Multi-Sensory
Autonomous
Ground vehicle
Intercollegiate

1. Introduction

The United States Military Academy's Civil and Mechanical Engineering Department in conjunction with Computer Science, Electrical Engineering, and System Engineering departments are entering our vehicle "MAGIC" to compete for the first time in the Intelligent Ground Vehicle Competition. MAGIC stands for multi-sensory autonomous ground vehicle intercollegiate competition. Since this is our first year competing, we have set our goal to compete in two of the four competitions, the challenge and design. We developed MAGIC using a specific five-phase design plan, which resulted in our final project. Our complete team consists of 18 undergraduate junior and senior students who are advised by numerous faculty members. We estimate 3000 man hours were spent on this project. Despite being undergraduates, we have developed a vehicle that is complex, innovative, safe and competitive.

2. Design Process

For our development of MAGIC, we followed David Ullman's five-phase design process.[1] Figure 1 below shows the five phases. Our team followed the design process very closely and this is one of our strongest aspects of our design. By strictly following this process we ensured that we had every aspect of the competition covered, as well as ensuring an efficient and safe vehicle.

Figure 1: 5-Phase Design Process

2.1 Phase I: Identify the need

In this phase we arrived at our problem statement. We broke the team up into sub-teams. These sub-teams then reviewed pertinent reports brought from other universities and information collected at the competition in July of 2000. These sub-teams then each conducted a mind map

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[1] David Ullman, *The Mechanical Design Process* (New York: The McGraw-Hill Companies, Inc., 1997), p 60.

and how-why analysis to help grasp the scope of their portions. Then each team provided a problem statement for their particular sub-teams. The project manager took the three sub-teams analysis and problem statements to develop a mind map, figure 2, and scope of the problem for the project. The team problem statement and mission was to "Develop an autonomous vehicle capable of successfully navigating the challenge course and win the design competition." As mentioned earlier, we set our goal to compete in those two competitions for our first year of competition.

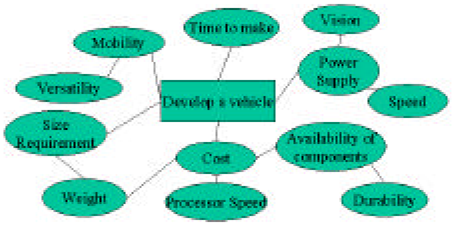


Figure 2: Mind Map

2.2 Phase II: Plan the Process

Phase II began the systems integration portion of the project. It is vital for multidisciplinary projects to have structure, direction, and effective communication throughout the span of the project. This task fell to the Systems Engineer Cadet Brandon Thompson. The first goal of Phase II was to establish a structure for the project. The design team established a chain of command in order to facilitate information flow and meet all of the objectives. We selected a CIC (Cadet in Charge) for the year, an ACIC, a Logistics and Budget Officer, and three Sub-team leaders for each discipline. By doing this we made a working chain-of-command for the project that allowed us to remain on target and communicate. Figure 3 below shows our MAGIC team layout.

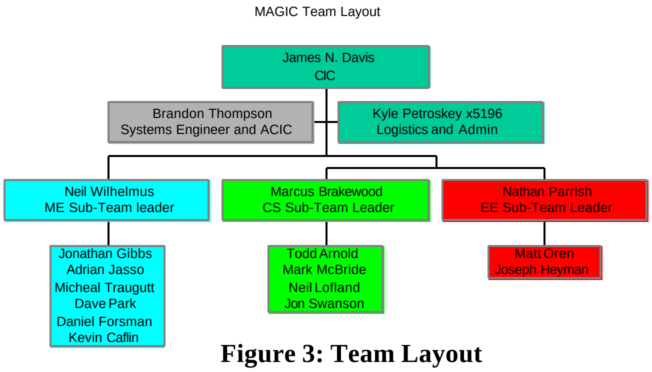


Figure 3: Team Layout

We began to plan our process using a Gantt chart and a Pert chart. The Gantt chart is a plan of times when we will accomplish each task within the project. The Pert chart shows the flow of critical activities. We used the program Microsoft Project to make the construction and modification of both charts easier and more organized. First we put the major requirement dates into MS Project. Then with the sub-team leaders we decided what we wanted to achieve before each of these requirements and the length of time for each task. The final concept of the Gantt chart contained every event each team was working on during both semesters, the starting and finishing dates of each task, and the interaction between all of the tasks. To ensure efficiency and effectiveness, the Gantt chart was updated during weekly meetings.

ID		Task Name	Duration	Start	Finish	Predecessors
88	▦	Wire all components that cannot use 24VDC	2 days	Thu 2/1/0	Fri 2/2/0	42
89	▦	Mount Caster	4 days	Thu 2/1/0	Mon 2/5/0	84
87	▦	Bolt Plating	3 days	Mon 2/5/0	Wed 2/7/0	84
90	▦	Work on EE 408 written requirements	2 days	Tue 2/6/0	Wed 2/7/0	89
91	▦	Mount bearing hangers	4 days	Tue 2/6/0	Fri 2/9/0	84
48	▦	Test the motors on the dynamometer	2 days	Thu 2/8/0	Fri 2/9/0	90
49	▦	Mount Sprockets	4 days	Thu 2/8/0	Tue 2/13/0	87
50	▦	Accessibility trays mounted	5 days	Mon 2/12/0	Fri 2/16/0	91
51	▦	IPR #1	1 day	Tue 2/13/0	Tue 2/13/0	48
52	▦	Mount Axles	3 days	Wed 2/14/0	Fri 2/16/0	49
53	▦	Mount hubs	3 days	Wed 2/14/0	Fri 2/16/0	49
54		Find an amplifier that will work with the motor	2 days	Wed 2/14/0	Thu 2/15/0	51
55		Order the amplifier	1 day	Fri 2/16/0	Fri 2/16/0	54
60	▦	Power Plant Mounted	6 days	Fri 2/16/0	Thu 2/22/0	91
56		Conduct bench tests with the motor in the power lab	4 days	Sat 2/17/0	Wed 2/21/0	55
61	▦	Tires Mounted	1 day	Sat 2/17/0	Sat 2/17/0	53,52

Figure 4: Gantt Chart for Feb 1-18

The Pert chart is a flow diagram that shows the interactions between every task on the Gantt chart. The final Pert chart resembles a tree diagram that branches off three ways into mechanical, electrical, and computer science tasks. These branches interact with each other and joined to complete the vehicle in March 2001 and begin testing. These two charts helped the MAGIC team remain focused and integrated the different disciplines. The combination of the charts and other tools helped our three sub-teams to function as one unit.

2.3 Phase III: Develop Specifications

In the third phase of this project we developed our project specifications. We determined the engineer requirements, its measurable targets, and its relative importance. We used a QFD, Quality Functional Deployment, as a format. The QFD, figure 5, helps to tie the customer requirements to the engineering

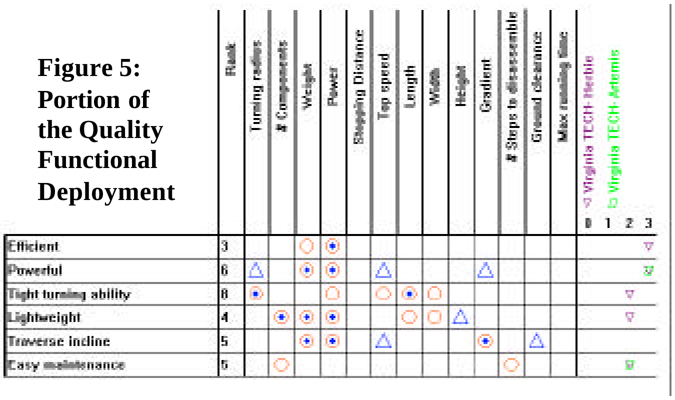


Figure 5: Portion of the Quality Functional Deployment

	Rank	Turning radius	# Components	Weight	Power	Stopping Distance	Top speed	Length	Width	Height	Gradient	# Steps to disassemble	Ground clearance	Max running time	0	1	2	3
Efficient	3			○	⊙													▽
Powerful	6	△		⊙	⊙		△				△							▽□
Tight turning ability	8	⊙			○		○	⊙	○								▽	
Lightweight	4		⊙	⊙	⊙			○	○	△							▽	
Traverse incline	5			⊙	⊙		△				⊙		△					
Easy maintenance	5		○									○					□	

requirements and benchmarks the competition.

2.4 Phase IV: Generate Concept

In this phase we developed our final concept. Using functional decomposition and a morphological chart, we were able to go from function to form to develop multiple concepts, compare them, and select a final concept. Additionally, each sub-team identified the specific components they could use to meet their needs. Then each team did an absolute/relative comparison of the different concepts to determine the best concept. By the end of this phase we had our final concept for MAGIC. We used the program Pro-D to help visually generate our concept. Figure 6 shows our Pro-D concept drawing with and without the shell.

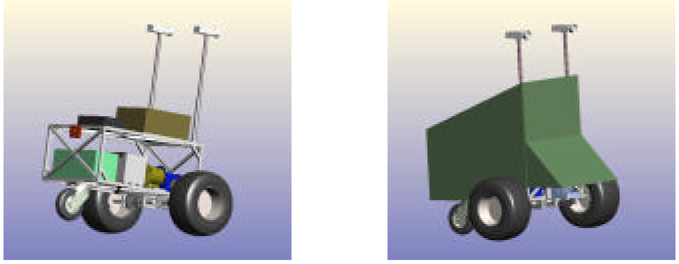


Figure 6: Concept Drawings

2.5 Phase V: Generate Product

In this phase we generated our product. Working together, we combined the three disciplines and our MAGIC vehicle finally was built and tested. Using our generated concept as our vehicle plan, we purchased the parts necessary and began our production of MAGIC. During each step of production, we evaluated performance, configurations and cost. During this phase, we also conducted component and operational testing and debugging to ensure our vehicle's performance, safety, and efficiency.

3. Mechanical System

3.1 Vehicle Frame

The vehicle frame was developed with two main considerations. The first was strength. The vehicle must be able to support the weight of all of the components. Static stress analysis of our frame indicated a factor of safety of 15. The second was component mounting capability. The frame is a standard box design, which was the simplest to weld and easily allows for mounting. The bottom section of the frame contains the most reinforcement because this will be holding the majority of the components, including most of the heavier ones. For the material of the frame, we chose 6063 Aluminum. We saw the weight advantages of the aluminum, especially compared to a steel design. We chose 3/4in square tubing with 1/8in wall thickness for the specific size. We determined that the 3/4in-wall width is the minimum amount required for successfully mounting the components. The 1/8in wall thickness is the optimum thickness for the MIG welder.

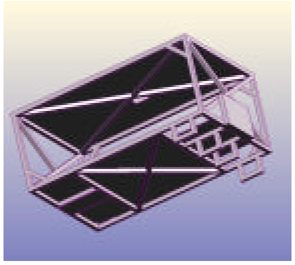


Figure 7: Frame Design

3.2 Drive Train and Dynamic Components

By limiting the vehicle to 5mph maximum speed, we are able to have a very high torque ratio. This allows us to use smaller motors. Although this produces a very low speed, the torque transferred to the tires is very high. In order to transfer the power from the motors to the tires, and to increase the torque, a gearbox was required. The ratio we chose for the vehicle's gearboxes is 20:1. With this gear ratio, the required motor horsepower is 0.48hp per motor (4.62 ft-lb. torque). This ensures enough power to start from a stop at 15 degrees of angle. For safety, availability and performance reasons we chose two 1 hp brushed DC motors to provide the necessary power.

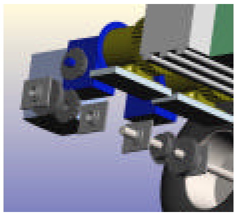


Figure 8: Drive Train

We desired the tight turning radius of skid steering, so we decided to use a three-wheel design, with two front wheels and a rear castor wheel. The front wheels are the actual drive wheels. They are connected to the motors through sprockets, chain, and 20:1 ratio gearboxes. The axles used for the vehicle are 1in diameter free wheeling axles. This means that the two motors

Figure 9: Team Member w/ Vehicle

will each drive their respective tire. The two axles are each supported by two sets of bearings, which are sealed, and mounted securely to the frame. In order to ensure the success of the design of the vehicle, torque, vibration and stress analyses were performed on the different systems. The static stress analysis indicated a factor of safety of 15. This will allow us to have slightly imperfect welds yet maintain a safe vehicle.

3.3 Shell Design

We assembled an aluminum shell to protect the vehicle from the environment. It consists of an aluminum outer covering kept together with rivet fasteners. The shell attaches itself over the top of the vehicle with its primary fastener to the vehicle. The shell was spray painted and weather seal was placed in significant spots, such as near the camera supports, to ensure that a relatively tight seal is kept. Besides protection, the shell serves to make the vehicle aesthetically pleasing. Performance was our primary focus, but the look of the vehicle was also important.

3.4 Electrical/Sensing Devices and Mechanical System Interaction

Originally, we had decided to completely fabricate aluminum supports for the cameras. There were several faults to this design, to include ease of use. In the redesigns, we were able to use steel pipes with screws mounted as the base. This allows the mounts to be removed for transport. We also decided we needed professional tripods that would allow the CS and EE teams to orient the cameras in the position that would best allow the vehicle to navigate. Additionally, the laser was mounted to the front of the vehicle using the mounting device sent with the laser. The encoders were placed directly on the axles, and a special sliding drawer was constructed to allow for easy battery access.

Figure 10: Vehicle during Production

4- Electrical System

The electrical design portion was broken down into three sub-tasks. These three tasks included the motion control sub-task, power sub-task and the emergency stop sub-task.

4.1 Motion Control (Requirements, Goals, Innovations)

The motion control sub-task would allow the computer to interface with the motors in order to provide coordinated motion of the vehicle. The motion control layout has three major components: the motion control card, the amplifiers that control the motors, and the motors. The motion control card takes instruction from the computer and converts this into a –10V to +10V signal that is sent to the amplifier, which in turn sends an output voltage to the motors. There were five requirements that the motion control sub-task team had to meet. The motion control system would have to allow the computer to interface with the motors and provide position and velocity feedback to the computer. The vehicle also had to be able to start from a dead stop up a 15° incline and provide a top speed of at least 5mph. Finally, we wanted the vehicle to operate smoothly without oscillation or over-damping.

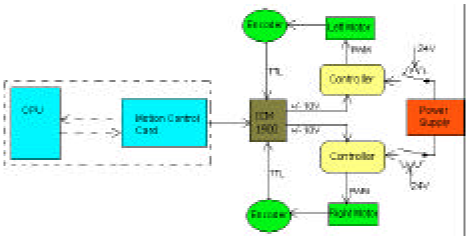


Figure 11: Motion Control Layout

4.2 Power Supply

The electrical power sub-system provides the electrical power source to the vehicle and all of the components. It also includes the wiring, fusing, busses, circuit breakers and other devices to protect the electrical components from power surges.

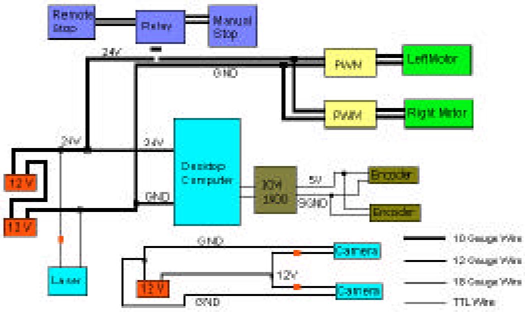


Figure 12: Electrical Power Layout

Our main power source is a 24V DC bus, provided by two deep cycle marine batteries connected in series. The bus provides 80 Amp-hours at 24V. This was a tradeoff between weight and power. The marine batteries added a lot of weight to the vehicle, but in order to ensure that we could power it reliably for one hour, we decided that we would take this weight in order to get the required power. The 24V bus except for the cameras and the encoders can power all of our electrical components. Our cameras operate at 12V DC, so we added a separate 12V source to power them. The encoders need 5V DC, and this is provided by one of the outputs of the motion control card. The emergency stop relay cut off power between the batteries and the pulse width modulating controllers. We also added fuses to protect the sensitive items from current surges. Our battery will last up to 1.03 hours based on our 24 V batteries and rate of amperage needed by each piece of equipment per hour.

4.3 Emergency Stop

One of the requirements in the competition is an emergency stop sub-system for the vehicle. In order to manually and remotely stop the vehicle, we used relays to cut the power between the battery supply and the pulse width modulating controllers. The criteria that this sub-task had to meet include a manual stop button, a wireless remote stop from up to 50', stopping the vehicle in at most 12ft, an easy restart after an emergency stop, and each motor had to be capable of operating independently. For the remote stop, we used a RF transmitter and receiver to toggle a 12V relay. This relay was connected in series with a manual switch. The 12V remote stop relay and the manual switch were then connected in series with another relay. If either the remote stop relay was toggled or the manual switch was opened, the relays between the main batteries and the controllers would open. This would cut power to the amplifiers and stop the vehicle.

4.4 Sensing Equipment (Cameras, Encoders, and Laser)

The cameras that we are using are Pulnix TMC-7DSP cameras. The dual cameras are mounted to the front of the vehicle on vertical supports. The cameras will be used in conjunction with a "findline" program. The images seen by the camera will be sent to this program, which will process the image and calculate the slope and distance of the line.


Figure 13: Pulnix Camera

In addition to the dual cameras we also equipped the vehicle with a LMS (Laser Measurement System) 200-30106. The operating principle of the laser range finder is based on time-of-flight measurement. The LMS calculates the distance to the object using the time of flight of pulsed light; i.e. the length of time between sending and receiving the beam of light. The data collected by the LMS will be used to calculate the angle and distance to the nearest obstacle.

Figure 14: LMS 200 Laser

The encoders that we have selected are external to the DC brushless motors. Our design utilizes two shaft encoders in order to provide feedback to the computer about the position of the vehicle. One encoder is mounted to each of the left and right axles of the vehicle. The encoders are optical devices that use a beam of light to count the number of revolutions of the motor shaft. The encoder counts these revolutions as beats and then sends this data to the motions control card via a TTL line. As the axle turns, the individual encoder (left or right) will send position information to the motion control card in the form of six square waves, as can be seen in the figure 15.

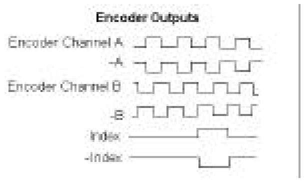


Figure 15: Encoder Output

Channel A, B, and Index are the main outputs from the encoder that are used by the motion control card. The other three outputs are differential outputs and represent the inverse of Channels A, B, and Index respectively. Each peak in the square wave from either channel A or channel B signifies one “pulse” of the encoder. The encoder is made so that it will output 1000 “pulses” for each complete revolution that it makes. The motion control card then translates the number of beats into a revolution per second value and uses this value to determine the vehicle speed and position. The motion control card will compare the number of counts sent from the encoder over a given time to that of the desired profile and compute the error signal, which drives the motor.

5- Computer Science System

5.1-Software Design (Requirements, Goals, and Innovations)

The goal of the computer software that will serve as the “brain” of the vehicle is to analyze the map and decide upon the best movement path for the vehicle to take. This software controls all of the sub-tasks within the computer and makes the decisions on where the vehicle will move. After the vehicle has gathered input from the cameras and LMS, a 2-D map with plots of all obstacles and lines are sent to the brain. The brain after conducting path planning, sends distance and direction information to the motion control card to move the vehicle (Figure 16). The path planning is processed using Dykstra’s Algorithm. Each node of the 2D map is assigned a weighted value based on its proximity to sensed obstacles or lines. Path is chosen along nodes with lowest values. After finding the best path, the brain will conduct a virtual test to make sure that the vehicle will not hit an obstacle. If it will, then Dykstra’s Algorithm will run again with a minimum bound greater than the previous best path’s weight.

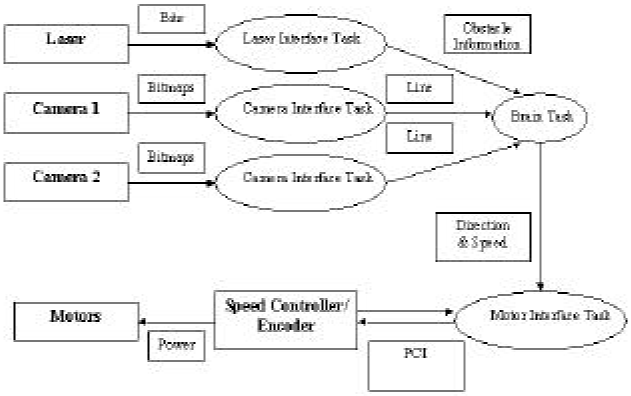


Figure 16: Software Design Layout

5.2- Camera Image Processing

An important objective of the challenge course competition is that the vehicle is able to recognize its surroundings in order to avoid obstacles. It is also critical that the vehicle identifies the white line boundaries of the course and remains within these lines. The dual camera system serves this imperative function of the vehicle. The cameras will send image data to a “findline” program. This program will process the image and calculate the slope and distance of the line. The concept of the software is simple: given an image, find the lines and determine their direction and distance. This data is then passed on to the brain program that

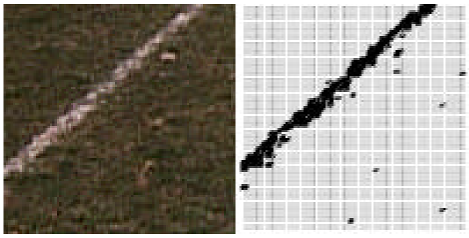


Figure 17: Camera Processing

determines what the vehicle needs to do with the information that it receives about its environment. The program produces three float outputs: the slope of the line, the y-intercept, and the standard deviation. These outputs are then converted to 2-D data to be placed inside a 2-D map. The program determines where white and yellow pixels are located and then processes these RGB values. Based on the relation between the three colors, the program decides whether or not to accept or reject the pixels as white or yellow. The program then, using mathematical models, finds white or yellow straight or dotted lines and white circles. All other white or yellow pixels are rejected.

5.3- Laser Processing

In addition to the dual camera sensors, a laser range finder is located on the bottom front of the vehicle to determine the distance of any objects that are in front of the vehicle. Input from the laser is used to calculate the angle and distance to the nearest obstacle. The concept of the software is to take the detected obstacles from the laser for every degree from 0 to 181 and convert the distances of the obstacles to a 2-D map overlay. The laser function will output a 2-D map overlay, which will be used by the brain to determine the best path for the vehicle to travel. The program will take the input from the laser and place the data into a 181-element array. The obstacle distances will then be converted to a 2-D map overlay for the brain to analyze.

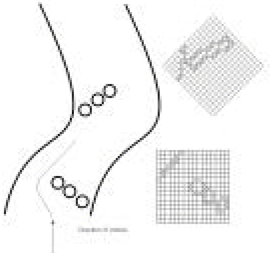


Figure 18: Laser Processing

5.4- Navigation

The brain of the vehicle, which controls all of the sub-tasks within the computer and makes the decisions on where the vehicle will move, will control the navigation of the vehicle. The input from the cameras and the LMS will allow the vehicle to locate obstacles and plot a navigation route for it to travel. For example, it will look twenty feet, though it can look up to 450 feet, ahead of itself, calculate a path, then move ten feet. This will allow prediction of the course in front of it while it moves and allow it to recapture obstacle information that was farther away before it makes a move. The cameras, if not detected by the laser, will pick up low debris, and then the course will be adjusted depending on the debris.

6. Vehicle Design and Performance

6.1 Safety

Safety is one of the most important aspects of design and there is no exception in our design. As stated earlier, we have an approximate factor of safety of 15. This is fairly high, but there are many reasons for this. First, we are using a material that is stronger then we need, but practical because of its cost and weight. Second, the motors we selected are more powerful then needed, but that provides more ability to climb ramps and ability to compensate should more weight be added. The emergency stop that is put on the vehicle for remote and manual stop create the ability to stop the vehicle whenever necessary. The gearing mechanism quickly stops the vehicle when the motors are not powered due to the worm gear configuration. One issue may be the danger of the batteries. However, as long as safety is always considered when handling the batteries, there should be no problems.

6.2 Reliability and Durability

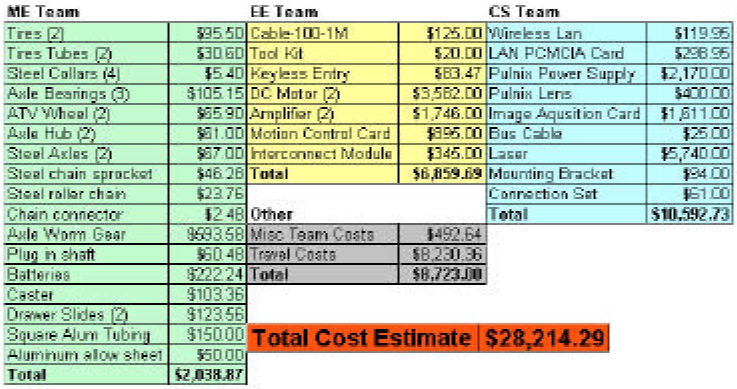
The reliability of our vehicle at the component level is excellent. At the system level, further testing is required. Currently we are conducting operational tests. Because we over designed the vehicle, the safety and performance of our vehicle are quite good. Any reliability issues we may have are in the path planning program, which we are debugging now. Our vehicle is extremely durable because of our strong materials, connections, and welds. We ensured that every part of the frame was welded correctly to ensure strength and each component mounted was put in a spot, which would ensure no damage.

6.3 Problems Faced

Our original design was to have motors that came with internal encoders attached to them. However, we could not find a company that would make the motors we wanted with encoders on them already. We solved this problem by ordering the motors and encoders from different companies. We redesigned the feedback system by putting the encoders directly on the axles of the vehicle instead of having them on the motors. The mechanical team's main problem was the fabrication process. With fabrication it takes an equally innovation and creative mind to find the cheap, quick, and suitable solution. In mechanical situations, we were faced with two issues, "does it fit?" and "is it structurally sound?" This really becomes a single problem that you must work into an individual piece within the assembly. We found that by working together as a team and working by trial and error in some instances, that the small errors in our fabrication could be overcome. In software development, we are using an innovative approach for the very difficult path planning program. We are using the Dykstra's Algorithm mentioned above. In tests, the program is very successful.

6.4 Estimated Cost

The following figure shows our estimated cost of over $28,000. All the specific parts are exact prices, but the travel costs are estimated.



ME Team

Tires (2)	$95.50
Tires Tubes (2)	$30.60
Steel Collars (4)	$5.40
Axle Bearings (3)	$105.15
ATV Wheel (2)	$65.90
Axle Hub (2)	$61.00
Steel Axles (2)	$67.00
Steel chain sprocket	$46.28
Steel roller chain	$23.76
Chain connector	$2.48
Axle Worm Gear	$693.58
Plug in shaft	$60.48
Batteries	$222.24
Caster	$103.36
Drawer Slides (2)	$123.56
Square Alum Tubing	$150.00
Aluminum allow sheet	$50.00
Total	**$2,038.87**

EE Team

Cable-100-1M	$125.00
Tool Kit	$20.00
Keyless Entry	$63.47
DC Motor (2)	$3,562.00
Amplifier (2)	$1,746.00
Motion Control Card	$895.00
Interconnect Module	$345.00
Total	**$6,859.69**

CS Team

Wireless Lan	$119.95
LAN PCMCIA Card	$298.95
Pulnix Power Supply	$2,170.00
Pulnix Lens	$400.00
Image Aqusition Card	$1,611.00
Bus Cable	$25.00
Laser	$5,740.00
Mounting Bracket	$94.00
Connection Set	$61.00
Total	**$10,592.73**

Other

Misc Team Costs	$492.64
Travel Costs	$8,230.36
Total	**$8,723.00**

Total Cost Estimate	**$28,214.29**

Figure 19: Cost Estimate

6.5 Predicted Performance

The speed of our vehicle can go well beyond the allowed 5 mph, but we are designing our vehicle to go slightly less then 5 mph. This is fast enough to keep forward momentum, but slow enough to pick up obstacles and maneuver. The vehicle's reaction time is still being determined. However, current testing shows reaction time of less than one second. The vehicle's ability to negotiate dead ends, traps, and pothole is currently being determined through our tests. However, the primary strategy is to avoid them. The vehicle looks 20 feet and moves only 10 feet. By doing this using our innovative path planning program, we will avoid dead ends and traps. Potholes are easily recognized by our vision sensors and software.

7. Documentation

Accu-Coder *Optical Shaft Encoders Documentation Pamphlet.*

Borenstein, Johann *Where am I? Sensors and Techniques for Mobile Robot Positioning*, (CD ROM)

Conner, David, *Sensor Fusion, Navigation, and Control of Autonomous Vehicles.* Thesis submitted to the Faculty of the Virginia Polytechnic Institute and State University

Galil *Motion Control Product Catalog* (2000).

Ullman, David. *The Mechanical Design Process.* New York: The McGraw-Hill Companies, Inc., 1997.

Virginia Tech 2000 Design Report (Used for report format ideas)