United States Military Academy

MAG

2004 Intelligent Ground Vehicle Competition

Design Report

Multi-Sensory
Autonomous
Ground
Vehicle
Intercollegiate
Competition

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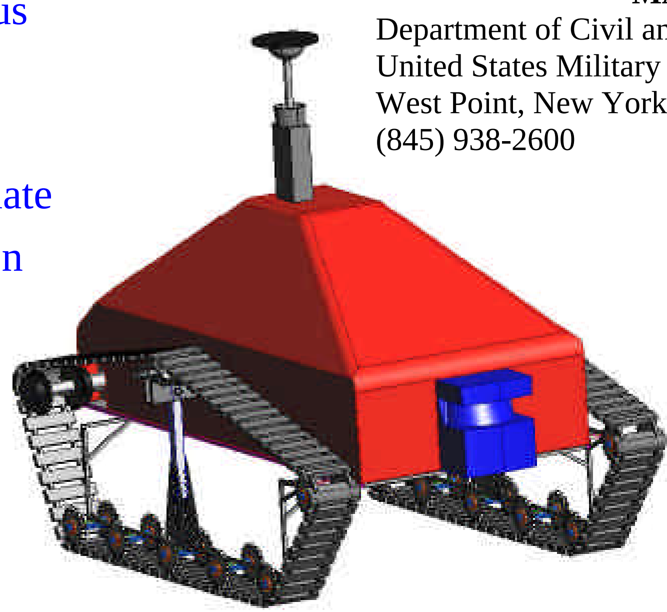

The 2004 MAGIC Senior Vehicle

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1.0 Introduction

The United States Military Academy's 2004 MAGIC Senior team is excited to be competing in the 12th annual Intercollegiate Ground Vehicle Competition. West Point's 2004 entry to the competition, which will be held in Rochester, Michigan, marks the Academy's fourth consecutive entry. This year the MAGIC team will compete in the Design Competition and the Autonomous Challenge at the IGVC. The team has elected not to compete in the Follow the Leader or Navigation Challenges.

Our team, comprising eighteen cadets, represents the computer science, electrical engineering, mechanical engineering, and systems engineering departments. This project allows cadets the opportunity to practice engineering skills that they learned during their course work, while also giving them the experience of working as members of a large multidisciplinary engineering design team.

The MAGIC Senior Team organized during the first semester to begin the year long process of modifying and testing the vehicle designed by the 2003 team. The final product, resulting from a year of hard work, required extensive cooperation between the team members from the various engineering disciplines. This year's team benefited from the experience that West Point gained over the past three years of competition. Past experience weighed heavily in the five-phase design process that the team used to produce this year's entry. As will be seen, the design process led the team to a radically different mechanical approach from that of previous MAGIC vehicles.

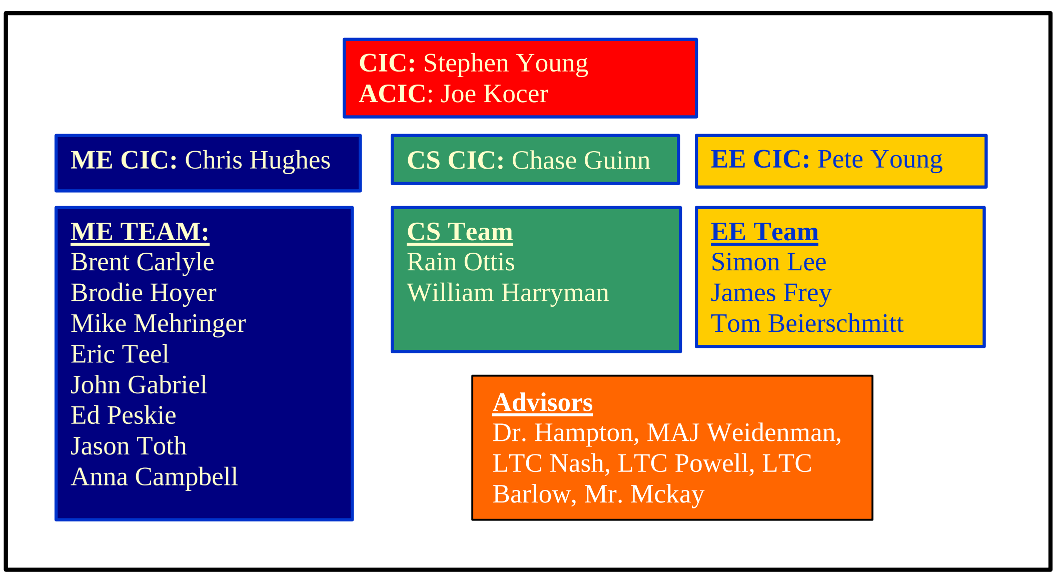

Figure 1: The 2003 MAGIC Senior Team

2.0 **Design Process**

In order to design the 2004 MAGIC Senior vehicle, the team relied heavily on the five-phase design process detailed by Dym and Little in their book, *Engineering Design-A Project Based Introduction*. The stages of our design process included problem definition, conceptual design, preliminary design, detailed design, and design communication. Successful completion of this complicated project, which included the efforts of three independent departments, depended on strict adherence to the design process.

2.1 Problem Definition

The challenging task of designing an autonomous robot began with defining the problem clearly. During the problem definition phase the team set out to identify the customer; determine what the vehicle should be, based upon the customer's needs; identify constraints; and create a refined problem or mission statement for each team. Our client, the IGVC board of judges, required that the team develop a fully autonomous, unmanned ground robotic vehicle to negotiate an outdoor obstacle course within specified constraints. While the immediate need for the MAGIC vehicle arises from this competition, there is also a compelling professional motivation for MAGIC team members.. The Army views autonomous technology as a way to deliver weapon systems to dangerous combat zones without risking the lives of soldiers. This makes the IGVC competition increasingly relevant to the MAGIC team's studies at West Point.

Revised Problem Statement

Goal: Design an autonomous vehicle that successfully navigates the IGVC course

Objectives: Be agile, maneuverable, reliable, cost efficient, safe, transportable, controllable, and autonomous.

Constraints

Design:

1. Must run on combustible fuel or electrical power.
2. Must be between 3 and 9 feet long.
3. Must be less the 5 feet wide.
4. Must be less then 6 feet tall.
5. Must have a 1 inch diameter red emergency stop 2-4 feet high.

Performance:

1. Must carry an additional 18 inch by 8 inch by 8 inch 20 pound load.
2. Must have a wireless emergency stop with a 50 foot range.
3. Must stop within 5 feet.
4. Cannot pause for more than one minute.

Budget Constraints

1. Vehicle and travel expenses cost less the $21,600.

Sub-Team Missions

-**Mechanical:** To design and build a vehicle chassis to house the intelligence and power systems, and to propel itself through the course

-**Electrical:** To design and build the electrical circuitry that will allow for the flow of power and data between the intelligence and power systems.

-**Computer Science:** To design and implement software that will collect and analyze the environmental data, plot an intelligent path based upon that data, and relay the desired path to the power system.

Figure 2: Refined Problem Statement

2.2 Conceptual Design

The purpose of the conceptual design phase is to generate and evaluate alternative solutions to the design problem. The team began the conceptual design by developing a functional decomposition in order to breakdown the complex tasks that the vehicle must accomplish into their most basic functions. After analyzing the vehicle's functions, the team set out to examine quantitatively the customer requirements, and to set the engineering targets using a quality functional deployment. QFD is a Japanese design tool that matches weighted customer requirements with specific, measurable engineering targets. By assigning relative correlation values to the customer requirements and their associated engineering requirements, one creates a weighted list of engineering requirements. This list becomes a specification list when specific engineering targets are chosen based upon the success of similar benchmarked designs.

				Engineering Requi		
	Weight (Customer Importance)	Operating Speed	Stopping Distance	Detection Range	Time to make decision	Turning Radius
Direction of Improvement		↑	↓	↑	↓	↓
compact	0.07		3			3
lightweight	0.06	3	9			
easy to operate	0.07	1	3	1	1	3
safe	0.13	9	9	9	1	
avoid obstacles	0.17	9	9	9	1	9
detect lines	0.17	9	9	9	1	

Figure 3: Excerpt from QFD

Once the team had a clear understanding of what the vehicle needed to be, it was time to generate concepts. A morphological chart organized brainstorming sessions and generated numerous alternative vehicle systems. In order to limit the options, an absolute comparison was done on the alternatives. The comparison included checks to ensure that the designs could accomplish the required tasks within the given constraints, and could be built using current technology, considering the team's level of expertise. After limiting the choices to five alternatives, the team conducted a relative comparison using Pugh's method. This method quantitatively rates each alternative's ability to meet each of the customer requirements. If done properly, Pugh's method indicates the best alternative to be the alternative with the highest cumulative score.

By November 2002, the concept for MAGIC Senior had been chosen. The team decided upon a tracked vehicle that would utilize skid steering; carry a parabolic mirror digital camera, and laser; and operate under a protective fiberglass shell. Specific details about the design are covered in sections 3, 4,

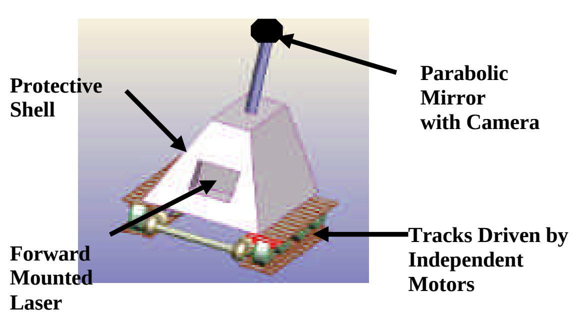

Figure 4: Initial Concept Model

and 5, which cover the preliminary and detailed designs of the mechanical, electrical, and computer science subsystems, respectively.

3.0 Mechanical Preliminary and Detailed Design

This year's vehicle bears little mechanical resemblance to the previous two MAGIC vehicles (Magic 2002 and Magic 2001).

The team changed the mechanical design to overcome problems with traction and weight that plagued the team last year. The changes resulted in an interesting chassis that has overcome the past mechanical problems and that will be sure to turn heads at the competition this June.

3.1 Frame Design

The mechanical design began with the frame. Since two of the important overall design goals were to make the vehicle small and light, the frame was designed to maximize the component layout efficiency. Hollow tubular aluminum and aluminum sheeting comprise the frame. In order to ensure that the frame would not fail, it was modeled and tested using a finite element analysis. The test showed that there would be negligible deformation in the frame, even under extreme loading conditions.

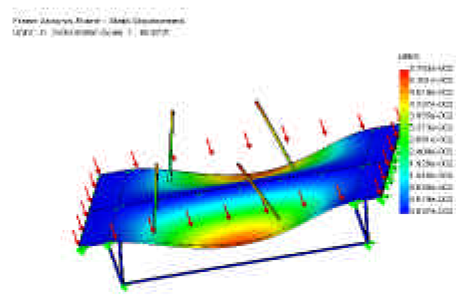

Figure 5: Max Frame Deformation in Hundredths of Inches

3.2 Drive Train Design

After completing the frame design, the mechanical sub team began to design the vehicle's drive train. The first step in designing the drive train was to design the motors. Since the vehicle is tracked, the team conducted an extensive analysis of grade resistance, compaction resistance, and sinkage extensively. For example, from *The Theory of Ground Vehicles,* by J. Y. Wong, compactive resistance is a function of the vehicle's weight, the tracks' contact area, and the soil parameters.

$$R_c = \frac{1}{(n+1)b^{\frac{1}{n}} \cdot \left(\frac{k_c}{b} + k_f\right)^{\frac{1}{n}}} \cdot \left(\frac{W}{l}\right)^{\frac{n+1}{n}} \qquad \textbf{(EQN 1: Compactive Resistance)}$$

The analysis showed that the vehicle required approximately forty pounds of force on the track to achieve the target speed of 0.6 feet per second, given the worst case scenario of sand on a 20 percent slope. Using a tractive effort speed diagram, the team chose appropriate motors for the vehicle. The motors chosen were two right-planetary, 1/7-horsepower motors, with a 30:1 gear ratio. When linked to the 3.8 inch diameter drive wheels, the motors provide 125 pounds of force at the target speed of 0.6 feet per second. The drive train can achieve a maximum speed of 1.35 feet per second under minimal load conditions. By carefully sizing the motors to the vehicle and the desired maximum speeds, the team was able to select dramatically smaller motors then last years' 1.0-horsepower motors. Consequently, the entire electrical system could also be downsized.

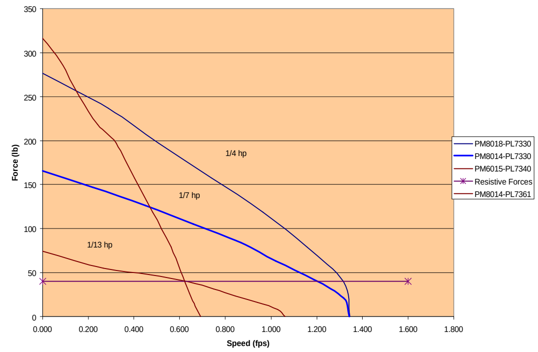

Figure 6: Tractive Effort Speed Diagram

3.3 Track Design

Once the motors had been chosen, the mechanical team moved on to the task of designing tracks for the vehicle. Tracks presented a unique challenge because there are very few commercial track systems that are compatible with this application. The tracks had to deliver the capability for zero slip even under the worst conditions because slip wreaks havoc on the vehicle's artificial intelligence system. They also had to be secured and tensioned in a manner that ensured that they would stay on in all course conditions. The mechanical team's solution was ingenious. Using commercial chains with mounting brackets, the team manufactured thin aluminum track pads and riveted them to the chain. The design provides exceptional traction and reliability.

Figure 7: CAD Model of Track

3.4 Shell Design

Since the vehicle carries expensive and delicate computer equipment on board, the mechanical team decided to design lightweight, waterproof shell. Again the team found a unique solution. The 2004 MAGIC Senior vehicle boasts a one-piece, handcrafted fiberglass shell. Constructing the final shell required countless hours of research into fiberglass, Kevlar, and carbon fiber, as well as countless hours of practice with the fiberglass. Although the team took a risk by attempting to work with fiberglass, the risk paid off by providing the vehicle with a functional, lightweight, aesthetically pleasing, and distinctive protective shell.

4.0 Electrical Preliminary and Detailed Design

The electrical sub team tackled the mission of providing power for all of the vehicle's electronics and a conduit for information flow between all of the vehicle's systems. In completing the electrical design, the team consistently tried to meet the goal to down size each system on the vehicle. This theme began with the battery choice, then continued with the choice of the amplifiers, the location of the terminal board, and the design of the meter panel.

4.1 Battery Selection

The electrical design began with the selection of batteries to power the vehicle. Since components on the vehicle operate on either 12 or 24 volts, the batteries needed to be able to supply both voltages. The batteries also needed to be able to provide power for at least 30 minutes of operation; the time required for one course attempt. In order to meet these requirements, the team chose to use two 12 volt sealed lead-acid batteries, wired in series. By accomplishing a good power analysis, the team determined that 18-amp hour batteries would provide approximately one hour of operating time to the vehicle. The 18-amp hour batteries represent a significant improvement over the 2002 MAGIC design, because they are approximately one quarter the size and weight of the batteries used last year.

Device	V (in V)	# of	Total Energy Consumed(in W*H)	
Laser	24	1	17.5	
Digital Camera	6.5	1	5.2	
Motion Controller w/ ICM	24	1	9	
24V Motor	24	2	153.6	
Amplifiers (without load)	24	2	29	
Total Power Required			215 W*H	
Battery	Cost ($)	Wgt. (lbs.)	Total Energy Supplied (W*H)	Run time(min)
SLA-12V18	29.95	13	216	60.27

Figure 8: Power Analysis

4.2 Amplifier Selection

Next the team chose amplifiers to control the motors. The amplifiers throttle the amount of current that goes to the motors, based upon voltage signals ranging from +10 volts to -10 volts that come from the motion control system. Staying true to the theme of keeping components small, the team drastically reduced the size of the amplifiers. The selected amplifiers provide currents ranging from zero to 25 amps and are the size of a note card. Again, this was a significant improvement over the 2002 design, which relied on shoebox sized amplifiers requiring large heat sinks for cooling.

4.3 Terminal Board Design

With many of the components chosen, the electrical team began the design of the terminal panel. To use space efficiently, the team mounted the terminal board to the bottom of the vehicle. This made it unnecessary to design a separate frame component for the wiring. The terminal board includes a 12 volt bus, a 24 volt bus, a ground bus, and a relay. The 24 volt bus powers the motion control system, the motors, and the laser. The 12 volt bus controls the relay and the digital camera. The relay works with the manual and remote emergency stop systems to ensure that they can kill power to the vehicle in the event that it must be stopped quickly. For safety reasons, each of the bus lines contains fuses for each electrical component, to minimize the risk of a catastrophic and unforeseen current spike.

4.4 Meter Panel Design

The meter panel on the 2004 MAGIC Senior vehicle has also been designed to be compact and efficient. The panel provides voltage readings for the 12 and 24 volt buses as well as a current reading for the entire vehicle. It allows the user to control power independently to the buses, the camera, the laser, and the joystick. Breaker switches are used as an added safety feature, to prevent current spikes from damaging any of the electrical equipment. Finally, the meter panel provides extra switches that can be used to control additional sensors, should next year's team decide to improve upon the design.

4.5 Wiring Design and Power Diagram

The final and most important electrical task was to wire the vehicle. Accurate wiring and power diagrams make this an easy task. A critical requirement given to the electrical sub-team with regard to the wiring was to keep the electrical system simple, well-packaged, and efficient. By relying on the early design work, the team properly sized all of the breakers, the relay, the terminals, the fuses, and all of the wiring.

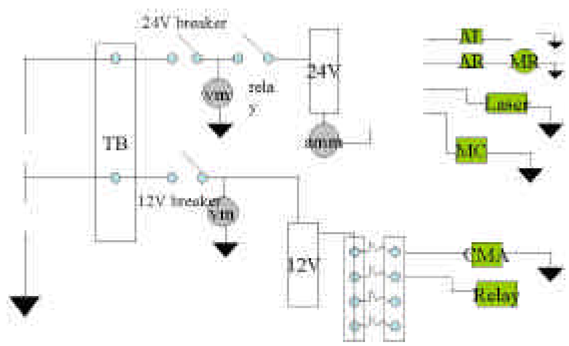

Figure 9: Vehicle Power Diagram

5.0 Computer Science System

5.1 Software Design Process

In the development of the software system for MAGIC this year our team used a form of the Rapid Application Development (RAD) design process. The particular method we followed was a Parallel Prototyping Methodology which divides the project into distinct sub-projects that are designed in parallel in a repeated “Analysis, Design and Implement” cycle until the system is complete. This approach allowed the team to provide test systems in a rapid manner to the group for continuous testing throughout the project cycle.

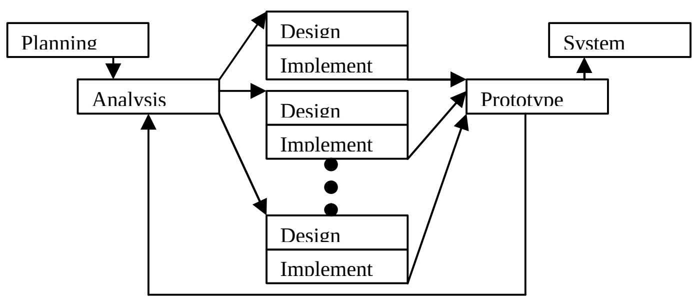

Figure 10: Software Design Process

5.2 Analysis

In this phase of the system development cycle we studied last year’s system to understand its strengths and weaknesses. We then identified opportunities for improvement and began to build a concept for the “to-be” system. Our team based this concept off of the requirements for the Autonomous Challenge rules. Analysis was collected in a Software Requirements Specification document (SRS) and submitted to the rest of the team as our software concept. The SRS detailed performance measures and standards to which our system design would conform

5.3 Design

Our design phase focused on how our system would meet the requirements developed in the Analysis phase. The project was broken into four logical sub-projects for parallel development. Our design of the system took large steps both to break away from the limited data model of the previous system and to create a system that would have as much information as possible to navigate the course. The design plan was captured in a Software Design Document (SDD), which clearly decomposes data and modules in the project and how they will meet the requirements of the SRS.

5.4 Computer Vision (Boundary Avoidance) Implementation

Our team decided to continue using the previous catadioptric imaging system, using a mirror and camera system to overcome the shortcomings of the typical multi-camera "human eyes" approach to the vision problem. Using a RemoteReality "One Shot 360" parabolic mirror, our system acquires a top-down mirror image of the region surrounding the vehicle. We then apply a coordinate mapping to remove the mirror distortion and create a "bird's eye" perspective of the vehicle and an approximately 20'x30' region around it.

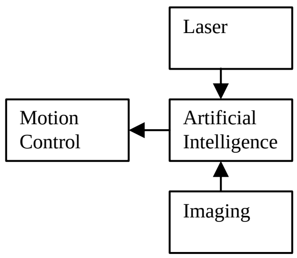

Figure 11: Computer Vision Diagram

Several passes of color threshold, edge detecting, and pixel chaining (line detecting) algorithms are then applied to detect the longest chains of pixels in the image, which are assumed to be course boundaries. The long range of our vision system ensures that our vehicle is always able to find the boundaries in an image, independent of line color or gaps in the lines.

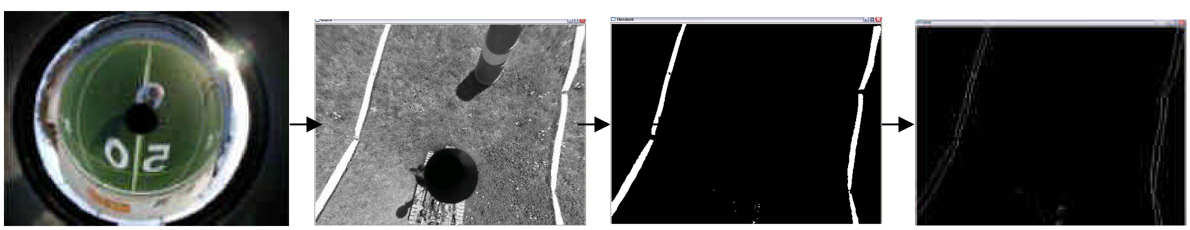

Figure 12: Image Processing

New this year is a software calibration and visualization package using OpenGL. This allows the user to calibrate the image on site, and to see the robots presentation as it does – showing the boundaries, barrels, current position, and path choice in a common coordinate system. This system has proven invaluable in the testing of the AI.

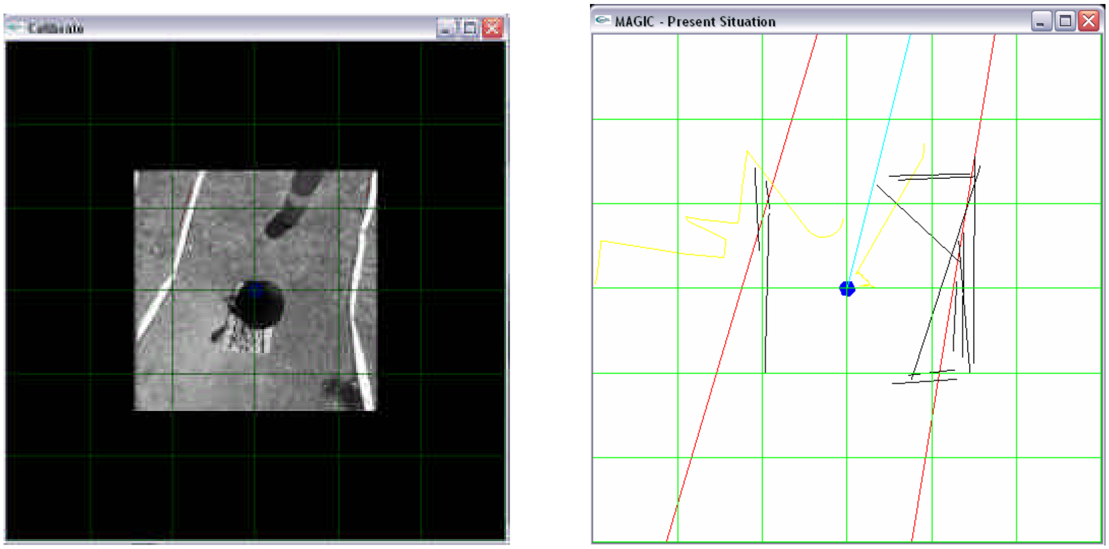

Figure 13: Open GL demonstration

5.5 Laser (Obstacle Avoidance)

Design on this module was centered around the SickOptic LMS-200 scanning laser. Our team decided to restrict the scanning range of the device to around 3 meters, as there is no need to scan further than our vision module can sense the course boundaries. The laser returns 180 degrees of measured distances. We decided to make the Laser Subsystem purely responsible for data collection, and allow the Artificial Intelligence to do all path decision making.

5.6 Artificial Intelligence (Path Planning)

The artificial intelligence subsystem uses the boundary data, in terms of coordinates of the boundary lines endpoints, and the laser data, in terms of distance to obstacle per degree scanned, to compute an optimal path. The general algorithm the laser uses is simply to check for gaps of *free space* – places where the robot can move forward and hit neither a boundary nor an obstacle. The algorithm chooses the largest gap and chooses a path and distance that will take it to the center of that gap.

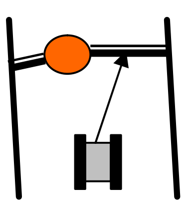

Figure 14: Path Selection

6.0 Concluding Remarks

Once each sub team finished construction of the vehicle, the team tested the design and prepared for the competition.

6.1 Testing

Upon completion of the design and construction of MAGIC Senior, the team began an extensive testing schedule. Testing was broken down into phases, with the first phase being reliability testing of the mechanical and electrical subsystems. Following those tests modifications were made to improve the vehicle's reliability and performance. For example, the original tracks provided to much lateral traction, making it difficult to conduct skid steering operations. To solve the problem, the corners of the track pads were flattened to provide additional lateral slip. Other modifications included strengthening the motor mount system to ensure that it would not fatigue and repackaging the wiring to ensure that it would not interfere with the vehicle. Once the sub-teams made modifications, the vehicle's AI was tested.

AI testing proved to be the most crucial aspect of the entire project. The vehicle's intelligence only expanded with each hour that the team spent testing it. Initial AI testing included testing the data collection from the camera and the laser. Experiments were run to determine how the parameters for each device needed to be set to gain maximum accuracy. Next, the distance and turning constants that correlate encoder counts to vehicular movement also had to be determined experimentally. Finally, the team tested the vehicle in various course scenarios. Each additional day of experience during this phase of testing only makes the vehicle better.

6.2 Budget

Since the 2003 MAGIC team improved upon the 2002 MAGIC team's intelligence system instead of starting from scratch, the project came in well under budget. In September, the team started with a budget of $10,200 to manufacture

	Parts Budget				
Optional	**Name**	**Model**	**Price**	**Quantity**	**Totals**
Y	Motion Control Card	Galil DMC 2020	1995	1	1995
Y	Interface Card	Galil ICM 1900	345	1	345
	1/7 HP Motor w/ Encoder and Gearbox		400	2	800
	Power Amp	Advanced Motion Contols 25A8	295	2	590
	LapTop	Sony VAIO® R505G SuperSlim Pro	1800	1	1800
	LapTop Bag	PCGA-CCP1	70	1	70
	Wireless Network Card	Wireless LAN PC Card	90	2	180
	Network Access Point	Sony VAIO® 2.4GHz Wireless LAN Access Point Pro (PCWA-A200)	250	2	500
	Extra Battery	Capacity Lithium-Ion Battery (PCGA-BP4R)	500	1	500
	Track		100	5	500
	Radio Contol System		500	1	500
	12 Volt Battery	840370 12 Volt 18 AH	45	4	180
	Misc Parts				750
	Total				**8710**
	Total Without Redundancy				6270

the vehicle and an additional $10,400 for travel expenses. In general, the expenses to build the vehicle were low, with the most expensive parts being new motors and amplifiers. The team will use the money that it saved to purchase tools that will be invaluable to future West Point MAGIC teams.

6.3 Summary

The 2004 MAGIC Senior team is excited to compete in the 12th annual Intelligent Ground Vehicle Competition. The team's entry represents an entire year of dedication and extensive team work. The final design builds upon the strengths of the 2002 vehicle, while improving upon its weaknesses. We are confident that the tracked design, fiberglass shell, and overall appearance of the vehicle is sure to turn heads come June 12th . Throughout our design, our commitment to the design process evidences itself, because components are small, space is used efficiently, and our specifications are met. We are proud that the concept briefed during the conceptual design phase nearly mirrors the vehicle that we manufactured. Our engineering analysis allowed us to predict the vehicle's performance before a single test was run. Finally, another year of experience has vastly improved the MAGIC vehicle's AI. The new software is more accurate, more reliable, and more easily modifiable. Its modularity is sure to be invaluable to future classes that begin where the class of 2004 left off. All in all, we anxiously await the opportunity to compete with our design.

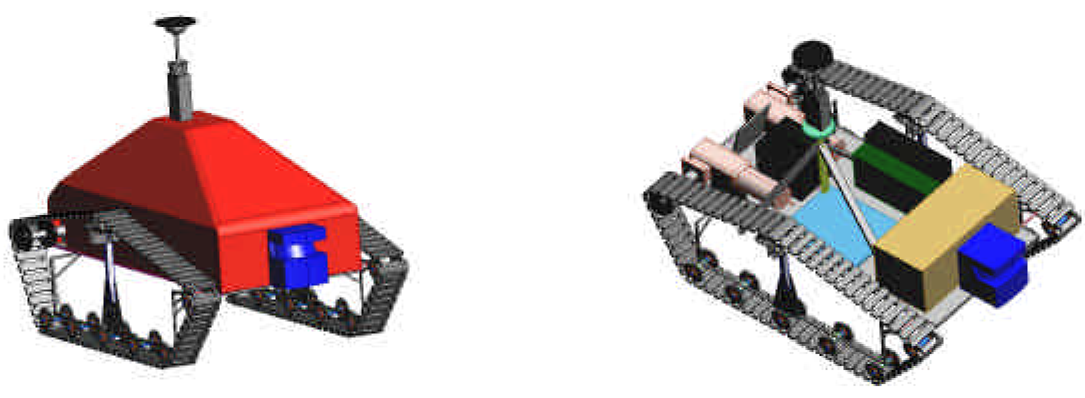

Figure 15: CAD Model of the 2004 MAGIC Senior Vehicle with and without Protective Shell