CARBON LAMINATE APPLICATION ROBOT

By

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With Honors in

Mechanical Engineering

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Approved by:

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STATEMENT OF ROLES AND RESPONSIBILITIES

The following is a group project conducted for the interdisciplinary engineering design program at the University of Arizona. This project was conducted with four group members including myself. The members included: Sajan Bhakta, a materials engineer, Corey Stedwell, a computer engineer, Jonathan Dufek, a mechanical engineer and myself, a mechanical engineer. In this project I was responsible for all design modeling, finite element analysis, part selection, and final testing once the project was assembled. I was in charge of delegating machining and assembly tasks to other group members and determining all machining and assembly process techniques necessary for this project. I also did a large quantity of the machining and assembly for this project and all breadboarding and printed circuit board design for the electronics. Every group member took part in the initial brainstorming and concept design for this project. Sajan Bhakta acted as group leader responsible for setting timelines for the project, coordinating schedules and meetings between group members and communicating with our sponsor. He also put in the most time of the three other group members on machining and assembling the robot. Corey Stedwell helped with some assembly of the robot and worked on software development. Jonathan Dufek helped with machining and assembly of the robot. We all worked together in producing the final written report with the majority of the technical descriptions written by myself.

Carbon Laminate Application Robot

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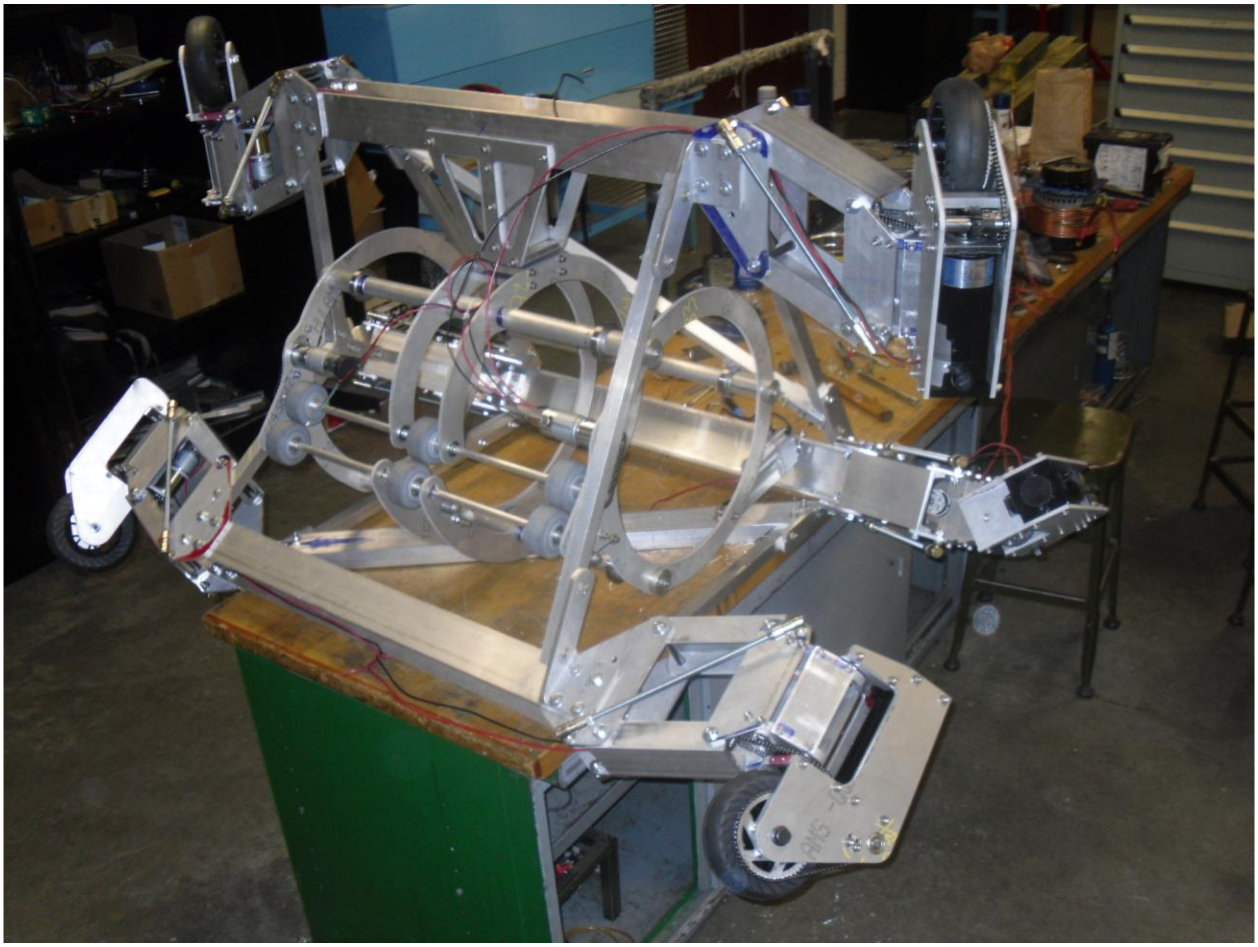

ABSTRACT: *This report details the design, development, and implementation of a robotic system for applying Carbon Laminate Reinforcement to the inside of large diameter pipes. The design was undertaken to replace the time and labor intensive method of applying this reinforcement by hand, so that these structural reinforcements can be applied to all pipes in need of retrofit. The process of designing and building a robot to meet this goal was taken in increments, with care taken to ensure each of the developed parts functioned with all others. The outcome of this effort yielded a fully assembled robot with all of the basic functionality needed to apply Carbon Laminate Reinforcement to a pipe wall.*

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1. Introduction to problem

The customer contracting our services is QuakeWrap, a company focused on providing repair services of structures and pipes using Carbon Fiber Reinforced Polymer (CFRP). One CFRP application is the strengthening of large diameter Pre-stressed Concrete Cylinder Pipe (PCCP) with carbon fabric. PCCPs ranging from 3-12 feet are frequently used in water and sewer networks throughout the world. Hand laying carbon fabric inside PCCPs becomes a labor and time intensive process when considering the large pipe lengths which are commonly used. Large projects, where thousands of feet of pipe need to be quickly reinforced, become impossible with the current methods. A new kind of carbon laminate was developed and recently patented to overcome this obstacle. This new system is a carbon fiber which is pre-infused with epoxy and hardened at the factory. This rigid laminate is then rolled up for transport. Due to its rigidity, it will attempt to unwind and return to its flat state. The self-straightening and pre-hardened properties of the material can be harnessed to increase installation speeds dramatically. This can be accomplished by using the self-straitening nature of the laminate to force itself against the contours of the pipe.

Our group has been contracted for the design and implementation of a robotic system to install the new carbon laminate. This robot will increase the company's efficiency and market share within the industry by allowing for faster and cheaper installation of carbon laminate within PCCPs. Reductions in installation cost will be achieved by the small number of workers needed to operate the new system. In some cases as little as one worker is needed on site. This robot will also provide a substantial decrease in the per foot installation time. Large profit increases, and larger job sizes, become possible when fewer workers install substantially more reinforcing in less time.

The customer requested a working prototype that applies carbon laminate in a spiral manner while controlling overlap. The prototype will also need to apply epoxy on the back of carbon laminate to help adhere to the inside walls of the pipe and between layers of laminate. The overlap is necessary to create a shingle effect so liquid does not penetrate the barrier between the pipe and laminate. The carbon laminate will provide hoop stress reinforcement within a pipe, which will protect against further deterioration of the pipe walls and potential rupture.

2. System Requirements

The robot's top level functional requirements are: the application of laminate in a spiral manner, controlling overlap and applying epoxy. When comparing to Quake Wrap's current method of hand application using woven carbon fiber and epoxy within PCCPs, it is possible to determine the House of Quality (Appendix A), and the Target values and Tolerances needed to evaluate the functional requirements significance. The application speed of laminate and epoxy shall be greater than 300 square feet per man hour. The epoxy shall be applied no thinner than forty mil to the back side of the laminate. The thickness of epoxy is subjected to increase depending on the type of epoxy used for the application and method of installation. The laminate overlap for a specific job will be determined by engineers working on the project. The amount of overlap control needed between conjoining laminate sheets will vary from two inches to the full width of the roll. This will allow the customer to use spiral or loops application of the laminate depending on the strength need for the job. The robot needs to be constructed so it can be easily assembled and disassembled within the large diameter pipes by one or two operators in less than two hours. Each component of the robot needs to fit through an access point or manhole with a minimum diameter of twenty inches. The steps leading down the shaft must be accounted for, and their protrusion from the wall will be no greater than six to twelve inches. The laminate dimensions, when rolled up, shall be no smaller than twelve inched in diameter, with a roll weight of fifty pounds, so one operator is capable of resupplying the robot within the pipe. Spring loaded roller will push the laminate against the wall of the pipe to insure adhesion between the pipe wall, epoxy and laminate; no more than five psi should be needed. The maximum allowable force the robot can apply to the wall of the pipe is 100psi. A six point support structure was developed to distribute the weight of the robot over six different locations on the pipe to help protect the pipe from damage. A modular system approach was taken to create a more efficient design that meets all the customer requirements.

3. Design Concepts

Due to the complexity of the project, a compromise was made in defining conceptual designs that would be pursued in the next phase of development. This adjustment allowed for the modification of one of the largest components of the design, which would have a far-reaching effect on the remainder of the design. This allowed for drastically different design choices, without creating the enormous overhead of developing three separate designs, each extremely complex in its own right.

Each of the designs have similarities in comparison to each other, and each design has its own merits and flaws. Similarities in the designs include electrical power being delivered from the surface through an umbilical power cable. The laminate, when applied, should be in lengths as long as possible, to preserve its reinforcing structure. The robot would not be fully automated, but would be allowed at least one worker to control and maintain performance.

3.a - Concept 1: Segmented Rotational Robot

The first concept design was to have a large robot which would span the inside diameter of the pipe. In order to deliver a continuous roll of laminate, it would have a rotating portion which would spin as the robot advanced. This design allows for a stable platform to keep anything that might be needed during the application, and special precautions would not be needed if extra systems were to be added to the robot. Further, it would allow for storage of the epoxy that is needed to apply the laminate, without devising a suitable container for something that is to be rotating. The weight of the drive system would be distributed on the non-rotational segment, allowing the rotating segment to be lighter and not as strongly reinforced.

This design has one major drawback, and it is that any joint between the rotating segment and the non-rotating segment would have to be perfectly rotating, and the two segments would have to be clear of any connections not specifically designed to rotate. In effect, this means the rotating portion would either be unpowered, battery powered, or powered through a special rotating power-coupling.

3.b - Concept 2: Electrically Powered Fully Rotational Robot

The second concept design was similar to the first, except it would have no stationary segment. Removing the problematic joint between the stationary and rotating segments from the design simplified the future development greatly. As the entire robot would spin, however, a new set of challenges was introduced, including balancing the weight of electrical drive motors, and balancing the load on the wheels so as not to stress any leg too greatly at any one time.

3.c - Concept 3: Hydraulically Powered Fully Rotational Robot

The final concept was conceived as an effort to simplify the design of the fully rotating electrically driven robot. By using a hydraulically powered system, the weight of the motors required to drive the wheels would be greatly reduced. This would reduce the peak weight exerted on the legs and wheels which would be applied as the robot rotated. Drawbacks of this design included the high cost of hydraulic systems, as well as the relative inexperience with hydraulic systems of the design team and customer.

4. Robot Design

Applying laminate in a continual spiral was determined to be the most efficient method for reaching all surfaces inside the pipe. A robotic system that is fully rotational was found to be the best solution for applying laminate in this manner. This design was also chosen due the necessity to avoid a complex joint between rotating and non-rotating sections. This robot consists of subsystems that will now be discussed. The current robot structure located inside and outside of a pipe is seen in Figure 1.

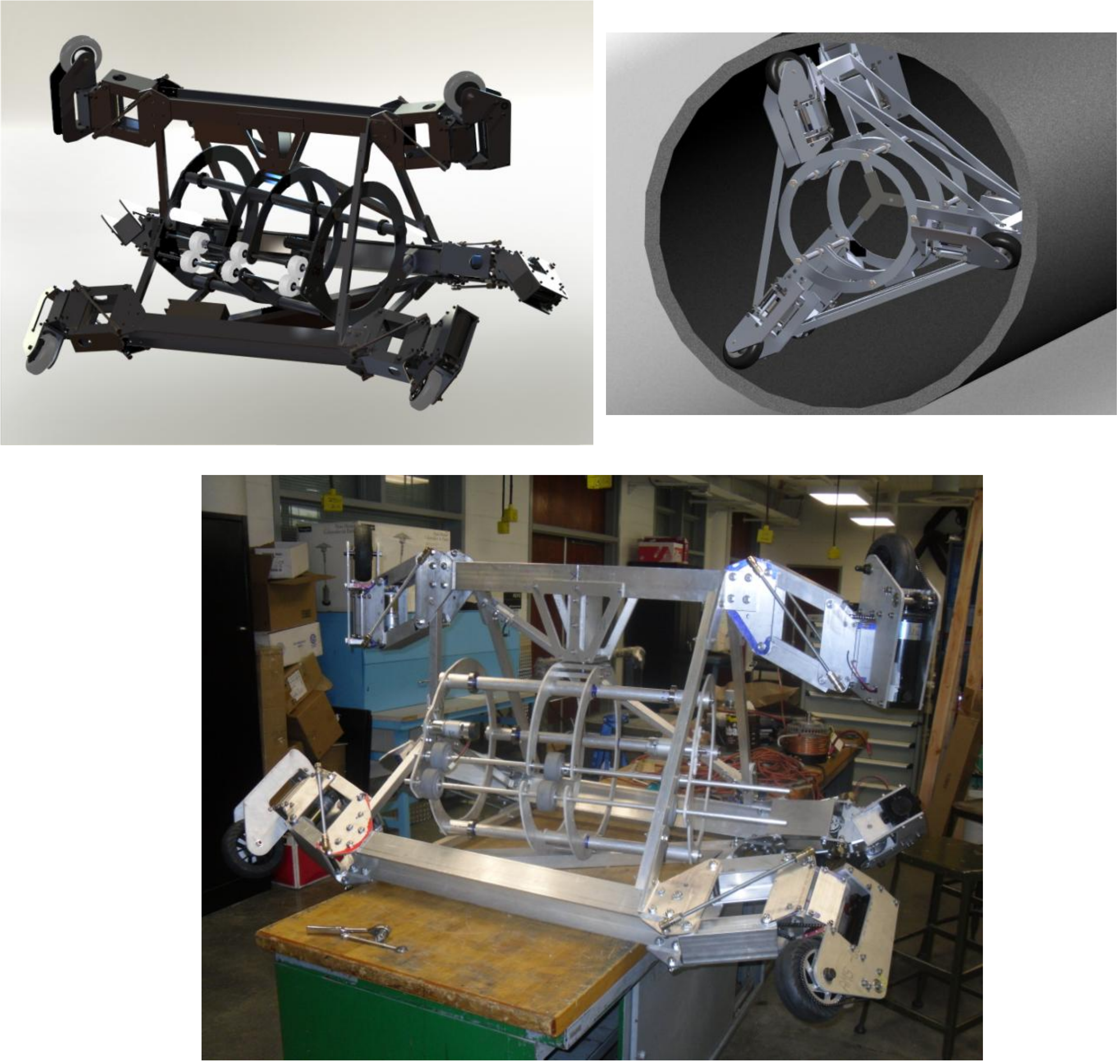


Figure 1. Robot structure.

The most prominent system of the robot is the support structure which holds all other systems in place. This system consists of aluminum tubing assembled in the shape of a triangular prism. This shape is the most resistant to the forces which will be applied to the robot while operational. The structure of the robot must be disassembled, moved through a 20 inch diameter pipe, and reassembled. The prism shape is simple to disassemble and reassemble. The prism shape also leaves the center of the robot hollow so that the other systems required on the robot have room to be installed. This space is primarily used for the laminate feed, storage, and installation system.

The laminate feeding system serves to unravel the wound roll of laminate, to feed it at the desired rate, and apply epoxy to the back of the laminate before it is applied to the pipe wall. The most basic of functions, keeping the roll of laminate from unspooling during transport is achieved through housing the roll in a circular cage. When laminate is required to be unrolled, it is kept at a controlled unspooling rate by rubber grip wheels which advance at the speed required. The epoxy is pumped from a reservoir which contains pre-mixed epoxy through the use of a peristaltic pump, a special pump which minimizes contact with epoxy, as will be described later. This epoxy is then applied to the laminate through distribution rollers, which ensure an even and uniform application. The final structural component of the laminate distribution system is the pressure applying arm which extends from the robot and pushes the prepared laminate against the pipe walls, creating a secure bond.

The robot advances through the pipe by means of its three drive wheels. The robot has six points of contact with the wall of the pipe, and the front three wheels are powered through electric DC motors to provide the robot's forward movement. Given that only the front three wheels have a secure footing, they are the ones chosen to act as the drive wheels, and each was given its own motor. To make the robot spin, a series of secondary motors were put onto all six wheels, which will control the angle of the wheel. Based on the angle of the wheel, the robot will automatically spin as it advances, creating the desired motion discussed earlier. Running these motors creates a fairly large power requirement, one which can be met by a generator running on the surface. Power can be delivered in either 110V or 220V through a power tether which runs to the generator. The robot will be controlled through the use of LabVIEW on a wirelessly linked handheld computer that will interface with an in/out box located on the robot. The in/out box will then communicate with the robots peripherals.

4.a Structure

The robot's structure is made primarily out of T6-6061 aluminum. This material was chosen for several reasons. The biggest reason is because of it has the best price to strength ratio. Another reason is because it is readily available and can be easily processed and machined.   Lastly it was chosen because of its light weight.

The architecture of the robot's structure is specially designed to have a center of gravity concentric to the pipe. This structure must rotatable so it can act as a platform from which laminate can be applied. It is designed with the concept equal weight applied to each support beam, so the weight is evenly distributed across the structure. This is an important concern to prevent lurching of the robot, which would cause uneven application of the laminate, perhaps even stressing, cracking, or breaking the laminate as it is being applied.

In order achieve the balanced center of gravity the main structure is an equilateral triangular prism made up of aluminum I-beams, square tubing and channel. This equilateral triangular prism combined with cross-bracing yields a rigid structure. The prism shape also provides the minimum amount of contact points to apply carbon laminate concentric with the pipe.

4.a.i Disassembly

The robot is able to be disassembled, as every connection between aluminum parts is secured with 3/8”-16 hex bolts or 1/4”-20 stainless steel caps screws. Due to this, the robot can be disassembled in a number of ways to fit through as small an opening as a twenty inch manhole. While time consuming, this ensures maximum flexibility for the prototype system. In the future, different securing mechanisms can be used on frequently unbolted sections, allowing for faster disassembly.

4.b Propulsion

The propulsion sub-assembly provides all forward and rotational motion for the robot structure. All three front wheels make up this system. Only front wheel drive is possible because the back three wheels will be running on the freshly applied laminate, which will slip out of alignment if much force is applied. The front wheels consists of three independent drive trains all powered by separate direct current motors. These motors will be provided by Leeson. Their continuous duty rating is one-third horsepower while operating off of twenty-four volts direct current. Larger individual horse power ratings were needed to provide the needed torque in order to rotate the robot structure. They were also needed because of the changing drive potentials as the robot rotates. This occurs as a result of the robot’s shape and its need to spin within the pipe. As the assembly rotates different sets of wheels support the robot’s weight and therefore affect how much torque the wheels can deliver to the pipe wall. Not all wheels can deliver their full torque all the time so the wheels currently at the bottom of the pipe, as the robot rotates, need to make up for the lack of torque that the rest of the wheels cannot deliver, resulting in larger motor sizes. The motors have twelve pitch worm gears attached to their output shafts that drive corresponding eighteen tooth spur gears. Mounted on the same shaft as the spur gears are size number twenty five, drive sprockets with nineteen teeth. The drive sprockets are attached to corresponding fifty six tooth sprockets mounted to the robot’s wheels using steel roller chains. The completed assembly of one wheel can be seen in Figure 2.

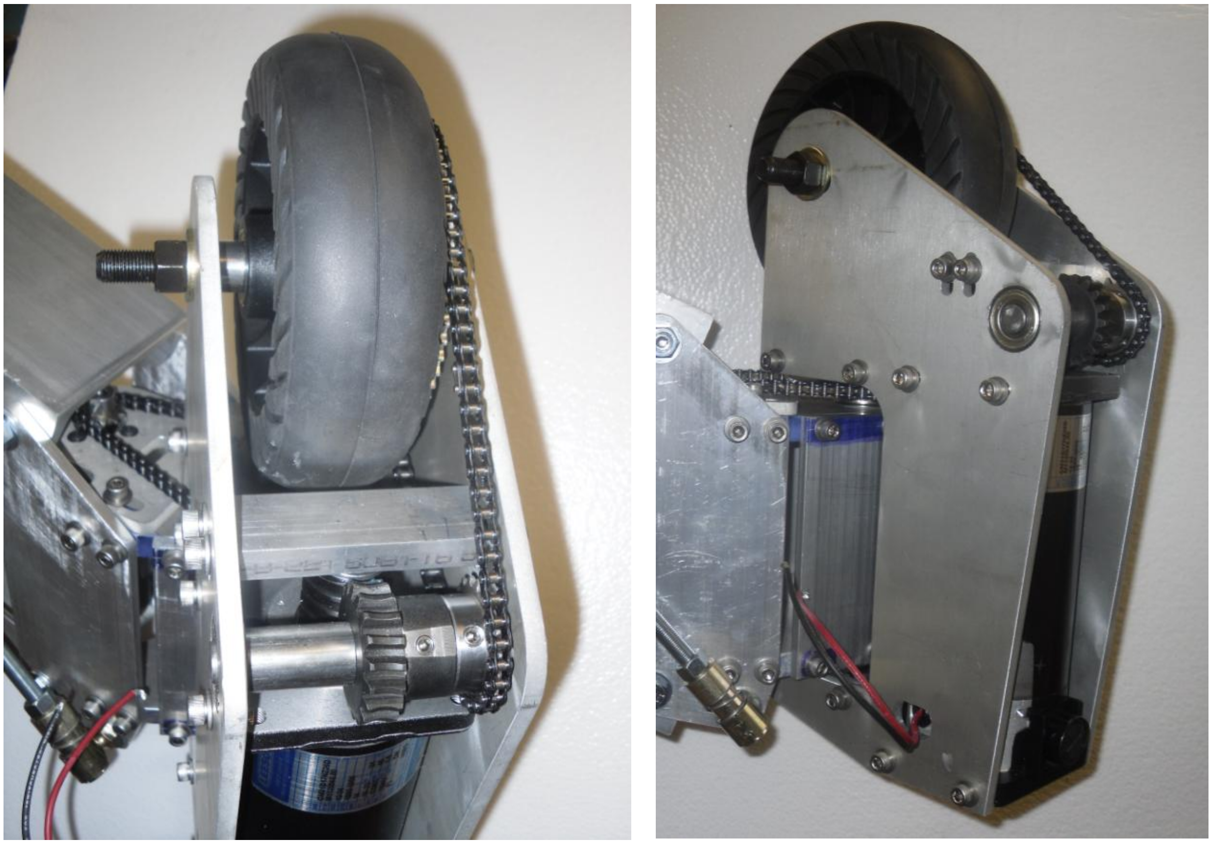


Figure 2. Robot propulsion wheel assembly.

The gearing setup described will provide each wheel with a fifty-three to one gear ratio and will spin the wheel at seventy-four revolutions per minute. With the continuous rated one-third horsepower motors, each wheel will deliver forty-seven pounds of tangential force to the pipe wall. The combined force off all three wheels is expected to meet any demands placed on the robotic system. The gear train is mounted onto a one-half inch hardened tool steel shaft that runs in two radial flange bearings. These bearings are inserted into the conjoining aluminum walls. The walls are made of one-fourth inch T6 -6061 aluminum sheet. Also attached to the walls is the drive motor. All attachment in the drive assembly uses 1/4”-20 socket cap screws that are threaded into the motor or aluminum cross supports. The wheel is mounted to the aluminum walls through the use of five-sixteenth inch hex bolts that has a steel tube mounted around the bolt. The wheels chosen are originally intended as replacement parts for GoPeds. These wheels are cheap, designed to take the large loads presented by a human rider and easily implemented into our robotic system, because the same mounting and drive train can be used. Thrust bearing were placed on the top and bottom of the worm gear to reduce the frictional load on the drive motor caused by the worm gear.

4.c Steering

A sub-assembly is now needed to control the direction of the force applied to the pipe walls by the wheels. This is accomplished by steering all six wheels independently of each other. Steering all six wheels allows for precise control of the rotational angle through the pipe. This is necessary to maintain constant laminate overlap and also to prevent any wrinkles in the applied laminate. Each wheel can be steered through a complete one hundred and eighty degree turn by having the steering motors located within the wheel structure. The motors chosen are high gear ratio, low current, twenty-four volt, direct current motors. Unlike the drive motors, the stall torque of these motors is of more interest because they will not be in continuous operation, only being used when turning the wheels to change the angle of the robot. These motors can provide a stall torque of seven hundred ounce-inches. Attached to the motor is a size number twenty five sprocket, with nine teeth that drives its corresponding forty tooth sprocket. The larger sprocket not only is mounted to a half inch hardened steel shaft that the wheel assembly rotates on, but is also bolted through the flange of the sprocket into the aluminum support structure of the wheel. This is necessary to transfer the large torque from the sprocket to the steerable wheel assembly. The maximum achievable torque using this set up is sixteen foot-pounds which corresponds to two hundred pounds of shear that the bolts and shaft must support. A rendering of one steering system can be seen in Figure 3, and the exploded view of the same assembly in Figure 4.

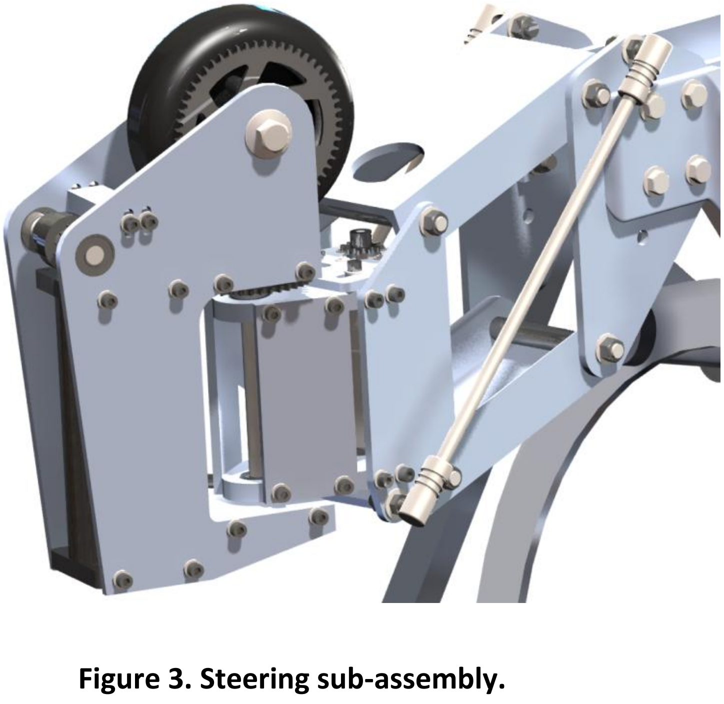


Figure 3. Steering sub-assembly.

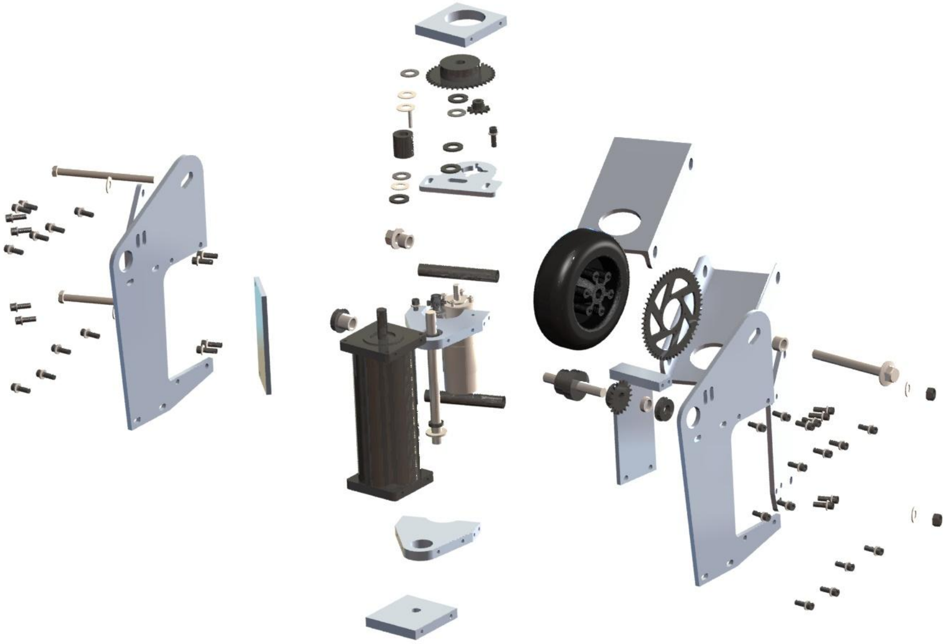


Figure 4. Exploded view, steering sub-assembly.

Another aspect of this assembly is the bearings needed to prevent excess friction and wear on the aluminum parts while under operation. These bearings are mounted on or around the steel support shaft for the wheel assembly. Going down from the top plate directly under the wheel, one encounters the thrust bearing. This bearing transfers the majority of the load presented by the robot to the moving wheel assembly. Needle thrust bearings are chosen because of their larger contact areas which correspond to larger dynamic load handling over ball thrust bearings. Beneath the thrust bearings are two radial bearings located around the shaft. These bearings are placed four inches apart to allow for easy transfer of the twisting forces presented by the drive wheels to the main frame of the robot. The bearings are installed around a steel shaft which is located in alignment with the point at which the wheel makes contact with the pipe wall. This orientation is essential to keep the angle of the wheels and forward motion of the robot decoupled. If this alignment is not met, changing the wheel angles would change the wall contact point, with respect to the structure of the robot, therefore changing the position of the robot within the pipe when only the wheel angle needed to be changed.

4.d Control & Electrical

The planned control and electrical subsystems should be implemented in the future and will consist of power conditioning, distribution, signal processing and a user control interface. Power for the robot will originate on the surface in the form of two hundred and twenty volt, single phase, alternating current. The power on the surface will be provided by a gas generator that will be sized to meet the demands of the robot. The larger voltage was chosen due to the long power cord lengths necessary to connect the robot to the surface. With a larger voltage less current is needed to transfer the same amount of power, so less voltage drop occurs over a given length of cord, or a smaller and lighter cord can be used. Once the power reaches the robot it will make the transition to the rotating robot through a slip ring, a device that allows the transfer of power between rotating and non-rotating positions. The power will then be transferred through a circuit breaker, a failsafe contact relay, and finally will arrive at the three power supplies mounted on each of the main support tubes. The failsafe relay is necessary to provide complete system shut down in case a fault occurs within the system or radio communication is lost to the wireless control board. After the relay three high efficiency 24 volt, 600 watt, switching power supplies will be implemented. These power supplies are light weight, easy to install and offer a good array of power control benefits. This power is now delivered to the central control receiver and all the peripheral control boards.

All control processing is planned to take place on a ruggedized tablet computer running LabVIEW with a wireless radio frequency uplink to a multi channel breakout box on the robot. The breakout box will send pulse width modulated signals to the h-bridge motor control boards and receive feedback information from hall effect sensors mounted on the output shafts of the main drive motors. The box will also receive analog signals from feedback pots located on all the wheel angle drive systems and the linear actuator that controls the laminate cage angle. This information will be sent to LabVIEW where a proportional integral derivative control sequence will be implemented for each motor on the robot. Such a setup will allow for precise servo control of rotational speed and angle, both critical in the application of the laminate. This setup would also allow for easy loading of saved programs for specific pipe sizes and laminate overlaps while offering fast reprogramming for new applications.

The motor control h-bridge boards where designed off of a proven circuit used for large current direct motors seen in figure 5.

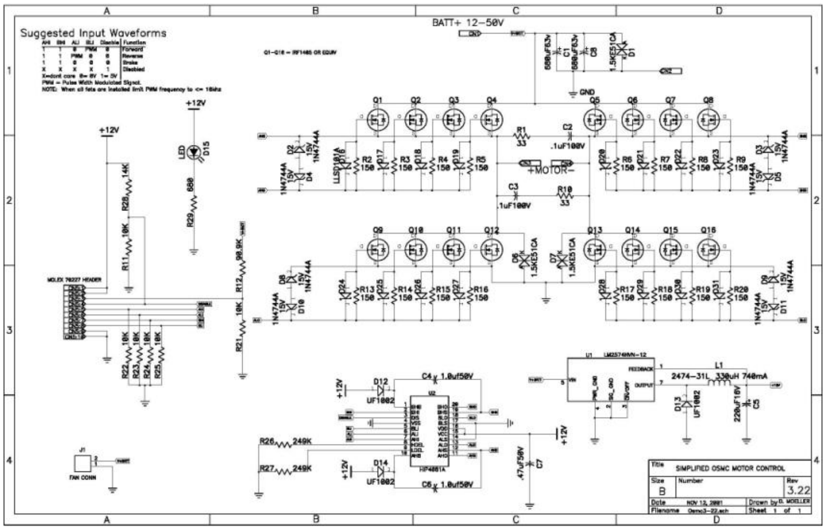


Figure 5. Open source h-bridge motor control circuit.

This circuit was breadboarded with our selected components and tested before the final printed circuit boards were manufactured seen in figure 6.

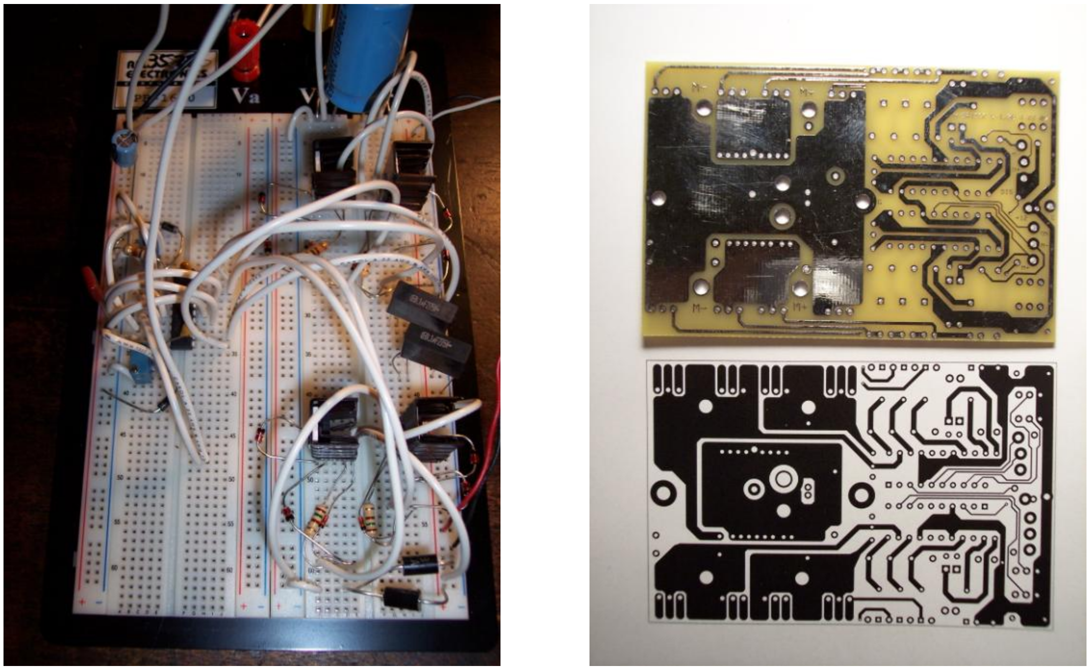


Figure 6. Bread boarded h-bridge circuit and final printed circuit board.

The decision was made to implement two complete h-bridges per board to decrease the number of boards needed to control twelve motors. The selected MOSFETs were International Rectifier's IRFB3206 which provide extremely low on resistance and more than enough current handling at 210 amps. These transistors can be directly heat sunk to the aluminum frame of the robot so the maximum power this circuit can switch is not limited by the transistors but instead by the amount of power our switching power supplies can provide and the amount of current our printed circuit boards can take before melting. The chosen MOSFET driver chips where the HIP4081 devices by Intersil. This IC was ideal for our application because it provided a simple interface between h-bridges consisting of N-channel MOSFETs and the small signals present at our control boards.

4.e Laminate Application

The robot is to unspool laminate as it rotates down the pipe. This is accomplished through power feed rollers which unspool the rolled carbon laminate in a controlled manor. These rollers also help force the laminate onto the pipe wall and keep the roll from suddenly unspooling. The cage dimensions limit the laminate roll width to two feet wide and the roll length as a function of the fifty pound roll weight the cage was designed for. The cage has the ability to be angled in order to accommodate a variety of application angles that depend on the pipe size and the needed overlap between rotations. After leaving the cage, the future epoxy system will apply a predetermined layer of adhesive the back side of the laminate. The carbon sheet is then guided to the wall where a pressure arm will apply force to the laminate, securing the laminate to the wall and keeping the material from slipping out of alignment.

4.e.i Laminate Cage

The laminate cage is a four ring support structure designed to contain and assist in the unspooling of the laminate sheets as the robot rotates (Figure 7).

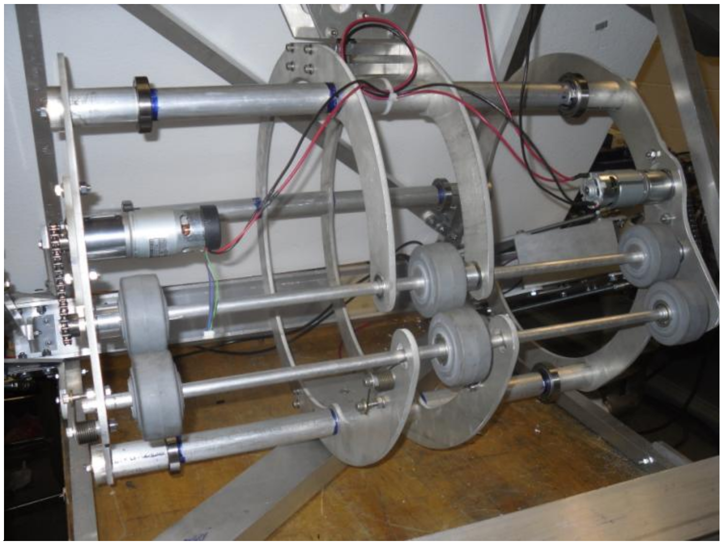


Figure 7. Laminate support cage.

The main support rings were water jet cut from 0.25 inch T6 6061 sheet aluminum and the cross braces were turned from 6061 aluminum tubing. The frame is held together using 1/4"-20 threaded rod placed in the center of the cross tubing. When a laminate roll is located in the center of the cage it spins on six large bearings located on the cross tubing. Thrust bearings are also located on the top and bottom of the cage to reduce friction between the main frame of the robot and the movable cage. Laminate is dispensed prom the cage between six rubber wheels that our held in contact with each other using torsion springs. The bottom three wheels can free spin on their 1/2" aluminum support rod that is linearly disposed within grooves so the wheels can adjust to varying widths of carbon laminate. The corresponding wheels are driven by to 24 volt DC gear motors located on either end of the cage. One of these gear motors has a rotation encoder built into the end of the motor so exact feed speed can be set. Both gear motors are coupled to the drive wheels using number 25 sprockets and roller chain. Also attached to the end of the cage is a 150 pound force linear actuator with build in feed-back resistor that is used to set the angle of the cage (Figure 8).

Figure 8. Linear actuator attached to laminate cage.

As previously mentioned this actuator sets the angle at which the laminate is dispensed from the robot. This is important in setting up the robot for the diameter of pipe it will be operating within and the amount of needed overlap between each sheet.

4.e.ii Pressure Arm

The pressure arm is a structure designed to apply force to the laminate in order to create a secure fit to the pipe walls. It both increases the surface area of the laminate exposed to the epoxy by creating a tighter fit as well as secures the laminate in place as the robot advances. The pressure is applied through a fifty pound pneumatic shock which keeps constant force of twenty-five pounds on the pipe walls. A five inch diameter free spinning wheel is attached to the end of the arm to ensure smooth movement of the arm's head along the laminate. The overall length of the arm can be adjusted for different diameter pipes.

4.e.iii Epoxy Delivery System

The epoxy delivery system was planned for as an attachable system to the basic structure. A peristaltic pump, which uses squeezing action to force the epoxy through rubber tubing, was considered the most effective powered delivery method. This pump allows disposable tubing to be the only part which is in contact with the epoxy in the delivery system. Having the motor isolated from the epoxy prevents excessive motor fatigue and failure, as well as preventing the motor from breaking due to cured epoxy buildup. Once the tubing has been used beyond its limit, it can be removed and replaced with very little effort or cost.

The epoxy used in this system would have to be less viscous than the current tack coat epoxy, which is comparable to mortar, but still thick enough to prevent it from running down the walls. Most viscosities of epoxy are viable to hold the laminate to the pipe walls, and most can be pumped with the peristaltic pump, so it would not be a difficult to find an epoxy which is suitable for this project.

4.f Failure Modes and Effects Analysis

The failure modes and effects analysis was done on the various subsystems in order to see possible results of various system failures. This analysis was then used to strengthen the systems to compensate for any critical failures. See Appendix B. for the failure modes effects analysis.

4.g Budget and Supplies

A purchased supply overview can be seen in Table 1. For a complete budget list with all parts and expenditures for this project see Appendix C.

Table 1. Budget overview.

Date	Discription	Req#		Allocated Funds
	Balance Forward			2000
	Funds from Eshani			4000
1/23/2009	Winans Elecric Motor Warehouse	1013370	593.82	
1/23/2009	Digikey.com	1013373	378.76	
1/23/2009	All Electric Corp.	1014676	161.65	
2/2/2009	McMaster-CaRR	1017344	453.94	
2/2/2009	Boca Bearing	1019182	134.28	
2/2/2009	Dave's Motors	1017343	227.94	
2/2/2009	McMaster-CaRR	1017345	39.15	
3/24/2009	Online Metals	1043056	874.66	
3/31/09	Johns Manville	K097597	805.32	
4/8/09	Superdroid Robots	1051041	63.15	
4/8/09	Superdroid Robots	1051040	383.87	
4/8/09	McMaster Carr	1050701	750.78	
4/13/09	Robot Marketplace	1052216	54.85	
4/13/09	McMaster Carr	1052063	37.37	
4/22/09	Express PCB	552860	64.26	
4/22/09	Firgelli Automations	552860	159.82	
4/22/09	McMaster Carr	552860	111.65	
Subtotals			5295.27	
Totals				704.73

5. Justification of Design

Design was chosen to accomplish three main goals. The overlap of the laminate had to be applied in a shingle-like manner, to prevent liquid from forcing its way under the laminate and damaging the reinforcement. Thus, the robot had to spin. It also needed to advance down the pipe, so a drive system was incorporated to ensure even advancement rate during application. The robot needed to support its own weight, as well as all the weight of the materials needed to perform the job. This included a fifty pound roll of laminate, as well as 5 gallons of epoxy, weighing about forty pounds. This dictated the structural strength needed for the robot, and therefore, its design.

6. Analysis, Testing and Design Results

Initial finite element analysis was conducted on critical components using COSMOSXpress to optimize their weight to strength ratio. One failure point that currently exists within the aluminum frame is on the center rings of the cage where the cross tubing goes through the water jet cut panels. This failure point is not present when the cage is assembled but becomes a problem when moving the individual parts through a twenty inch manhole. While handling, the rings can experience excessive torsional forces that can permanently deform or even break the part. A simple solution for the future would be to increase the web with at the thinner location on the panel. One other critical failure point was identified in the wheels that were chosen. The chosen wheels consist of a molded plastic structure with a solid rubber tires compression fit to the rims. These wheels have a maximum working load of two hundred pounds when loaded in alignment to with wheel. Assuming ideal loading conditions where the robots dry weight of two hundred and fifty pounds is evenly distributed across two wheels we are left with a working load potential of one hundred and fifty pounds. When the robot is in the end application and loaded with one hundred pound of reinforcing material the ideal conditions will not be present and failure of the wheels becomes likely. End application testing is the only way to truly determine if this failure mode will exist and if upgrading to aluminum wheels will be necessary.

Stress testing was also conducted on both the steering and drive mechanisms. The steering was driven into a stall condition where the wheel structure locked out against the frame. During initial tests the connection between the drive sprocket and the output shaft on the steering gear motors slipped, dragging the two setscrews out of the flat on the motor shaft. It was decided that a roll pin inserted through the sprocket and shafted would provide the needed sheer restraint. Once the modifications were made the sprocket no longer slipped but another failure point was identified. The tensioning plate required to take the slack out of the roller chain slipped during a stall condition. This was determined to be an acceptable failure mode because the plate can be easily adjusted and stall conditions should not exist in the end application.

The drive system was tested by running the wheels under load and free spinning. Initial test revealed interference between the ends of the motor shafts and the top restraining plates for the thrust bearings on the worm gear. This was easily remedied but cutting reliefs into the bottom of the restraining plates. Once this modification was completed one drive train was run for over an hour to check for excessive friction, shifting of part alignments and excessive vibration that could cause future damage. None was observed and it was decided that the next test should be conducted under load inside a pipe.

Bread board testing was conducted on the h-bridge motor control circuit. This was accomplished by connection the circuit to a direct current motor and providing a varying frequency and duty cycle signal from a function generator to the input of the h-bridge driver integrated circuit. The output wave form was monitored through the use of a Fluke ScopeMeter. Stable operation was confirmed through a frequency range of dc to 20 KHz and duty cycles of zero to one hundred percent. Motor off stability was also observed while turning the circuit on and off and while the input to the circuit was is a floating state. From these results it was determined that the circuit would be usable in our application and printed circuit boards were manufactured.

7. Conclusion

It should be obvious that the scope of the project in its initial phases was very ambitious. Dr. Ehsani, our sponsor from QuakeWrap was very adamant on having a completed working prototype. This caused reluctance among all parties to submit to a serious rescoping of the project, which led to a series of late-cycle problems. Immense amount of mechanical design and production has gone into the project thus far, and due to the enormous amounts of mechanical design needed, the design process far exceeded the time suggested for the class schedule. Because of this the assembly of the mechanical design has taken the focus of all project members, to the detriment of electrical and software design still needed to be completed. Given enough time, the robot could be completed with absolute certainty, but the nature of the class and the nature of the project schedule create an impossible obstacle.

The entire mechanical structure of the robot was completed. This will house all future systems that will be integrated into the robot to complete its functionality. The frame was designed with the intent of having an integrated series of systems on board. It has attachment points and space for all remaining systems, and space for further potential systems. The frame can support a great deal weight more than it currently is supporting, but the critical parts which inhibit future load size are the wheels. Currently each wheel can support 200 pounds of force. In the worst case scenario of all force being applied to only two wheels, the robot can support up to 400 pounds. Given that the robot weighs 250 pounds, and the laminate roll weighs 50 pounds, there is an extra hundred pounds of carrying capacity, which can be used to add further systems. This can be used to carry liquid epoxy or other systems to be integrated later, such as the epoxy delivery system which was not finalized or included.

The next stage of the project is to complete the control system and its implementation. Due to the lack of manpower and time constraints, the majority of the electrical design needs to be completed as well. Some of the h-bridge motor control boards were assembled for initial testing, but not all have been assembled. The break out box, which is a wireless interface box for the software and the circuits, needs to be selected. The software chosen to control this system is LabVIEW, which will be programmed to relay proportional integral derivative control sequence that can implemented for each motor on the robot. Once the electrical and software is completed application testing can began.

The initial test would be a stationary spin test to see if moving components work in the correct manner and to observe the stress applied to the frame. Application testing will take place in a four foot diameter pipe using carbon laminate without epoxy, so that multiple tests can be done. The next step is to implement and integrate the epoxy subsystem, to observe how the added weight of the liquid epoxy and the pressure arm affect performance. Some compensation may be required, and would be addressed at this stage. Once the systems have been integrated, the epoxy delivery system would be tested, so that the epoxy-backed laminate can be applied and examined for performance. Other tests would include traction tests and epoxy spillover measurements.

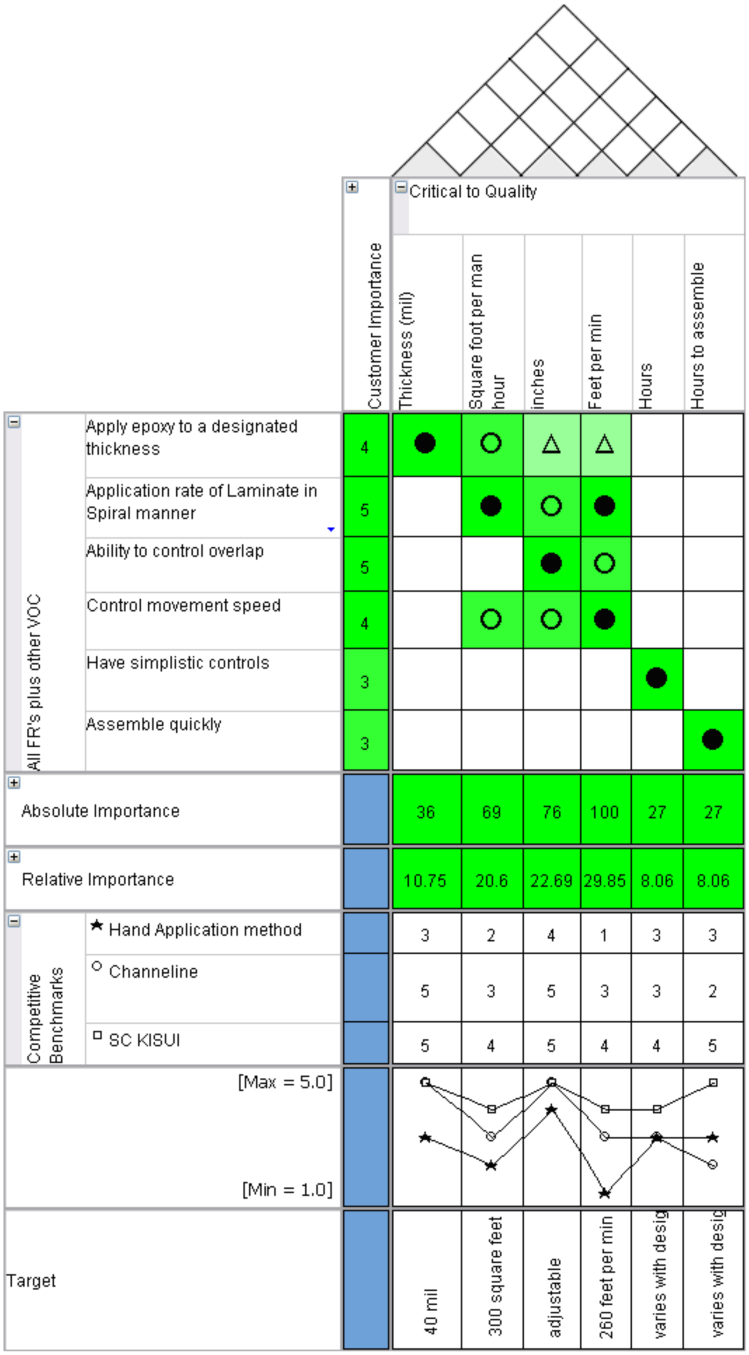
We hope that this project is successfully completed in the future, and have provided full documentation of our planned future systems to be implemented to facilitate any further development. The system which has been built can accommodate a large variety of implementations for the remaining systems, should the new design team find alternate designs more attractive. However, we firmly believe that our efforts have been productive, and hope that the robot is completed as envisioned.

8. Acknowledgements

As a team we worked incredibly hard on this project and did not realize how difficult the task at hand was going to be. Many individuals were key in helping us get throughout both the design and fabrication process. The first person that we would like to thank is Dr. Mo Ehsani, our sponsor, and president of QuakeWrap. Dr. Ehsani was easy to maintain contact with and understanding when allocating the additional funding that our project required. Second we would like to thank our mentor Kevin Prodromides. Kevin was very friendly and always trying to help in every possible way that he could. He was also very encouraging and motivating; making sure that we were caught up on all due assignments, and on the right track. Third we

would like to thank Pat Rodriguez; ordering parts and receiving them quickly was very important due to the lack of time. Pat was easily accessible, and notified us as soon as parts and packages arrived. Lastly we would like to thank Joe Hartley and Dale Drew from the AME machine shop. Countless hours were spent at the AME machine shop fabricating and putting together our robot. Joe and Dale have loads of experience in both industry and the machine shop. Whenever there was a question of how to make a part we designed, both were willing to give helpful advice. Sometimes Joe was even will to give advice about life in general whether we had asked for it or not.

I. Appendix A: House of Quality



			Critical to Quality					
		Customer Importance	Thickness (mil)	Square foot per man hour	inches	Feet per min	Hours	Hours to assemble
All FR's plus other VOC	Apply epoxy to a designated thickness	4	●	○	△	△		
	Application rate of Laminate in Spiral manner	5		●	○	●		
	Ability to control overlap	5			●	○		
	Control movement speed	4		○	○	●		
	Have simplistic controls	3					●	
	Assemble quickly	3						●
Absolute Importance			36	69	76	100	27	27
Relative Importance			10.75	20.6	22.69	29.85	8.06	8.06
Competitive Benchmarks	★ Hand Application method		3	2	4	1	3	3
	○ Channeline		5	3	5	3	3	2
	□ SC KISUI		5	4	5	4	4	5
[Max = 5.0] [Min = 1.0]								
Target			40 mil	300 square feet	adjustable	260 feet per min	varies with desig	varies with desig

II. Appendix B: Failure Modes and Effects Analysis (FMEA)

Item	Function	Potential Failure Mode	Effect	Potential Cause	Current Control
Robot Structure	Support robot and components	Part of structure buckles	Damage to robot, components, improper installation of carbon laminate, damage to inside of pipe	High compressive stresses	Reinforce structure beyond expected requirements
				High torsional stresses	Triangular structure designed to withstand high torsional forces
				Fatigue	Replace parts at first signs of fatigue
		Bolt/pin becomes loose or breaks	Damage to robot, components, improper installation of carbon laminate, damage to inside of pipe	Improper installation	Implementation of assembly checklist and installation manual
				Fatigue	Scheduled analysis of bolts/ pins with replacement cycles
				Threads of bolt become loose	assembly and disassembly, replace as needed
Item	Function	Potential Failure Mode	Effect	Potential Cause	Current Control
Propulsion system	Advances and steers robot through pipe	Drive motor or angle control motor failure	Damage to wheel, gears, or other components, improper installation of carbon laminate, possible damage to inside of pipe	Motor bearing failure	Not loading motor over specifications, keep motor in lower rpm range
				Stator winding/overheating	Keep motor cool, and in lower rpm ranges
				Overloading	Select a motor that can handle applied load
				Voltage overload	Circuit breakers
		Gear failure	Further damage to gears, wheels, or other components, improper installation of carbon laminate, possible damage to inside of pipe	Bending fatigue	Check gears routinely for crack propagation
				Pitting/scuffing	Check gears routinely for pitting and/or scuffing
				Wear	Check gears routinely for wear
		Wheel bearing failure	Damage to wheel, gears, or other components, improper installation of carbon laminate, possible damage to inside of pipe	Overloading	Keeping load under bearing specifications
				Overheating	Robot doesn't move fast enough to become a problem
				Fatigue	Replace parts at first signs of fatigue
				Lubrication failure	Keep bearing lubricated, have scheduled routine maintenance
		Thrust bearing failure	Damage to wheel, gears, or other components, improper installation of carbon laminate, possible damage to inside of pipe	Misalignment	Check that bearings a properly tightened
				Overloading	Keeping load under bearing specifications

Item	Function	Potential Failure Mode	Effect	Potential Cause	Current Control
Epoxy System	Applies epoxy to carbon laminate	Peristaltic Pump failure	Improper installation of epoxy	Improper pump flow rate	Calculate proper rpm for desired flow rate
				Motor bearing failure	Not loading motor over specifications, keep motor in lower rpm range
				Stator winding/overheating	Keep motor cool, and in lower rpm ranges
				Overloading	Select a motor that can handle applied load
				Voltage overload	Circuit breakers
		Tubing failure	Improper installation of epoxy	Tubing ruptures	Use proper tubing to handle pressures
				Tubing develops a hole	Disposable tubing or if reused check for holes before use
		Epoxy roller failure	Improper installation of epoxy	Rollers quit rotating	Check rollers are clean before use
				Rollers clog up with epoxy	Check rollers are clean before use

Item	Function	Potential Failure Mode	Effect	Potential Cause	Current Control
Electrical System	Power motors	Loss of Power	Motors freeze	H-bridge fail	Using high tolerance electronics
				Voltage overload	Circuit breakers
		Surge of Power	over-rev motors	Short circuit across H-bridge	Isolate H-bridge, and current limiters/fuses
	Power Microcontrollers	Microcontrollers Overheat	Loss of control	Improper voltage supplied	Integrated circuit with power regulation chip
Software	Control Motors	Faulty feedback	Awkward motor movement	Damage to feedback equipment	Redundant feedback system
				Damage of variable resistor	Multiple resistors
				Damage of Tachometer	Multiple tachometers
		Loss of signal	Indendent motor operation, damage to motors, robot, or components	Operator control box out of range	Automatic fail safe
				Wireless receiver card damaged	Protective casing
				Wireless control battery depleted	Scheduled replacement of batteries
		Software logic	Infinite oscillating corrections of wheel angle	Poor software	Simulation testing
				Improper gains	Gain adjustment and testing

III. Appendix C. Budget and Supplies

McMaster-Carr

Quantity	Part Number	Description	Unit Price	Total Price
1	6261K14	Standard ANSI Roller Chain #25, Sngl Strand, 1/4" Pitch, Rollerless, .13" Dia, 10'L (Same as 6261K171)	$32.40	$32.40
4	91860A032	17-7 Ph Stainless Steel Flat Washer 7/16" Screw Sz, 1/2" ID, 1-1/4" OD, .073"-.083" Thk, Packs of 5	$13.79	$55.16
6	2737T281	Steel Finished-Bore Roller Chain Sprocket for #25 Chain, 1/4" Pitch, 40 Teeth, 1/2" Bore (Same as 2737T28)	$11.64	$69.84
6	2737T1	Steel Finished-Bore Roller Chain Sprocket for #25 Chain, 1/4" Pitch, 9 Teeth, 1/4" Bore	$4.01	$24.06
3	2737T127	Steel Finished-Bore Roller Chain Sprocket for #25 Chain, 1/4" Pitch, 19 Teeth, 1/2" Bore (Same as 2737T12)	$6.53	$19.59
3	57545K527	Stl Worm, 12 Pitch, W/ 1/8" X 1/16" Kwy for 14-1/2 Deg Pressure Angle Worm Gear	$24.10	$72.30
3	57545K511	14-1/2 Deg Pressure Angle Worm Gear Cast Iron, 12 Pitch, 18 Teeth, 1.5" Pitch Diameter	$49.74	$149.22

Shipping/Tax	$31.37
Total	**$453.94**

Dave's Motors

Quantity	Part Number	Description	Unit	Total

			Price	Price
3	gg365	Stock 56 Tooth GSR/ESR Sport Quad Sprocket	$20.00	$60.00
3	kk150	GSR Sport Rear Wheel (no sprocket)	$24.95	$74.85
3	kk112	Mach 12 Full Wheel	$27.00	$81.00

Shipping/Tax

Total **$227.94**

All Electronics Corp.

Quantity	Part Number	Description	Unit Price	Total Price
3	FHP-2	IN-LINE AGC (3AG) FUSE HOLDER	$0.85	$2.55
10	FS-10	10A 3AG FUSE	$0.15	$1.50
25	FS-1	1 3AG FUSE	$0.15	$3.75
20	HS-325	T0220 HEATSINK W/ MONTING PIN	$0.20	$4.00
1	PS-6524	24VDC 6.5A POWER SUPPLY	$24.95	$24.95
10	FS-6	6A 3AG FUSE	$0.15	$1.50
1	18WT-100	18 GA. WHITE HOOK-UPWIRE, STR.100'	$9.95	$9.95
1	PB-1680	BREADBOARD, 1680 CONTACTS	$15.95	$15.95
1	IR-230	30 WATT SOLDERING IRON	$24.95	$24.95
1	50B-205	SOLDERING STAND	$4.00	$4.00
1	SOL-564	SOLDERING PASTE FLUX 2 OZ	$14.00	$14.00
1	SP-44	1/2 LB ROLL, 60/60 SOLDER, 0.032'' DIAMETER	$5.00	$5.00

1	WS-503	SOLDERING PASTE FLUX 2 OZ	$11.75	$11.75
200	293-10K	CUT-N-STRIP TOOL	$0.02	$4.60
200	293-1K	1K OHM 1/2 WATT	$0.02	$4.60
10	2200R63	2200 MFD 63V RADIAL ELECTROLYTIC CAP	$1.15	$11.50
1	HUG14B	1/4'' X 4, HS TUBE, BLACK	$1.90	$1.90

Shipping/Tax	$15.20
Total	**$161.65**

Digi-Key

Quantity	Part Number	Description	Unit Price	Total Price
35	P107030-ND	CAP .IUF 250/275V AC ECQ-UL	$0.17	$5.99
10	478-1836-ND	CAP TANTALUM IUF 50V 10% RAD	$0.50	$4.95
20	P4544-ND	CAP .47UF 63V STACK METAL FILM	$0.18	$3.58
45	UF1002DICT-ND	DIODE ULTRA FST SW 100V 1A DO-41	$0.31	$13.86
10	CT6EP504-ND	POT 500K OHM 6MM CERMET TOP	$0.63	$6.32
14	490-2890-ND	TRIMPOT CERMET TOP 500K OHM 25TRN TOP	$0.78	$10.93
1	SP132C-10K-ND	POT 10K OHM WW ST CONT ROT	$27.83	$27.83
3	M1439-ND	INDUCTOR TOROID 330UH 15% HORIZ	$4.75	$14.25
5	PCE4445CT-ND	CAP 330UF 35V ELECT FP SMD	$0.93	$4.63
5	MUR410GOS-ND	DIODE ULTRA FAST 4A 100V AXIAL	$0.53	$2.65
4	LM2576HVT-12-	IC REG SIMPLE SWITCHER TO-220-5	$5.85	$23.40

	ND			
10	P5313-ND	CAP 100UF 100V ALUM LYTIC RADIAL	$0.29	$2.89
1	DV164120-ND	KIT STARTER PICKIT 2	$49.99	$49.99
5	LM7805CT-ND	IC RED 1A POS -40-+125DEG TO-220	$0.45	$2.25
10	478-3400-ND	CAP POLYFILM BOX.33UF 63V 10%	$0.16	$1.58
20	IRFB3206BF-ND	MOSFET N-CH 60V 21A TO-220AB	$2.60	$52.00
5	HIP4081AIPZ-ND	IC DRIVER FET FULL BRIDGE 20 DIP	$6.86	$34.30
100	IN4744ADICT-ND	DIODE ZENER 15V 1W 5% DO-35	$0.17	$17.40
100	SD101ADICT-ND	DIODE SCHOTIKY 60V 400MW DO-35	$0.29	$28.80
10	1.5KE51CADICT-ND	TVS BI-DIR 51V 1500W DO-201	$0.65	$6.51
200	150H-ND	RES 150 OHM 1/2W CARBON FILM	$0.02	$4.16
5	PIC16F684-I/P-ND	IC PIC MCU LASH 2KX14 14DIP	$2.45	$12.25
100	CF1/233JRCT-ND	RES 33 OHM 1/2W 5%CARBON FILM	$0.02	$1.96
5	14.3KXBK-ND	RES 14.3K OHM 1/4W 1% METAL FILM	$0.11	$0.53
1	C2117W-100-ND	WHITE22AWG HOOKUP WIRE SOLID	$18.03	$18.03

Shipping/Tax	$27.72
Total	**$378.76**

Electric Motor Warehouse

Quantity	Part Number	Description	Unit Price	Total Price
3	M1120046	Leeson 12/24V DC TENV Motor	$178.88	$536.64

Shipping/Tax	$57.18
Total	**$593.82**

Boca Bearings Company

Quantity	Part Number	Description	Unit Price	Total Price
2	1/2-TP		$5.95	$11.90
6	FR8-ZZC		$11.95	$71.70
6	NTA815		$4.95	$29.70
14	99R1212-2RS		$0.99	$13.86

Shipping/Tax	$7.12
Total	**$134.28**

McMaster-Carr

Quantity	Part Number	Description	Unit Price	Total Price
6	2737T3	Steel Finished-Bore Roller Chain Sprocket, for #25 Chain, 1/4" Pitch, 11 Teeth, 1/4" Bore, Originally Your Line 4 Replace	$5.39	$32.34

Shipping/Tax	$6.81

Total	**$39.15**

Online Metals

	Quantity	Part Number	Description	Unit Price	Total Price
AL02	3		4" (A) x 3" (B) x 0.17" (C) x 0.29" (D) 0.250 (R) 6061 T6 I-BEAM	$46.75	$140.25
AL06	8		1" (A) x 0.125" (B) 6063 T52 SQUARE TUBE	$9.84	$78.72
AL09	12	Cut to 8 in.	4" (A) x 1.647" (B) x 0.247" (C) 6061 T6 CHANNEL	$11.68	$155.16
AL10	2		4" (A) x 4" (B) x 0.375" (C) 6061 T6 ANGLE	$43.58	$87.16
AL25	5	Cut to 4 in	0.5" X 4" ALUMINUM 6061-T6 EXTRUDED RECTANGLE	$5.25	$30.75
AL26	2		0.25" X 1" ALUMINUM 6061-T6 EXTRUDED RECTANGLE	$4.29	$8.58
AL27	1		2" (A) x 4" (B) x 0.125" (C) 6063 T52 RECTANGLE TUBE	$13.30	$13.30
AL29	1		3" (A) x 1.5" (B) x 0.258" (C) 6061 T6 CHANNEL	$31.42	$31.42
					$0.00
P01	2		1" NOM. (1.32" OD X 0.18" WALL X 0.957" ID) ALUMINUM 6061-T6 PIPE SCHEDULE 80	$16.37	$32.74
P02	2		0.39" ID x 0.625" OD x 0.12" WALL A513 TYPE 5 TUBE	$11.63	$23.26
P03	2		0.5" ALLOY STEEL 4340 NORMALIZED TURNED COLD FINISH ROUND	$6.93	$13.86
P04	2		0.51" ID x 0.75" OD x 0.12" WALL A513 TYPE 5 TUBE	$3.16	$6.32

P05	1		1.5" OD x 0.125" WALL x 1.25" ID 6061 T6 TUBE	$17.02	
P06	1		0.25" ID x 0.5" OD x 0.125" WALL 6061 T6 TUBE	$6.00	$6.00
P07	2		0.5" ALUMINUM 6061-T6 EXTRUDED ROUND	$3.44	
P08	1		1.25" ALUMINUM 6061-T6 EXTRUDED ROUND	$7.83	
Al24	6	Cut to 3.2 in	0.5" X 4" ALUMINUM 6061-T6 EXTRUDED RECTANGLE	$4.19	$31.14
AL23	2		0.25" X 2.5" ALUMINUM 6061-T6 EXTRUDED RECTANGLE	$13.29	$26.58
AL22	2		Aluminum 6061-T6 BareExtruded Rectangle 0.25" x 3"	$18.01	$36.02
AL21	2		0.25" X 5" ALUMINUM 6061-T6 EXTRUDED RECTANGLE	$27.79	$55.58
AL20	1		0.5" X 1" ALUMINUM 6061-T6 EXTRUDED RECTANGLE	$6.10	$6.10

Shipping/Tax

Total

Johns Manville

	Quantity	Part Number	Description	Unit Price	Total Price

Water Jet Cut Parts

Shipping/Tax	
Total	**$805.32**

Superdroid

Quantity	Part Number	Description	Unit Price	Total Price
1	TD-044-122	IG42 24V DC 122 RPM Gear motor with Encoder	$59.80	$59.80

Shipping/Tax	$3.35
Total	$63.15

Superdroid

Quantity	Part Number	Description	Unit Price	Total Price
1	TD-044-122	IG42 24V DC 122 RPM Gear motor	$47.40	$47.40
6	TD-044-022	IG42 24V DC 022 RPM Gear motor	$49.90	$299.40

Shipping/Tax	$17.65
Total	**$364.45**

McMaster CaRR

Quantity	Part Number	Description	Unit Price	Total Price
1	92530A100	18-8 Stainless Steel Key Stock Undersized, 1/8" X 1/8", 12" Length	$2.08	$2.08

8	5909K31	Steel Needle-Roller Thrust Bearing Cage Assembly for 1/2" Shaft Diameter, 15/16" OD	$2.66	$21.28
1	91247A628	Grade 5 Zinc-Plated Steel Hex Head Cap Screw 3/8"-16 Thread, 1-1/2" Length, Packs of 50	$9.59	$9.59
24	6058K34	Ball Joint Linkage Quick-Disconnect, 3/8"-24 Stud & Shank Thread Size	$7.07	$169.68
1	91236A644	Znc-Pltd Stl Low-Strength Hex Head Cap Screw 3/8"-16 Thread, 5" Length, Packs of 25	$12.32	$12.32
2	90126A031	Zinc-Plated Steel Type A SAE Flat Washer 3/8" Screw Size, 13/16" OD, .051"-.080" Thick, Packs of 140	$3.23	$6.46
1	90473A031	Zinc-Plated Grade 2 Steel Hex Nut 3/8"-16 Thread Size, 9/16" Width, 21/64" Height, Packs of 100	$4.20	$4.20
16	5909K44	.032" Thick Washer for 1/2" Shaft Diameter Steel Needle-Roller Thrust Bearing	$0.90	$14.40
1	93286A013	Lighweight Aluminum Flat Washer 2024-T4, 1/4" Screw Sz, 11/16" OD, .035"-.055" Thk, Packs of 100	$3.59	$3.59
1	92316A640	Grade 8 Alloy Steel Hex Flange Cap Screw 3/8"-16 Thread, 4" Length, Packs of 10	$7.77	$7.77
1	92196A542	18-8 Stainless Steel Socket Head Cap Screw 1/4"-20 Thread, 1" Length, Packs of 50	$9.45	$9.45
4	98842A031	Zinc-Plated Steel Threaded Rod 3/8"-24 Thread, 3' Length	$4.02	$16.08
1	90473A205	Zinc-Plated Grade 2 Steel Hex Nut 1/4"-28 Thread Size, 7/16" Width, 7/32" Height, Packs of 100	$1.96	$1.96
2	60645K121	High-Strength Ball Joint Rod End 1/4"-28 Right-Hand Male Shank, 2225 lb Load Cap (Same as 60645K12)	$3.68	$7.36

1	92196A546	18-8 Stainless Steel Socket Head Cap Screw 1/4"-20 Thread, 1-1/2" Length, Packs of 25	$7.78	$7.78
2	92137A307	Metric Flange Button Head Cap Screw Alloy Steel, M4 Size, 12 mm Length, 0.70 mm Pitch, Packs of 25 (Same as 92137A100)	$7.78	$15.56
1	9271K321	Music Wire Torsion Spring 180 Deg Angle, .803" Coil OD, .078" Wire, Ccw/Rh, Packs of 6 (Same as 9271K32)	$8.97	$8.97
1	9271K322	Music Wire Torsion Spring 180 Deg Angle, .803" Coil OD, .078" Wire, Cw/Lh, Packs of 6 (Same as 9271K32)	$8.97	$8.97
3	98017A660	18-8 Stainless Steel AN 960 Flat Washer 1/4" Sz, .5" OD, .057"-.069" Thk, Dash No. C416, Packs of 100	$5.81	$17.43
5	92196A540	18-8 Stainless Steel Socket Head Cap Screw 1/4"-20 Thread, 3/4" Length, Packs of 50	$7.52	$37.60
6	6383K39	Steel Ball Bearing Plain Open for 1/2" Shaft Dia, 1-9/32" OD, 5/16" W	$5.62	$33.72
4	2737T105	Steel Finished-Bore Roller Chain Sprocket for #25 Chain, 1/4" Pitch, 14 Teeth, 1/4" Bore (Same as 2737T6)	$6.08	$24.32
1	9271K581	Music Wire Torsion Spring 270 Deg Angle, .826" Coil OD, .070" Wire, Ccw/Rh, Packs of 6 (Same as 9271K58)	$8.58	$8.58
1	9271K582	Music Wire Torsion Spring 270 Deg Angle, .826" Coil OD, .070" Wire, Cw/Lh, Packs of 6 (Same as 9271K58)	$8.58	$8.58
1	92316A778	Grade 8 Alloy Steel Hex Flange Cap Screw 1/2"-20 Thread, 5" Length, Packs of 5	$9.88	$9.88
1	95479A122	Black Oxide Grade 5 Steel Hex Nut 1/2"-20 Thread Size, 3/4" Width, 7/16" Height, Packs of 10	$5.47	$5.47

1	98023A033	Zinc & Yellow Grade 8 Steel Flat Washer SAE, 1/2" Screw Size, 1-1/16" OD, .097"-.177" Thk, Packs of 25	$5.23	$5.23
16	6384K361	Steel Ball Bearing Flanged Double Sealed for 1/2" Shaft Dia, 1-1/8" OD	$8.52	$136.32
1	90473A215	Zinc-Plated Grade 2 Steel Hex Nut 3/8"-24 Thread Size, 9/16" Width, 21/64" Height, Packs of 100	$4.20	$4.20
1	91247A550	Grade 5 Zinc-Plated Steel Hex Head Cap Screw 1/4"-20 Thread, 2" Length, Packs of 100	$9.79	$9.79
2	90473A029	Zinc-Plated Grade 2 Steel Hex Nut 1/4"-20 Thread Size, 7/16" Width, 7/32" Height, Packs of 100	$1.93	$3.86
1	92311A535	Type 18-8 SS Cup Point Socket Set Screw 1/4"-20 Thread, 3/8" Length, Packs of 100	$6.83	$6.83
4	98841A029	Zinc-Plated Steel Threaded Rod 1/4"-20 Thread, 3' Length	$1.59	$6.36
6	60355K821	Steel Ball Bearing--ABEC-1 Dbl Shielded, No.R20 for 1-1/4" Shaft Dia, 2-1/4" OD	$11.44	$68.64
10	6261K108	#25 Connecting Link for Standard ANSI Roller Chain	$0.79	$7.90

$722.21

Shipping/Tax $28.57

Total $750.78

Robot Marketplace

Quantity	Part Number	Description	Unit Price	Total Price

7	0W-BPDWC05	Colson Wheel 3 x 1-1/2	$6.50	$45.50

Shipping/Tax	$9.35
Total	$54.85

McMaster CaRR

Quantity	Part Number	Description	Unit Price	Total Price
6	6383K39	Steel Ball Bearings, Plain Open For 1/2" Shaft DIA, 1-9/32 OD, 5/16"W	$5.62	$11.24

Shipping/Tax	$26.13
Total	$37.37

Express PCB

Quantity	Part Number	Description	Unit Price	Total Price
3		coustom printed circuit boards		$51.00

Shipping/Tax	$13.26
Total	$64.26

Firgelli Automations

Quantity	Part Number	Description	Unit Price	Total Price

1	FA-PO-150-12-4	4" Stroke Standard Force Linear Actuator		151.98

Shipping/Tax

Total $159.82

McMaster CaRR

Quantity	Part Number	Description	Unit Price	Total Price
1	6261K285	Standard ANSI Roller Chain #25, Sngl Strand, 1/4" Pitch, Rollerless,.13" Dia, 5'L (Same as 6261K171)	$16.20	$16.20
1	98025A029	Extra-Thick High-Strength Steel Flat Washer 1/4" Screw Size, 5/8" OD, .090"-.108" Thick, Packs of 100	$11.11	$11.11
1	98017A660	18-8 Stainless Steel AN 960 Flat Washer 1/4" Sz, .5" OD, .057"-.069" Thk, Dash No. C416, Packs of 100	$5.81	$5.81
1	8974K681	Multipurpose Aluminum (Alloy 6061) 1-3/4" Diameter, 1' Length (Same as 8974K68)	$13.66	$13.66
7	5909K44	.032" Thick Washer for 1/2" Shaft Diameter Steel Needle-Roller Thrust Bearing	$0.90	$6.30
25 ft.	71245K41	Single-Conductor Machine Tool Wire (MTW) 12 Awg, .156" OD, 600 VAC, Black (Same as 71245K4)	$18.48	$4.62
25 ft.	71245K44	Single-Conductor Machine Tool Wire (MTW) 12 Awg, .156" OD, 600 VAC, Red (Same as 71245K4)	$18.48	$4.62
50 ft.	71245K21	Single-Conductor Machine Tool Wire (MTW) 16 Awg, .120" OD, 600 VAC, Black (Same as 71245K2)	$10.23	$5.12

50 ft.	71245K24	Single-Conductor Machine Tool Wire (MTW) 16 Awg, .120" OD, 600 VAC, Red (Same as 71245K2)	$10.23	$5.12
1	9416K343	Gas Spring with Threaded Ends 50 Force, 13.74" Extended Length, 5.47" Stroke (Same as 9416K16)	$12.28	$12.28
2	59935K72	Metric Ball Joint Rod End M6 X 1.0 Rh Female Shank, 2674 Pound Load Capacity (Same as 59935K52)	$6.02	$12.04
1	2439T43	Easy-Roll Rubber-Tread Wheel 5" X 1-1/4", for 3/8" Axle, 250# Cap	$8.85	$8.85

	$105.73
Shipping/Tax	$5.92
Total	$111.65

IV. Appendix D – List of Acronyms

CFRP - Carbon Fiber Reinforced Polymer
PCCP - Pre-stressed Concrete Cylinder Pipe
FMEA – Failure Modes and Effects Analysis