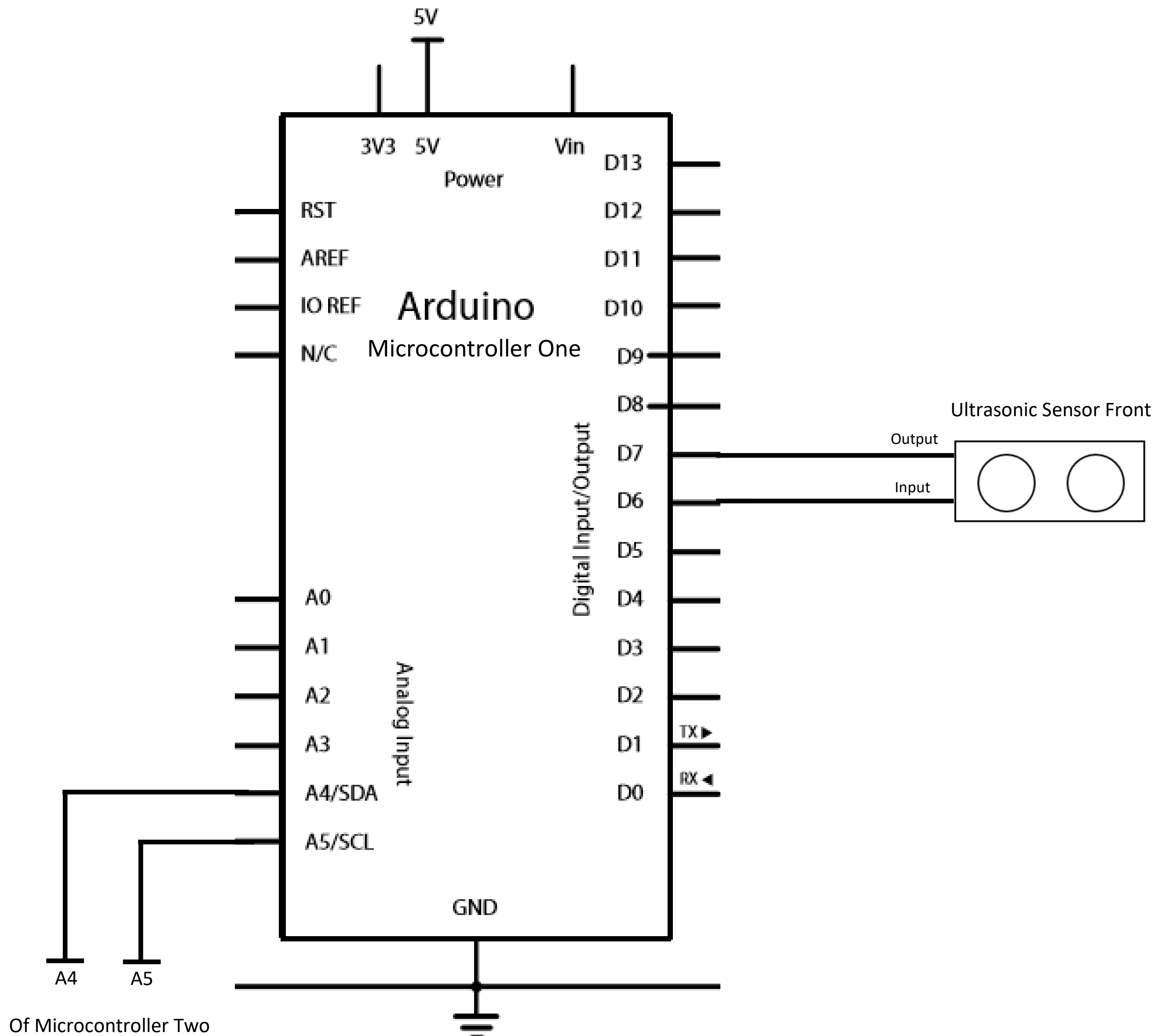


Final robot assembly

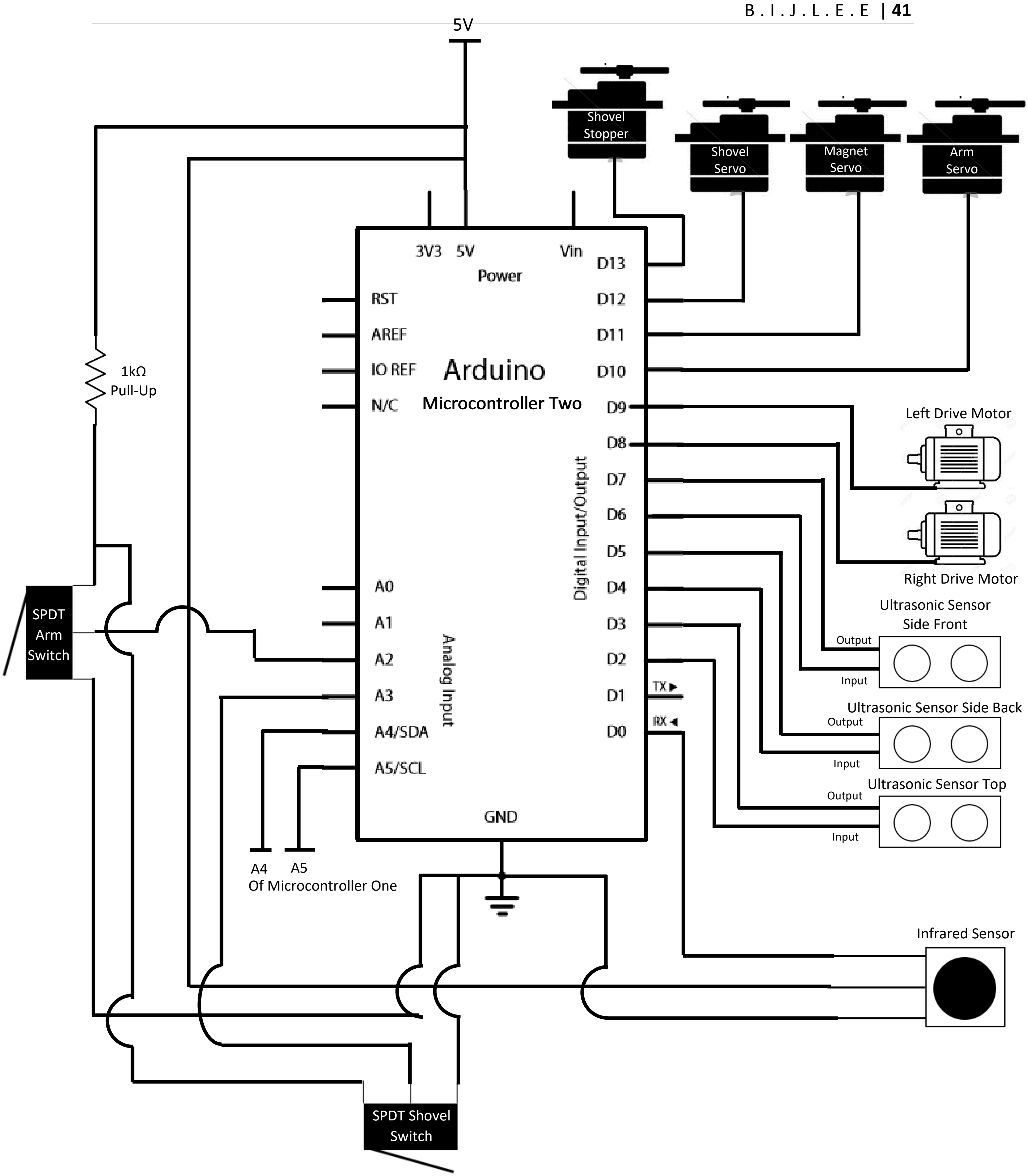


Drawing created for a part in Solidworks

Appendix E: MSEduino Circuit Pinouts

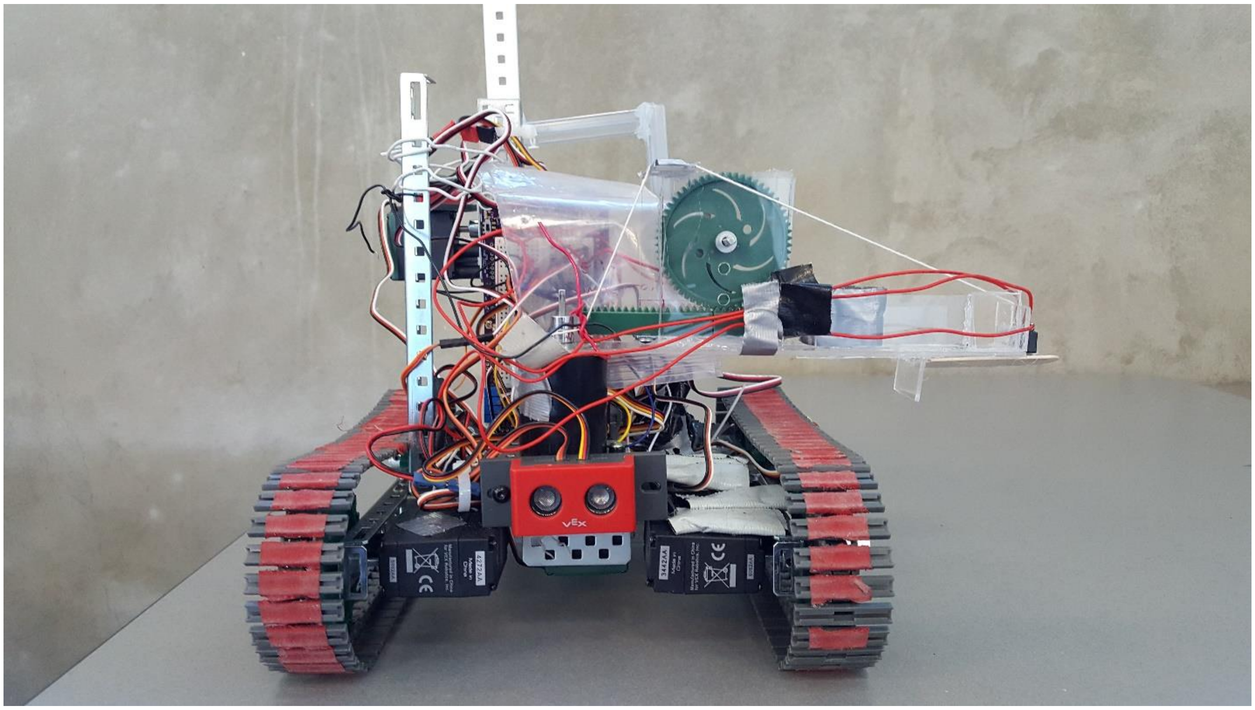


Circuit Diagram for the Second Microcontroller of the Arduino

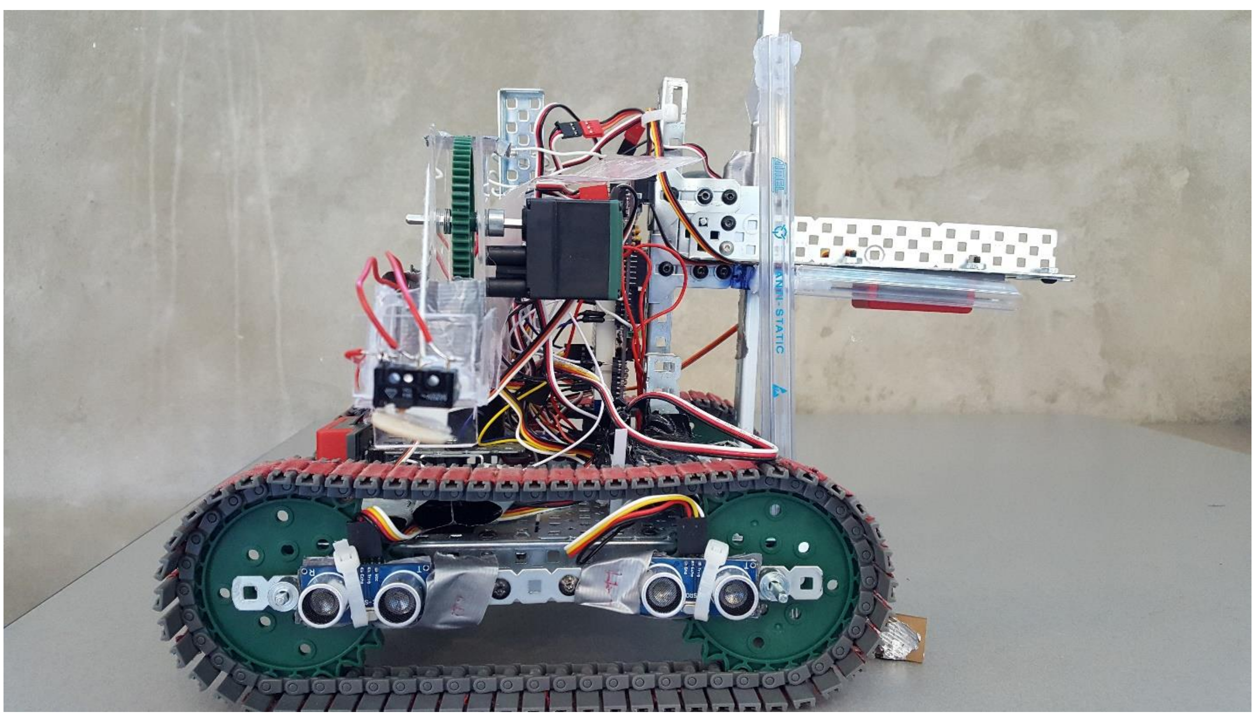


Circuit Diagram for the Second Microcontroller of the Arduino

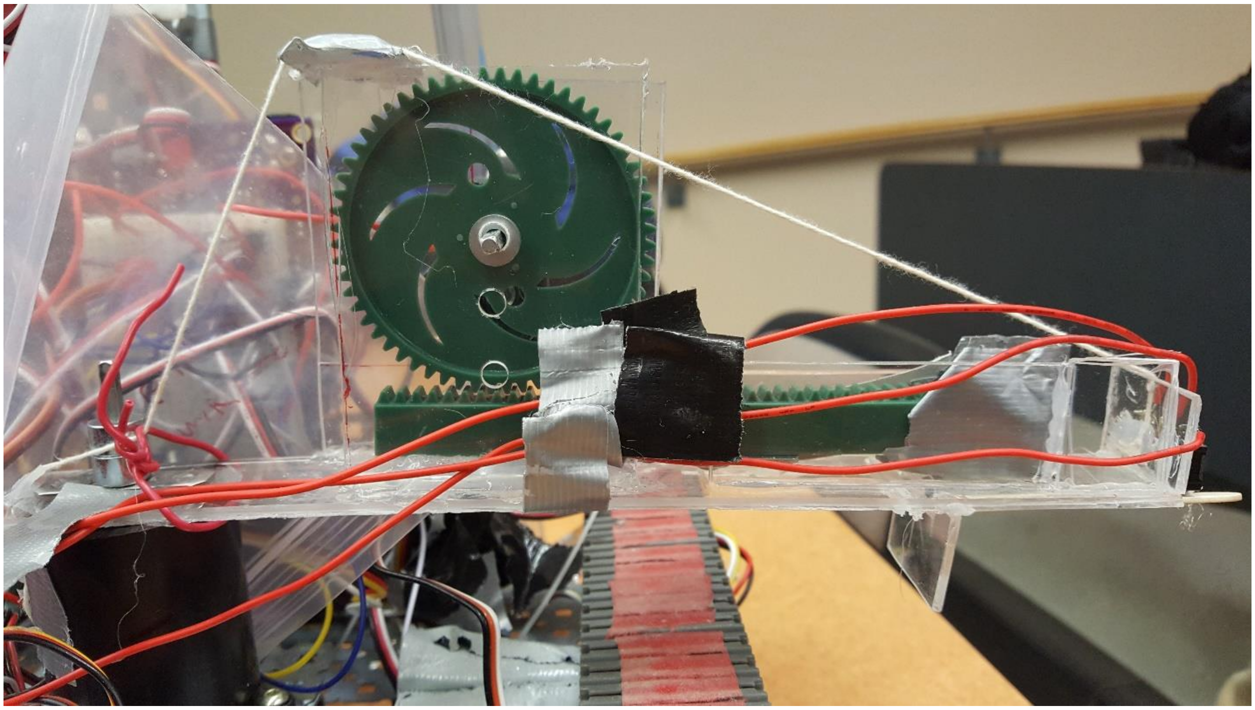
Appendix F: Final Prototype Design



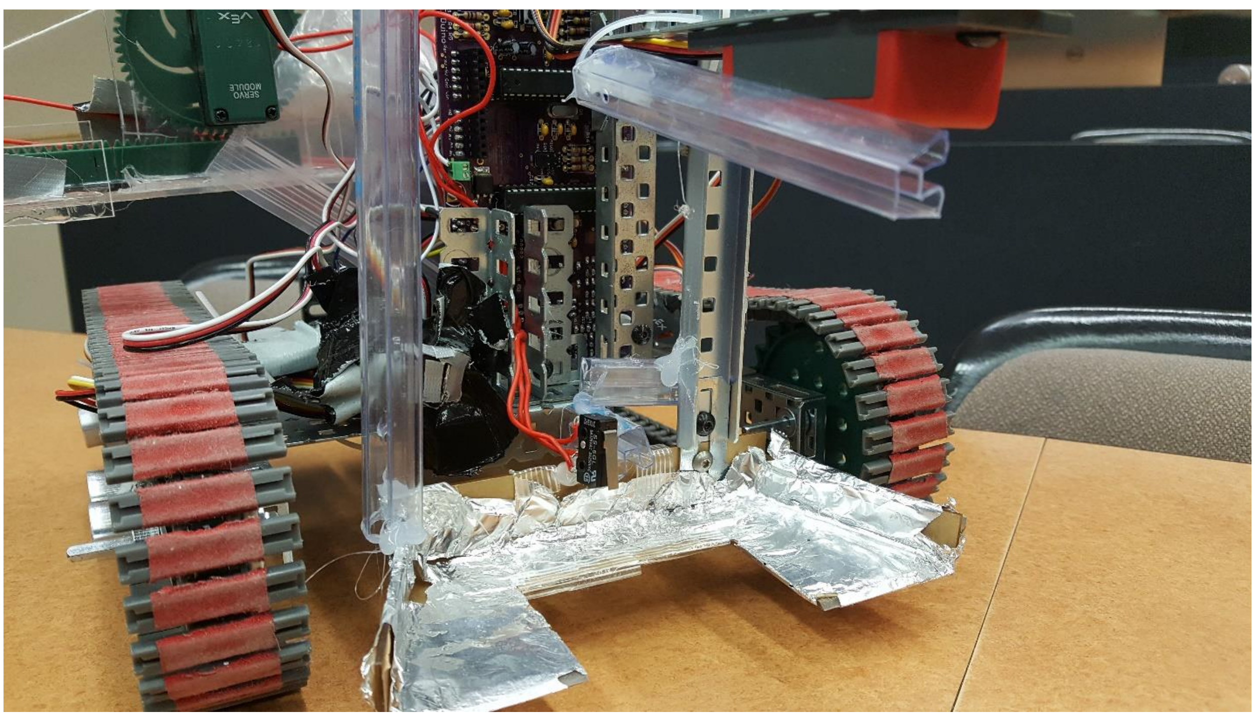
Rear view of the final prototype



Right view which shows the ultrasonic sensors in between the treads



Cube retrieval piston arm assembly with the stopper at the bottom face



Pyramid retrieval assembly featuring the shovel and lift