Black MAGIC

Multi-Sensory
Autonomous
Ground Vehicle
Intercollegiate
Competition

United States Military Academy

2005 Intelligent Ground Vehicle Competition
Design Report

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1.0 Introduction

MAGIC (**M**ulti-sensory **A**utonomous **G**round vehicle **I**ntercollegiate **C**ompetition) is the United States Military Academy's code name for its robots that enter the Intelligent Ground Vehicle Competition each year. At this year's competition in Traverse City, Michigan, MAGIC Junior is returning for its second appearance, aptly renamed "Black MAGIC." While it shares a few components with its predecessor, Black MAGIC looks and operates nothing like the 2004 MAGIC Junior vehicle. The 2005 MAGIC team will be entering the Autonomous Challenge and the Design Competition, but has opted out of the Navigation Challenge.

The 2005 MAGIC team consists of 11 cadets from four different departments at West Point: computer science, electrical engineering, mechanical engineering, and systems engineering. The MAGIC project is the culminating capstone of our undergraduate education, spanning two semesters and integrating material we have learned in our engineering courses. As an interdisciplinary effort, the MAGIC project also teaches teamwork as well as giving cadets respect for and an opportunity to learn about different engineering fields.

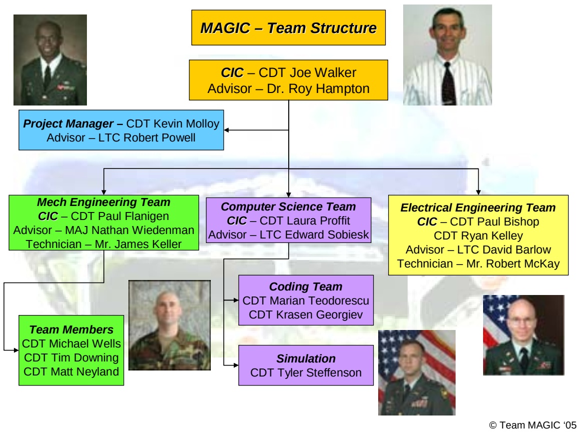


Figure 1. 2005 MAGIC Design Team

Black MAGIC is returning to the competition this year with a new frame and drivetrain design, a modified electrical system, and a new AI approach, all encased in new aesthetics. The vehicle represents the hard work of each and every cadet on the team and we are excited to see how it will perform in the 13th annual IGVC.

2.0 Design Process

The 2005 MAGIC team followed a five step design process as outlined by Dym and Little in the 2nd edition of *Engineering Design*. The five stages of design are problem definition, conceptual design, preliminary design, detailed design, and design communication. Originally started as a limited redesign project, the team realized we would have to complete the entire design process to produce a successful vehicle.

2.1 Problem Definition

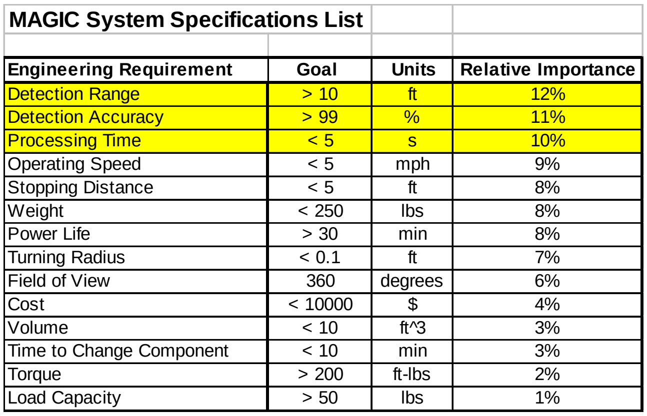
After reviewing the goals and constraints of the IGVC, the team analyzed the vehicle inherited from the 2004 team. With help from the previous team's comments, we were able to identify the vehicle's main weaknesses and develop a plan to overcome them. We also identified our primary goal to be successful in the Autonomous Challenge and decided not to design the vehicle to enter the Navigation Challenge. The problem statement for the 2005 team is the following:

> "The 2005 MAGIC team will compete successfully in the 13th annual Intelligent Ground Vehicle competition held in Traverse City, Michigan from 11-13 June 2005 with Black MAGIC by designing a new frame and drivetrain, making necessary modifications to the electrical system, and continuing to improve the AI code"

In this phase we also established weighted design objectives with a pairwise comparison and completed a functional decomposition for the vehicle.

2.2 Conceptual Design

During this stage of the design we completed a quality functional deployment (QFD) on the vehicle and benchmarked it against the only vehicles to successfully complete the Autonomous Challenge in the past. From this we determined our engineering specifications list and design targets. We determined our three most important areas of interest to be processing time between movements, detection accuracy, and detection range. From our morphological chart where we considered several ideas to perform each function on the vehicle, we developed our three primary concepts: a tracked vehicle, a wheeled vehicle, and a half-tracked vehicle.



MAGIC System Specifications List

Engineering Requirement	Goal	Units	Relative Importance
Detection Range	> 10	ft	12%
Detection Accuracy	> 99	%	11%
Processing Time	< 5	s	10%
Operating Speed	< 5	mph	9%
Stopping Distance	< 5	ft	8%
Weight	< 250	lbs	8%
Power Life	> 30	min	8%
Turning Radius	< 0.1	ft	7%
Field of View	360	degrees	6%
Cost	< 10000	$	4%
Volume	< 10	ft^3	3%
Time to Change Component	< 10	min	3%
Torque	> 200	ft-lbs	2%
Load Capacity	> 50	lbs	1%

Figure 2. Specifications List

2.3 Preliminary Design

Previous MAGIC teams had steered away from wheeled vehicles because of the higher amount of slippage inherent in them when compared to tracked vehicles, but we chose to return to a wheeled vehicle for simplicity's sake. At this stage we incorporated an electronic compass into the design to help the machine know when it had slipped and failed to complete a turn. We chose to retain the same AI package as previous years which allowed the computer science sub-team to make improvements on the already existing AI code instead of starting completely from scratch. The detailed design work will be discussed further for each sub-team.

3.0 Mechanical Design

The mechanical team has four members and their system consists of the frame, drivetrain, component shelf, camera stabilizer, and shell.

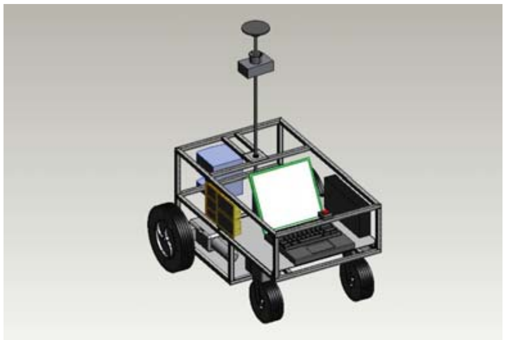


Figure 3. Initial CAD Design

3.1 Frame Design

The frame of Black MAGIC is constructed of 3/4” hollow square aluminum tubing of 1/8” thickness that is welded at the joints. Aluminum was chosen for construction because of its high strength to weight ratio. The box-like design of the frame allows the maximum room for components while keeping the total size of the robot small. The frame is shorter and wider than the frame of the previous vehicle to allow for easier turning. An aluminum sheet on the bottom tier of the frame supports the motors and batteries, keeping much of the vehicle weight forward on the driving wheels.

3.2 Drivetrain Design

After completing a tractive effort speed diagram the team determined that the same 1/7 hp motors connected to a 90° differential with a 30:1 gear reduction ratio cannibalized from the old vehicle would suffice to provide necessary power for the new design. This allowed us to cut costs. Sleeves to fit the existing axle shafts of the differential were machined and welded into two 12” pneumatic tires. Based on the design of the frame and the desire to keep a clear field of view for the vehicle’s camera, the driving wheels were placed at the front of the vehicle. The supporting wheels in the rear of the vehicle are 8” pneumatic casters. The casters pivot easily to help the vehicle steer. Black MAGIC uses reverse steering, so when the vehicle makes a left turn the left wheel is in reverse and the right wheel is going forward. We predicted a top speed of 1.5 mph for the vehicle under full loading conditions and testing confirmed that our estimate was accurate. Our initial drivetrain testing also confirmed the ability of the vehicle to climb greater than 15% grade slopes.

3.3 Components Shelf Design

Because the vehicle frame has no suspension, the team was concerned with potentially harmful vibrations the electronics might be subject to as the vehicle traverses the course. To counter this threat the team designed the components shelf, an aluminum sheet on which the electrical components of the vehicle are mounted. Each corner of the shelf is mounted on a vibration isolator chosen specifically to support a quarter of the shelf weight. The isolators are then mounted to the vehicle frame.

3.4 Camera Stability Control Design

Another concern annotated by the previous design team is that if the vehicle tilts at all while moving over uneven terrain that effect is magnified at the camera height and causes the camera to get a distorted perception of the surroundings. We devised a method to keep the camera vertically upright at all times despite the orientation of the vehicle. The camera is mounted atop a hollow, cylindrical aluminum tube. The tube is mounted to the frame through a gimbal. This gimbal allows the camera to rotate around both horizontal axes without rotating around the vertical axis. At the bottom of the rod is a 10lb counterweight to stabilize the system. However, without some damping force to slow the motion of the rod, the camera would oscillate continually as the vehicle moves. As a solution, two bungee cords are wrapped around the rod near the mount of the counterweight and run from left to right and front to back. These bungee cords provide frictional damping as the rod moves, and with their use we have created a nearly critically damped system.

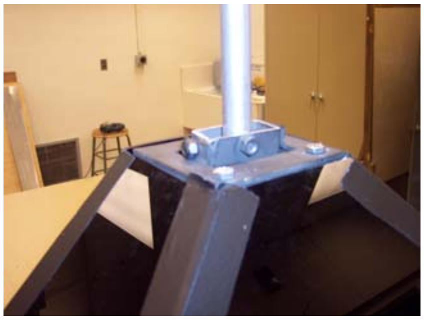


Figure 4. Gimbal

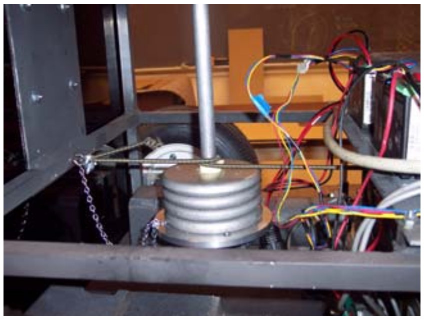


Figure 5. Damping System

3.5 Shell Design

The shell of the Black MAGIC is constructed of 0.144” thick opaque black Plexiglas. This shell material was selected for its aesthetic beauty as well as its ease of construction. The individual pieces of the shell are attached using Velcro tape and waterproof tape covers the seams. This results in a sharp, shiny finish that is impervious to the elements. Because the selected material is black and forms a tight enclosure, computer fans are used to cool the electronic components inside. Two 3” fans are mounted to the inside of each side of the vehicle and channel air through a drilled pattern in the side panels. One side blows hot air out of the vehicle and the other side pulls outside air in to create a draft directly across the most sensitive components.

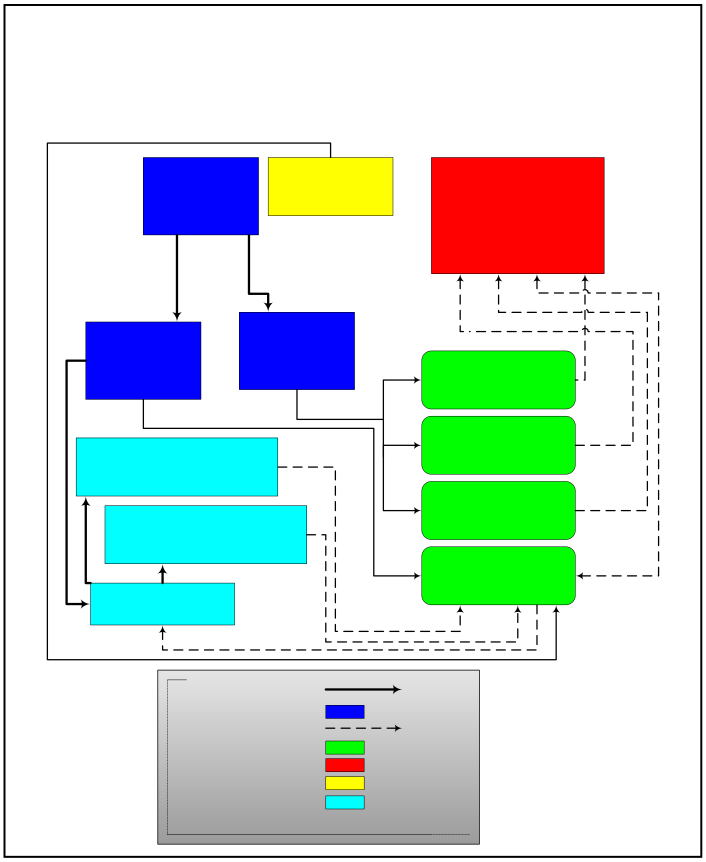


Figure 6. Electrical Circuit Block Diagram

4.0 Electrical Design

The responsibility of the electrical engineering sub-team is to provide a safe, efficient electrical system that adequately meets the power requirements of all the vehicle’s components. The two main subsystems of the electrical design are the motion control and power panel systems.

4.1 Motion Control Design

The motion of the vehicle is controlled by the independent drive of the vehicle’s two driving wheels. Independent directions for each wheel are sent from the heart of the vehicle’s AI, the laptop, to the Galil motion controller. The motion controller converts these directions into -10V to +10V signals that are sent to the respective amplifiers of each motor. The pulse-width modulated control amplifiers determine from that signal how much current to draw for each motor. Each motor has a shaft encoder on the axle shaft that then feeds back information about the number of rotations and angular velocity of the shaft to help the vehicle determine how far it has moved.

4.2 Power Panel Design

The power panel from the old machine was removed, refined, and redesigned to fit into the space requirements of the new Black MAGIC. The panel consists of two parallel DIN rails, mounted at the rear of the vehicle for easy access, with a wire conduit running between them. The DIN rails allow quick construction or modification or the wiring circuit because components, such as terminal blocks and relays, can be easily snapped on or off of the rails. Because the components of the vehicle run at different voltages, one of the DIN rails is a 24V circuit while the other is a 12V circuit. This physical separation of the circuits makes the circuit less complex and easier to troubleshoot. The main power source of the vehicle consists of two 12V batteries mounted at the base of the frame. To accommodate the emergency stop requirements of the competition, a wireless emergency stop controls a relay on the amplifier circuit and the manual emergency stop controls a switch. If either are activated, the motor amplifier circuit is broken and the vehicle ceases to move, but the other components of the vehicle retain power.

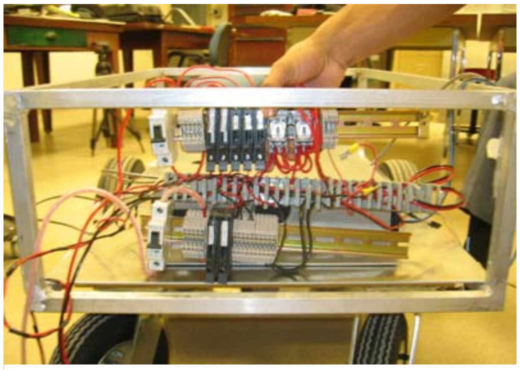


Figure 7. DIN Power Rails

4.3 Testing and Analysis

An area the team expanded on this year was extensive testing of the electrical system. The team used LabView to analyze the transient and steady-state power consumption of the vehicle. We were concerned with the effects that constant on/off switching of the motors would significantly affect the power usage of the vehicle and the safety of the components from voltage and current spikes. Our analysis has allowed us to better understand the actual power consumption of the machine. We have also verified that the vehicle components are adequately protected by the voltage and current transients produced by rapid on/off switching of the motors. Our results have verified our electrical system design as well as validated that we can meet our design objective of 30 minutes minimum battery life.

5.0 Computer Science Design

The computer science sub-team is tasked with creating the artificial intelligence of the system, essentially the “brain” of the MAGIC vehicle. The major subsystems of the AI are boundary detection, obstacle avoidance, path planning, and motion control.

5.1 Boundary Detection Design

Our team decided to continue using a 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 360 degree bird’s eye image of the area around the vehicle. Last year’s team focused on creating an algorithm to map the white boundary lines on a coordinate system. The process consists of five phases shown in Figure 8. The basic algorithm for identifying the two line segments from the original distorted image is to first convert the image from color to gray scale. Using a gray scale image makes it easier to set up thresholds when identifying white objects such as boundary lines. The gray scale image is then undistorted using a previous years’ code. During the next step, the undistorted image is analyzed for patterns and an algorithm uses line segments to estimate the course boundary lines found within the image. The final step creates a list of found line segments, identifies its recommendation for which segments to use, and passes these to the navigation module for use in determining the next move by the vehicle. Figure 8 portrays these steps. The most challenging problem that lies within this process is creation and identification of correct line segments. This process is very successful for straight lines, but fails to recognize curves. Our main task in boundary detection was to modify the process so that curves could be detected.

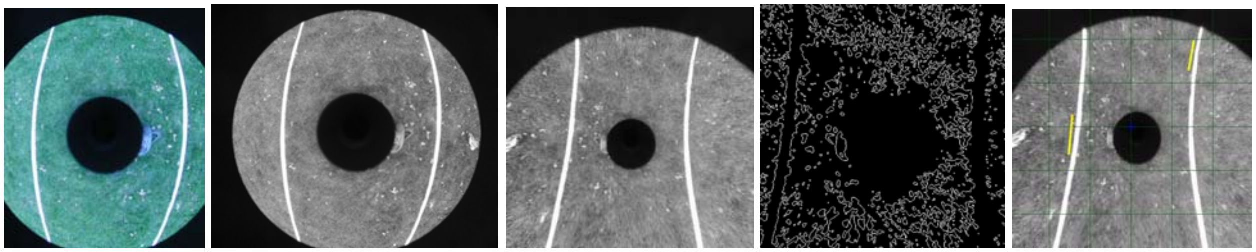


Figure 8. Five Phases of Boundary Recognition

Figure 9 shows an example of an image with curved lines and image portraying the results of running the previous year’s algorithm against this image to produce two line segments. When there are curved lines, the line segments identified (if any) will often not aid the navigation module in computing future movement.

In order to deal with these curved line situations, this year’s team has enhanced the image processing algorithm. Now, the code decomposes the original image into several horizontal slices, as shown on the left of Figure 9. In order to accomplish this, the image is converted from JPG to PPM format. The user can define the number of slices the image is divided into. The slices are then converted back into JPG format. Each of these slices of the image is then fed separately into the imagery module. From this point, each slice is processed through the algorithmic steps described in the above paragraphs to identify up to two line segments within the slice. The right side of Figure 9 shows the line segments produced based on this divide and conquer method. These line segments are now passed to the navigation module. This technique will be used for all images, even those with straight lines.

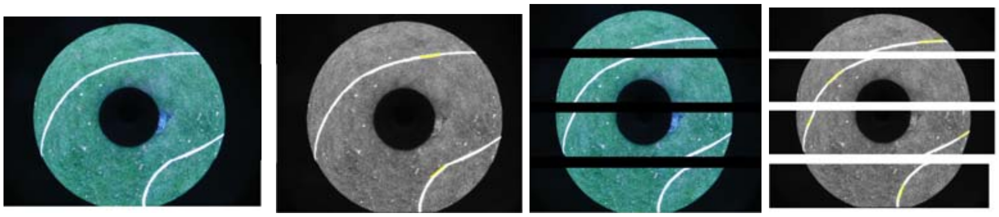


Figure 9. Original Image (left) and the Divide and Conquer Method (right)

5.2 Obstacle Avoidance Design

The intent of the laser sensor is to identify the relative location of vertical obstacles, such as barrels and cones that are within three meters of the front of the vehicle. The laser module conducts a 180 degree forward scan that will contribute to calculating the next movement by establishing the direction and distance to near vertical obstacles.

The most recent implementation of our CS code did not integrate the laser sensor into the system. Previous work supplied a working SICK laser, the manufacturer's drivers, cadet-written code for interfacing with the driver software and setting up the laser, and the hardware to allow the laser to make a 180 degree scan. This year's work with the laser is focused on fully implementing and integrating use of the laser for vertical obstacle detection and identification.

The laser acts as a range finder to targets allowing accurate relative mapping of obstacles in the path of the vehicle. Since not all detected targets are actual obstacles, the laser will also differentiate between a rise in the elevation of the terrain and a legitimate obstacle. The laser takes 181 separate reading from 0 to 180 degrees, with directly forward of the vehicle being 90 degrees. The returned readings represent the distance to any vertical masses detected at the respective direction in degrees. To determine if a return within three meters is an obstacle or a rise in elevation, the code identifies the directions of the first and last detected points of a vertical object. Using the angle formed by these two directions, it calculates the visible width of the object. If the difference between any two consecutive range readings is less than a specified constant, then the readings are considered to be part of the same object. To determine if the object is a rise in elevation or an actual object, the rule of cosines is applied. The distance and directions of the first and last detected points of the object are used to calculate the visible width of the object. If this resulting visible width is greater than a given constant, which represents the max diameter of any legitimate obstacle, then the object will not be considered as an obstacle and the returns will instead be attributed to terrain elevation. All readings, which are part of the elevation rise and had directions readings between the first and last detected points, will be overwritten with a value designating “no obstacle.” This same distance value is assigned to any returns that are greater than three meters so that it is clear to the navigation module where legitimate obstacles are located.

The readings, which include any vertical obstacle information, are then passed to the navigation module which uses them to calculate movement decisions as is described in the next subsection.

5.3 Path Planning Design

To calculate the navigation decisions, the navigation module of the system takes information about the environment from the two sensor modules described above, determines which direction(s) and distance(s) the vehicle should move for the next three meters, and then passes the movement information to the motion control module.

Previous implementations of the navigation module calculated the best direction to move based on boundary lines generated by the imagery module. The navigation module from last year verifies that two lines are passed to it and calculates the intersection of those two lines. If the intersection is forward of the vehicle, the vehicle turns towards it. If the intersection is behind the vehicle, the vehicle turns 180 degrees away from the intersection. The distance to move was calculated as the distance between the intersection and the vehicle with a maximum of two meters. The laser information was not integrated into last year’s navigation module’s decision process.

This year’s CS team is improving the navigation module’s treatment of curved course boundary lines, will incorporate the laser information into the movement planning process, and is improving the predictability of the overall CS systems.

The greatest challenge for our predictability and vehicle in past competitions has been the curved boundary lines on the course. Previous implementations that only identified two straight lines per picture simply could not deal with any significant curved lines. Fixing this shortfall is the primary contribution that this year’s team hopes to accomplish.

The multiple pairs of line segments will then each be run through the navigation module and instead of just one large movement per sensing, the vehicle will now make a series of movements, the intent of which is to maneuver it successfully through curves. As discussed in the imagery subsection, the team will empirically determine how many subsets of the original image provide optimal performance.

This year's team is also adjusting the distance calculation code within the navigation module. Prior to considering the laser information, the module determines the distance of the move. If there are two lines and they intersect, the vehicle distance is set to the distance between the vehicle and the intersection of the lines with a maximum of three meters. If there are less than two lines or the lines are mathematically parallel, the distance is set to three meters. Three meters was selected as the maximum distance based on the range of the image taken by the digital camera.

The navigation module uses the laser data to determine that its chosen path is clear. If the laser finds no obstacles on the path already designated, the vehicle will move on that path. If there is an obstacle within 12 inches of the vehicles projected path, the vehicle will move to a distance one meter in front of the obstacle. The vehicle will calculate determine which direction around the obstacle it should take.

5.4 Motion Control Design

The motion control module communicates with a GALIL motion control system to turn and propel the vehicle. In previous implementations of the vehicle, the navigation module sent movement instructions to the GALIL device, and the device would then attempt to move the vehicle the direction and the distance specified. Despite the proper communication, the vehicle sometimes did not make the correct movement due to slippage of the tracks. To aid in compensating for slippage, this year's team is incorporating an electronic compass into the motion control module. Prior to movement, the vehicle records both its current and target headings. The vehicle will continue to turn until the target heading is reached. Once the vehicle reaches its target heading, it moves forward. While the vehicle is moving forward, it will maintain its target heading. If it goes off of the heading by a certain number of degrees, the vehicle will stop, pivot to reorient and then continue movement.

6.0 Testing

Before the old electrical system on MAGIC Junior was dismantled, the mechanical system of the vehicle was tested for functionality. After the electrical system was updated, the team began an extensive schedule of testing. The initial phases reconfirmed the functionality of the mechanical system and evaluated the new electrical system of the vehicle. With fully tested mechanical and electrical subsystems, the team focused on safety and qualification tests. We verified that the remote and manual emergency stops worked properly and that the vehicle could perform basic movements. The rest of the testing was designed to simulate the actual conditions of the Autonomous Challenge with increasing complexity. Initially we tested the vehicle using white painted strips of plywood to simulate lines and orange construction barrels for our obstacles. As testing continued, we increased the length of our test course as well as the amount of curvature of the lines and the number of obstacles and difficulty of placement. This testing proved the vehicle’s ability to recognize obstacles and lines with relatively high accuracy out to a distance of three meters. Our final testing involved using painted lines representative of what the course boundary markers will look like. During this final testing we determined that the vehicle still has problem finding painted lines, and we are working to correct this issue before competition. In all of our testing, safety was a concern and none of the testing was performed without a working manual or remote emergency stop.

7.0 Budget

The 2005 MAGIC team received $18,000 in funds this year from the Association of Graduates to cover the fabrications for both of our IGVC entries, as well as the travel expenses for the competition. The total amount spent on the construction of Black MAGIC and the entry fees tops out at about $3300, putting us just under our budget of $3500 for the vehicle.

2005 Black MAGIC Expenditures	
Department	Cost
ME	$648.23
EE	$1,650.00
CS	$799.00
Team	$200.00
Total	$3,297.23
Alloted	$3,500.00
Remainder	$202.77

Figure 10. Black MAGIC Budget

8.0 Acknowledgements

Our project would not have been successful without the help, expertise, and guidance of our project advisors: Dr Hampton, Major Wiedenman, Lieutenant Colonel Sobiesk, Lieutenant Colonel Powell, and Lieutenant Colonel Barlow. We also owe many thanks to our technicians who helped us along the way with the more complex design work and machining that we performed. Lastly, we would like to thank previous MAGIC teams for their documentation and comments which have helped us redesign MAGIC Junior, now called Black MAGIC, into a successful vehicle.

9.0 Summary

The autonomous technology that we have researched this year is applicable to the future not only in the terms of developing science and technology, but also the social and ethical implications that we may see in unmanned ground and air warfare in our future as Army officers. We have been happy to take part in the initial stages of technology that may revolutionize the way we function as a society. The team is thrilled to see how the vehicle is going to compete this year in the 13th annual Intelligent Ground Vehicle Competition. Though we originally started out with the mindset of improving the existing vehicle, our redesign project produced a completely new design that bears no resemblance to the previous vehicle. Black MAGIC has improved by leaps and bounds over the vehicle we inherited from the 2004 Design team. The vehicle has an excellent mechanical design, an improved electrical system, numerous AI code improvements, and a beautiful shell to pull it all together. All of this is due to the estimated 1800 man-hours spent on the project. Our countless design changes will prove successful at this year’s competition and we will be able to leave an even better vehicle for the 2006 MAGIC team to improve upon next year.