

PROJECT MAXIMUS

2000-2001 Autonomous Vehicle Team Of Virginia Tech



Team Members:

Eric Ruggiero
Chris Cantrell
Fernando Perez
Peter Boelhouwer
Roy Robertson
Chris Terwelp

Faculty Advisor: Dr. Charles Reinholtz
Department of Mechanical Engineering at Virginia Tech

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Required Statement from Faculty Advisor

I, Dr. Charles Reinholtz of the Department of Mechanical Engineering at Virginia Polytechnic Institute and State University, do hereby certify that the engineering design of the new vehicle, Maximus, by the current Maximus team, has been significant and each senior team member has earned six senior design project credits from this University.

Signed, (Date)

Dr. Charles Reinholtz
(540) 231-7820

1. Introduction

The 2000-2001 Autonomous Vehicle Team of Virginia Tech has worked diligently over the past seven months designing a new, innovative vehicle. After carefully considering the strengths and weaknesses of past designs, Virginia Tech's design team developed a new concept vehicle superior to all predecessors—a differentially driven two-wheel vehicle with front and rear ball casters. Even more importantly, the vehicle integrates cutting edge technology with high-priority design issues like safety and modularity.

Innovation drives our new design. We designed the frame of the vehicle with T-slotted aluminum beams, which provide structural integrity and are easily fabricated. Further, the framing material allows for easy redesign, an important feature of a research vehicle of this type. The vehicle is controlled by an on-board personal computer, but all programming and debugging is accomplished off-board with wireless ethernet. Wireless ethernet eliminates the additional weight of an onboard monitor and keyboard. It also simplifies programming and monitoring vehicle performance. We designed the vehicle such that the weight is centered mostly over the differentially driven axles. By centering the weight, the vehicle has excellent traction. Further, we also developed a new, innovative caster ball support system for the front and rear of the vehicle that rolls in all directions and balances the vehicle as needed. Finally, in an effort to generate interest about our robot, we are going to install voice recognition software to make the vehicle interactive.

The vision and control systems of our new design are based on a hybrid technology developed for several previous vehicles. Yet unlike previous designs, the camera is mounted high in the rear of the vehicle, thus increasing the field of view. An onboard motor controller package drives the two differentially driven wheels. By developing a robust and adaptive navigational algorithm, the team is confident that the new vehicle will successfully compete in

all four phases of Intelligent Ground Vehicle Competition. This report outlines the intensive design process and development of Virginia Tech’s new autonomous vehicle, Maximus.

2. Design Process

2.1 Design Methods

One key to success in creating a superior autonomous vehicle is an organized approach to the design process. The conceptual development process used to create Maximus, as outlined by *Product Design and Development* (Eppinger & Ulrich, 2000), consists of seven stages (as shown in Figure 1).

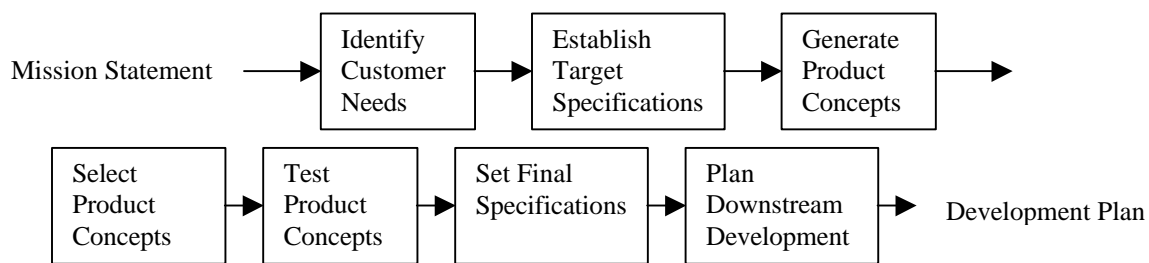


Figure 1. Seven Stages of Conceptual Development

The design process is both iterative and reflective – as each phase is completed, the team reflects on the results and decides whether or not to continue with the process.

To identify the strengths and weaknesses of past autonomous vehicle designs, the team interviewed previous student team members Colin Campbell and Philip Kedrowski, the team’s advisor, Dr. Charles Reinholtz, and a previous competition judge, Bill Agnew. From these interviews, we deemed the following design criteria most important: safety, overall vehicle weight, mechanical durability, maneuverability, dynamic stability, and ease of programming.

Next, using the design criteria, we established product specifications (for example, the vehicle’s ability to make zero radius turns) and advanced to concept generation. The team brainstormed various ideas and possible solutions to the identified customer needs. From these brainstorming sessions, four promising ideas were chosen and evaluated. Artemis, a highly successful previous design, was used to establish a point of reference within a selection matrix. The ultimately developed Maximus design scored higher in multiple areas of comparison among the ideas in the selection matrix, including Artemis.

After selecting the Maximus concept, a full-scale mock-up of probable mechanical and electrical components and framework was constructed out of cardboard. Using the mock-up, we were able to predict and modify the interior layout for optimal space and mass balance.

2.2 Design Team Organization

The team consists of seven mechanical engineering students and two electrical/computer engineering students. Table 1 shows the names, academic department, class level, and hours worked by each member of the team.

Table 1. Maximus team roster and member responsibilities

Name	Major	Class	Class Credit	Responsibilities	Hours
Peter Boelhouwer	ME	Senior	6 hr Senior Design	Frame design and construction	222.5
Chris Cantrell	ME	Senior	6 hr Senior Design	Vision and computing systems	192.3
Fernando Perez	ME	Senior	6 hr Senior Design	Frame design and CAD work	199.0
Roy Robertson	ME	Senior	6 hr Senior Design	Frame design and construction	188.0
Eric Ruggiero	ME	Senior	6 hr Senior Design	Team captain, frame design, and construction	265.5
Chris Terwelp	ME	Senior	6 hr Senior Design	Computer and motor controller systems	224.0
Kris Luisi	CpE	Junior	Volunteer	Software	30
Juan Vera	CpE	Junior	Volunteer	Software	30
Shazed Islam	ME	Junior	Volunteer	Software	25
TOTAL TEAM HOURS					1376.3

2.3 Computer Aided Design

All preliminary and final versions of the vehicle and its components were designed using Mechanical Desktop (MDT). Some of the benefits MDT provides include: a finite element analysis package to determine critical stress points within the frame; a 3-D part interference check to assure all components fit together properly; and material and mass analyses to determine the weight of the structure. MDT assured our design goal of producing a mechanically sound vehicle. Figure 2 is an exploded isometric view of the vehicle showing all major components.

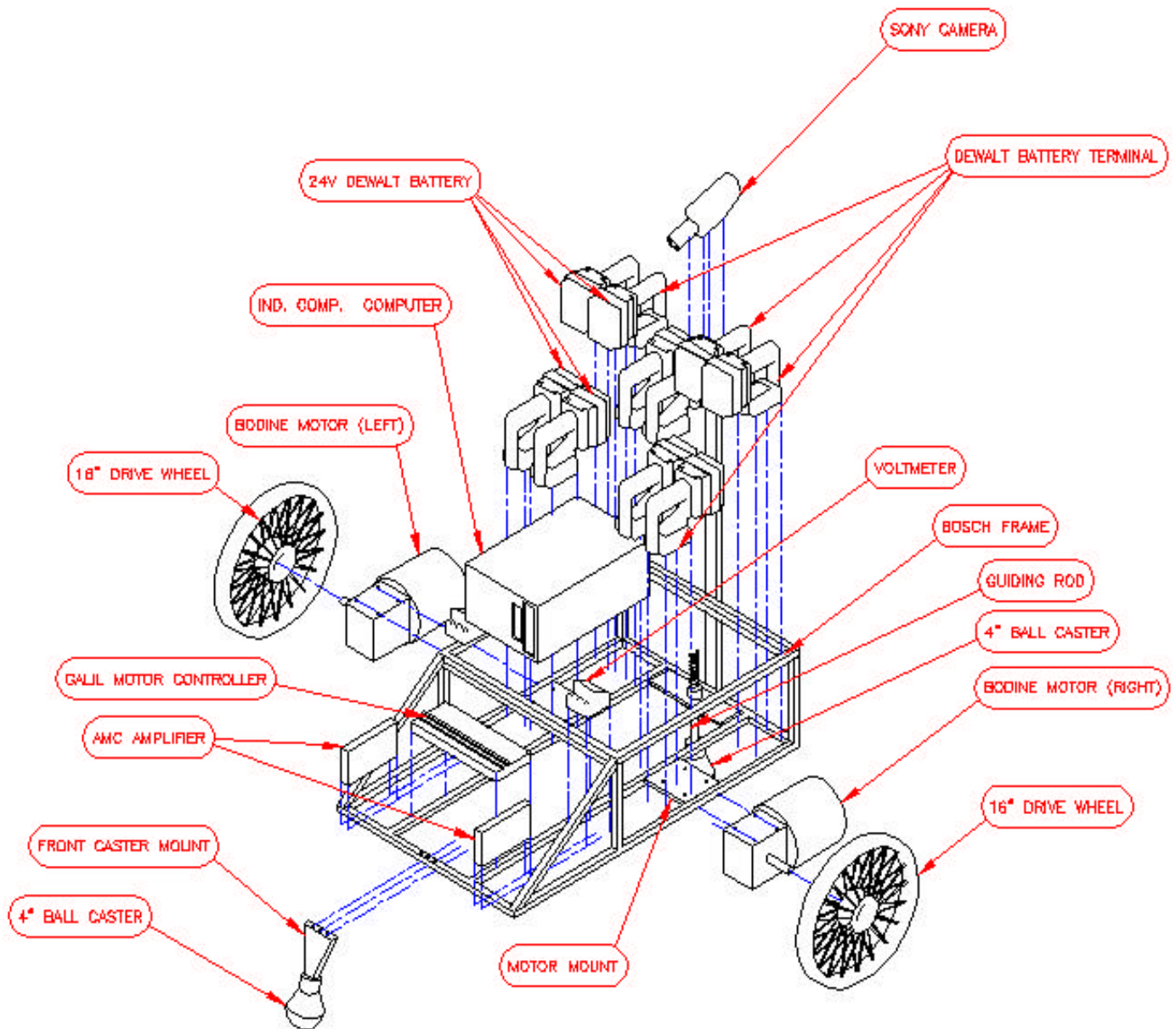


Figure 2: An exploded isometric drawing of Maximus

3. Drive Train

The vehicle employs two Bodine 24 volt DC, 15 amp, 0.45 hp, brush-type servomotors to drive the wheels. Each motor is connected to a 90 degree, 33:1 reduction gear head. The drive shafts are connected to the wheels through custom-made aluminum hubs. The motors include shaft encoders that determine the velocity and position of the wheels for feedback control. The motor configuration allows the trajectory of the vehicle to be controlled differentially rather than using additional steering mechanisms. An important feature of the Bodine motors is an

incorporated fail-safe brake system. When power is being delivered to the motors, the brakes are held disengaged by electromagnets. When the motors are deprived of power, the brakes lock and the vehicle is brought to a rapid, stable stop.

4. Design Innovations

Design innovation helped direct the conceptual fabrication of the new vehicle. From the earliest conceptual designs, the team attempted to employ innovative features. The skeleton frame of the vehicle consists entirely of T-slotted aluminum extruded beams. The modularity of T-slotted aluminum beams played a critical role in the manufacturing adaptability of our vehicle. The frame is lightweight, sturdy, and versatile. The entire assembly is fastened with bolts and stock assembly pieces, assuring easy design upgrades. No permanent features were used (such as welds), emphasizing the flexibility and adaptability of our design. Maximus' frame is shown in Figure 3.

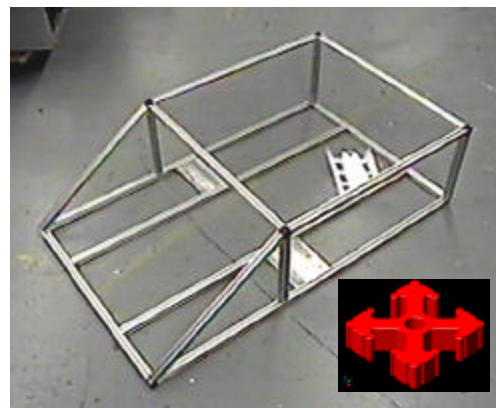


Figure 3. Maximus' frame and a cross-section of aluminum stock (bottom right) shown.

An integral part of the vehicle's design is the location of its center of mass. Ideally, for maximum traction, the center of mass should be located directly over the two drive wheels. With variations in component masses, placing the center of gravity in the ideal position is not easy. To solve this problem, the frame was designed so that counterweights could be moved and locked along frame grooves in exact positions to keep the center of gravity located slightly in front of the drive wheels. The forward biasing keeps the vehicle balanced on the front caster and stable during motion.

Two ball casters serve as secondary supports for the vehicle's frame. Unlike wheel casters, ball casters do not need to be turned to point in the desired direction of motion. This lowers the torque required by each motor to turn the vehicle. As shown in Figure 4, the front ball caster is mounted at a 15° angle from the vertical, which aids in clearing obstacles by exposing more of the ball in the front. The rear ball caster is vertically mounted on a spring-loaded shaft. The rear ball caster is limited to a 2" vertical displacement, allowing the vehicle some flexibility as it traverses rough terrain and low-lying debris. The assembled frame, from MDT, is shown in Figure 5.

It is important to emphasize that Maximus is a two-wheeled vehicle, and that the ball casters serve only as transient contact supports for the frame. When Maximus first contacts a ramp edge or a discontinuity in the terrain, a moment is created that shifts the weight of the vehicle from the front to the back. Maximus' weight distribution is

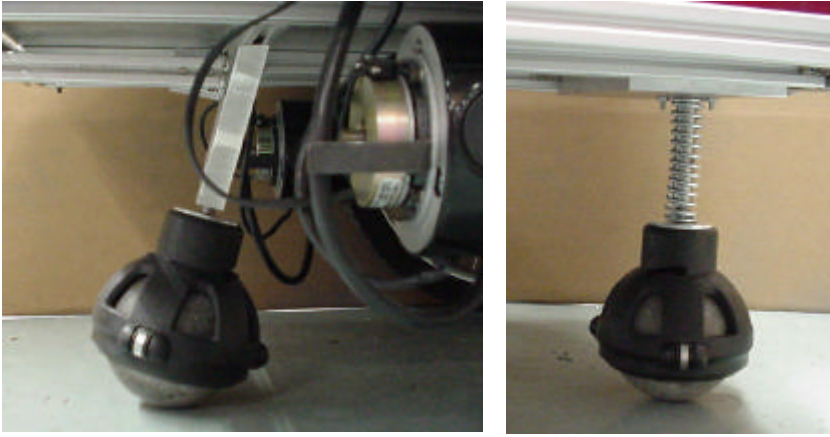


Figure 4. Pictures of the front, angled ball caster (left) and the rear, spring-loaded ball caster (right).

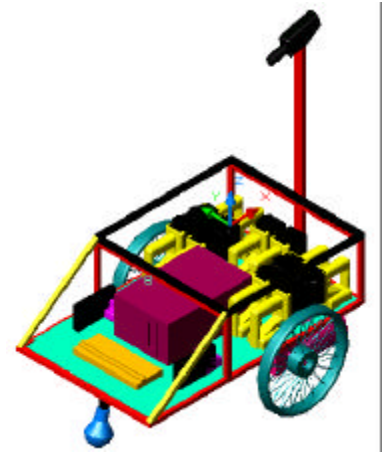


Figure 5. CAD representation of Maximus' overall frame design.

balanced so that such a weight transferal (from front to back) requires a minimal amount of contact force. After Maximus shifts weight, the front ball caster is able to ride over the obstacle. This method of obstacle clearance has been tested and proven in competition preparation.

Another design innovation is the use of “hot-swapped” batteries for continuous vehicle runtime. The use of 24V rechargeable DeWalt NiCd batteries provides a safe, lightweight and compact power source compared to conventional lead acid batteries. This innovative power system gives Maximus a competitive edge since it never has to be shut down during competition. The functionality of “hot-swapping” will be further discussed in section 5.2.

Maximus employs other technological innovations. Wireless ethernet brings many advantages to our new design. Off-board debugging allows the operator to inspect and modify the vehicle's navigation code from a remote location. The wireless network links Maximus to a laptop computer and also to the Internet. It also allows communication with other Virginia Tech vehicles for future applications, such as a convoy run. With the use of wireless ethernet, radio control components and an onboard monitor and keyboard were eliminated, making the vehicle lighter and electronically less complex.

Another innovative design feature of Maximus is that it is designed to be interactive. Using voice recognition software, the vehicle will be able to perform predefined routines from simple voice commands. The vehicle will respond with actions (movement) and explanations (playback recordings through speakers), stimulating interest among spectators regarding this new technology.

5. Electrical System

5.1 Computational Hardware

The onboard industrial PC uses an 800 MHz Pentium III processor with 256 MB memory and runs Windows 98 2nd Ed. The team chose this platform for its proven stability and networking capability. The vehicle also comes equipped with a Cisco Systems Wireless Ethernet card, enabling communication to other vehicles over the Local Area Network.

5.2 Power System

For safety, a low-voltage power source was employed on the vehicle. High-power density, rechargeable 24-volt DeWalt NiCd batteries were used in the power system. A total of ten batteries, six for the two motors and four for the PC, comprise the power system. As depicted in Figure 6, the batteries are connected in parallel to power the two

servo amplifiers, which drive the motors. Power to the PC is provided by the

remaining three batteries, which are also connected in parallel. The innovative “hot-swapping” technique was developed for the PC power. During a “hot-swap,” the user may change the PC power batteries without losing power to the computer system. The batteries are housed in terminal receptacles designed for 24 V DeWalt cordless tools, and each terminal is rated for up to 40 amps of current.

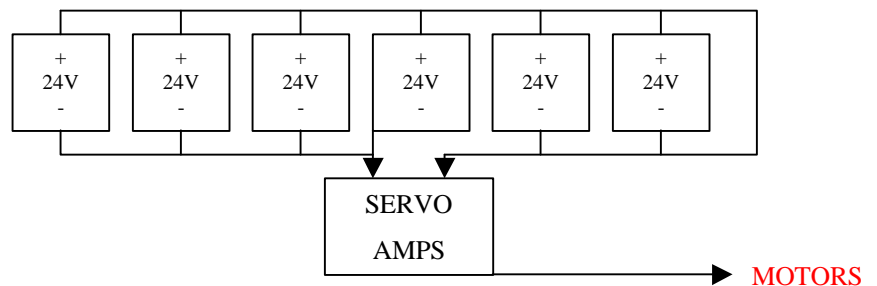
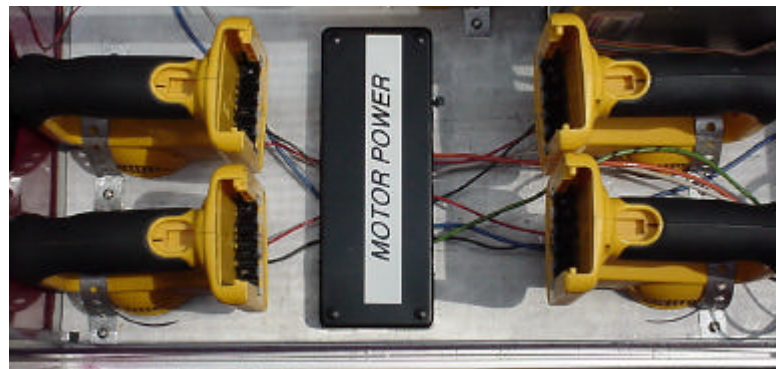
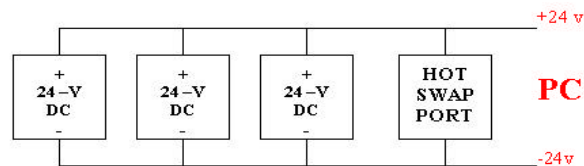
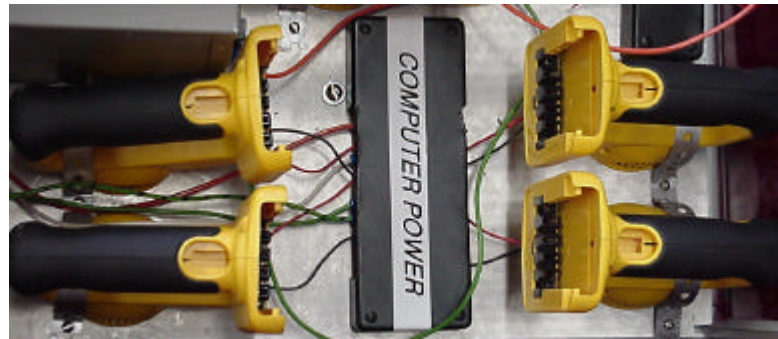


Figure 6. Computer (top) and motor (bottom) power system layouts. DeWalt terminals shown in pictures.

5.3 Control System

Maximus has several levels of control, the first of which is low-level motor control. A Galil DMC-1030 motor controller, internal to the PC, performs low-level motor control. The motor controller performs PID (proportional + integral + derivative) control using encoder feedback while accepting position and velocity commands from the PC. The motor controller outputs a ± 10 -volt signal that is accepted by the DC servo amplifiers, which in turn convert the signal into an amplified PWM (pulse width modulated) signal driving the motors. The flow of information in the control system is shown in Figure 7.

High-level control is performed by the vehicle's navigation manager program installed on the main computer. This program accepts input from the camera and laser range finder or the GPS sensor and decides upon a heading and velocity. This signal is then sent to the motor controller for lower level control of the motors.

The vehicle can be operated remotely by wireless ethernet. Remote mode is accessed with a laptop computer using Symantec's *PC Anywhere* software. The laptop sends commands to the motor controller via wireless ethernet, driving or stopping the vehicle on command. The remote laptop computer can also execute an emergency stop which disables motor power and allows a set of fail safe brakes to engage.

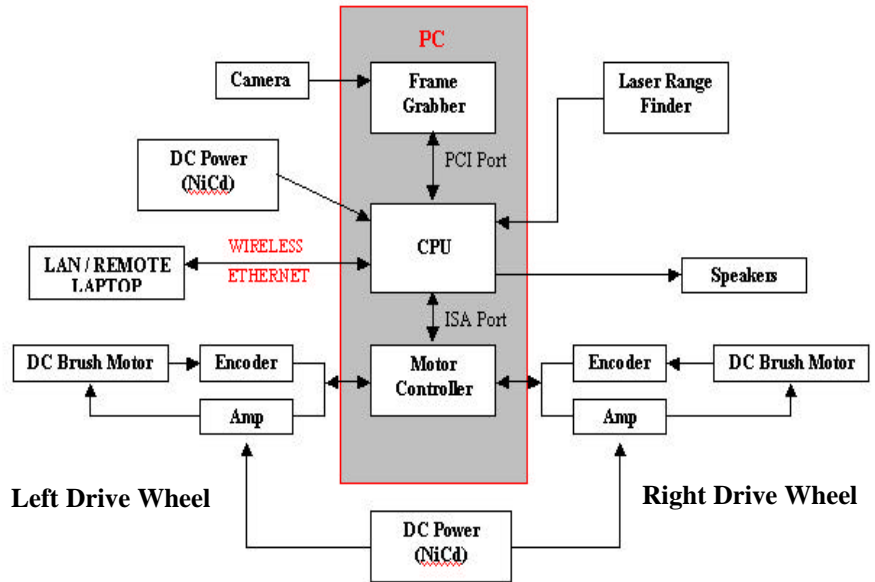


Figure 7. Functional layout of control system components

5.4 Sensors

The sensors incorporated on the vehicle are a Canon ES55 8mm camcorder, a Sick laser range finder, a microphone, and a GPS system. Video camera images are converted to digital format by an Imagination frame grabber, and the images are then sent to the navigation manager for interpretation. The frame grabber converts camera images into lines of pixels, and the onboard PC thresholds and process the image to distinguish bright colors (like the white or yellow boundary lines) from darker colors (such as dirt or grass). A Sick LMS-100 laser range finder interfaces to the PC through an RS-232 serial port. The range finder scans a 180° plane in front of the vehicle to detect obstacles. The information from this device along with camera data is sent to *Navigation Manager*, the vehicle's navigation algorithm, for interpretation. In making Maximus interactive, a remote microphone located on a laptop computer will use voice recognition software to send commands through the wireless ethernet connection to the vehicle for motor control. From voice commands, *Navigation Manager* interprets whether to execute motion commands or to provide auditory information through the speakers. The auditory response will include a description of the vehicle and the vehicle's name.

6 . Software

6.1 Software Design Goals

In choosing navigation software, modularity and proven functionality were important characteristics. Fortunately, a proven base software program written by the previous year's autonomous vehicle team was available. This piece of software, *Navigation Manager*, was designed for modularity and upgradability. *Navigation Manager* contained all the important user interface features and functional elements needed for Maximus. Software modifications were needed to accommodate communication with the Galil motor controller and to change the vision system input from two cameras to (used by last year's team) to a single high mounted camera.

6.2 Software Operation and Navigation

Navigation Manager is written in Visual C++ under Windows 98. The program employs the use of graphical user interfaces (GUI's) to communicate information such as motor speeds and parameter plots. Data can be saved for later review in simulation mode or it can be used to generate a global map for the additional dead-reckoning control algorithm. Similar GUI's used in the previous vehicle were used on this vehicle. *Navigation Manager* has been modified to fit Maximus' parameters, including basic camera location and output signals to the

motors. *Navigation Manager's* coded modularity made the programming change from Navigator to Maximus relatively simple. A typical view of the graphical interface of *Navigation Manager* is shown in Figure 8.

Inputs to *Navigation Manager* come from the laser range finder, the camera (via the frame grabber), the GPS system (during the GPS competition), and from the motor encoder feedback. All information is collected and translated into a vector field histogram, which is a graphical representation of the course ahead of Maximus. If a line, pothole, or obstacle is detected, the polar location and distance are used to calculate the obstacle density. A composite vector field histogram for both the laser range finder and camera data is created, using the maximum obstacle density at a given angle. *Navigation Manager* then selects the best path from the given data. Figure 9 shows a screen shot of *Navigation Manager* with the fused sensor data displayed.

If a valid path is not detected, the vehicle pauses for a short period of time in case of momentary problems caused by sensor noise. If the path is still blocked after this delay, *Navigation Manager* recognizes a trap situation and implements a trap escape algorithm. The program analyzes the data further for a recognized trap condition, and then steers the vehicle accordingly until the vehicle escapes.

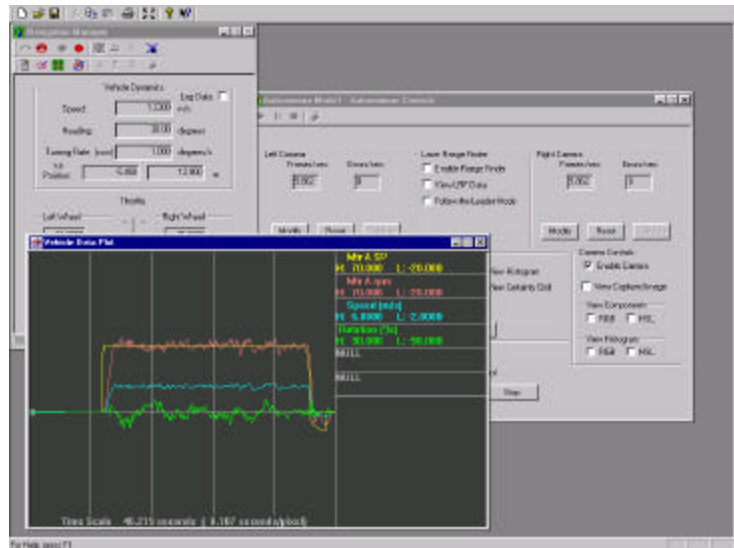


Figure 8. *Navigation Manager* screen shot

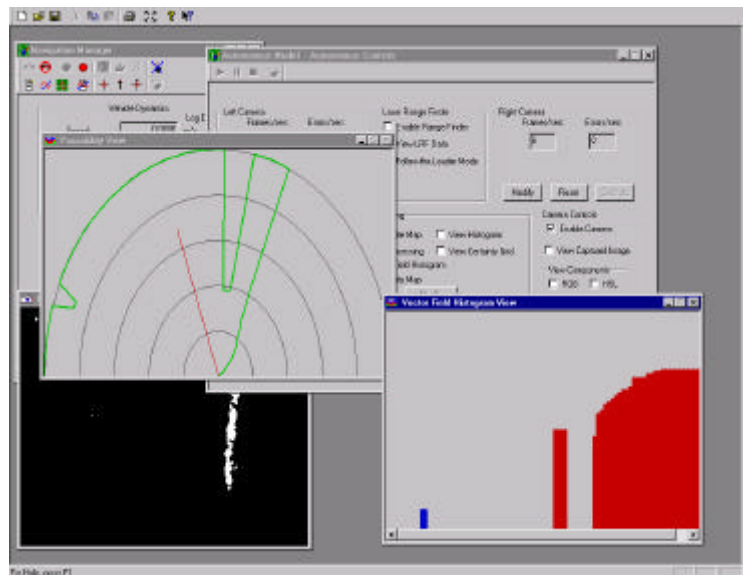


Figure 9. *Navigation Manager* with navigation data shown

7 . Predicted Performance of the Vehicle

7.1 Speed

The maximum speed of the vehicle, 5.24 ft/sec (3.57 mph), was determined from the maximum speed of the Bodine gear motors and the drive-wheel radius. Specifically, the limiting characteristic of the motors is a maximum speed of 75 RPM for a 24 V input. With a wheel diameter of 16", the maximum velocity of the vehicle on level ground is 3.57 mph. On a downward slope, the maximum speed of the vehicle is limited by the gears and motor controller to 3.57 mph.

7.2 Ramp Climbing Ability

The ramp to be used in the IGV Competition has an 8.5-degree incline (15% grade). In reviewing our propulsive needs, however, we chose to evaluate the vehicle on a 15-degree incline. Not only does this guarantee useful acceleration while the vehicle is on the ramp, but it also allows a margin of error for unclassified ramps such as the pits that wheels sit in while driving through sand or grass.

The ability of the vehicle to accelerate up the ramp is limited by the acceleration torque a motor can provide to the vehicle, T_{accel} . On level ground, this torque would be the same as the maximum torque T_{max} of the motor (269 lb-in). On an incline a torque T_{stable} is required to prevent the vehicle from rolling down the incline. The amount of T_{max} not used to provide the stabilizing torque T_{stable} is available to accelerate the vehicle up the ramp, with torque T_{accel} given by

$$T_{\text{accel}} = T_{\text{max}} - T_{\text{stable}} \quad (1)$$

The torque per wheel required to hold the vehicle on the ramp (whether at a stand still or a continuous velocity) is given by

$$T_{\text{stable}} = W * r * \sin(\alpha) / 2 , \quad (2)$$

where α is the incline of the ramp, r is the drive-wheel radius, and W is the weight of the vehicle. In specifying the weight of our vehicle, our team set a design of 150 lb. However, to maintain a margin of safety, the performance of the vehicle was evaluated using a weight of 200 lb. Substituting the numbers into Equation 1 yields a maximum acceleration torque per wheel while on the ramp of $T_{\text{accel}} = 62$ lb-in. This torque translates into an accelerating force along the ramp of $F_{\text{accel}} = 7.75$ lb and an acceleration up the 15 degree ramp of 1.25 ft/sec².

7.3 Reaction Times

Maximus was predicted to have short reaction times. The reaction times of the vehicle were determined by two responses: the ability of the vehicle to accelerate on level ground, and the ability of the vehicle to turn. As each

motor is capable of providing a maximum torque of 269 lb-in, this means 538 lb-in is available for making turns. Since most of the vehicle's mass is close to the axle, almost all of the maximum possible torque is available during a turn. The available 538 lb-in of torque will accelerate the 200 lb vehicle at 10.8 ft/sec^2 to its maximum speed of 5.24 ft/sec. At this acceleration, the vehicle would require 0.5 sec and 1.3 ft to attain its maximum velocity. While this level ground acceleration is not expected to be necessary in the navigation competition, it should be useful in the follow the leader event.

7.4 Distance at Which Obstacles are Detected

Obstacle detection is most important in the navigation competition, although it will play an important role in the follow the leader competition as well. The range of our obstacle-detecting laser range finder is more than sufficient at 75 ft. This allows us to threshold certain distances we would like for making decisions. Our algorithm makes decisions based on obstacles located from the laser range finder up to 15 ft from the vehicle. This forward distance is 150% of the course's width and allows the vehicle ample time to make path corrections.

7.5 Battery Life and Weight Minimization

As mentioned in the Power System section (5.2), Maximus' power supply takes advantage of "hot-swap" ports for the computer and a separate power source for the motors. Under this battery arrangement, we experimentally determined the computer battery life to be 4 hours, and the motor battery life (under normal operating conditions) to be 1 hour. Another advantage of using the rechargeable 24 V batteries is that they each only weigh 3.3 lbs (including the mounting terminal). Although the power density of the DeWalt NiCd batteries is lower than standard lead acid batteries, they are much easier to handle, have one-hour charging times, and can be readily adapted for hot-swapping. The convenience of hot swapping and the fast charge times allowed us to reduce the overall on-board battery weight compared to our previous vehicles.

7.6 Dead Ends, Traps, and Pot Holes

Maximus can handle any terrain laid out according to IGVC rules. As mentioned in section 5.2, Maximus' *Navigation Manager* software recognizes dead end situations and performs a series of predetermined maneuvers to try to escape. In dealing with sand traps, the vehicle has been mechanically designed to be strong enough for rugged maneuvering. Since nearly all the vehicle weight is on the drive wheels, drive traction in sand is excellent. In the detection algorithms, if no distinct line or pothole is picked out against the background, the vehicle continues to drive forward under the assumption it has encountered a sand trap. When the vehicle encounters a pothole, the detection algorithms will recognize it in the same way a line is recognized—as a concentration of intense white

pixels in the captured camera image. The navigation software ignores the darker pixels from a frame grab and uses bright pixels for navigation boundaries. As all potholes at the IGVC this year will be white, this algorithm should provide good pothole avoidance.

7.7 GPS Navigation Course

Maximus incorporates a Motorola Oncore GPS system for the GPS Navigation Course Competition. Relying on GPS velocity data, the vehicle will attempt to steer a velocity heading that is always pointed at the next target on the course. Position data will be used to determine proximity to the target. Once the vehicle is within a predetermined radius of the target, for example one meter, the navigation code will index to look for the next target on the course. Since the score is inversely proportional to distance from the target, the allowable target error will be reduced after each successful run. Our team is working on integrating a GPS code into *Navigation Manager* so that the vehicle can traverse from one waypoint to the next. Since *Navigation Manager* is already based on velocity vectors, integrating a trajectory code should be relatively easy and should further prove the modularity and robustness of the software.

7.8 Follow the Leader

At the start of the follow the leader event, the “leader” must be placed before the vehicle at a distance of 3 ft. At this time, Maximus “acquires” a target using its laser range finder. Once the competition has begun, the follow the leader algorithm looks for a target in closest vicinity to the leader’s previously acquired location. Using a radial map of obstacles detected, Maximus ignores the obstacles while tracking the leader. With re-mapping occurring every 200 ms, the leader is expected not to have moved very far from its previous position, and acquisition of the target leader is expected to be nearly continuous. During competition, Maximus will drive toward the leader while maintaining a set distance between itself and the leader. In the case where the leader accelerates, Maximus will also accelerate to maintain the set distance between the two.

7.9 Detecting Low-Lying Debris

In the event Maximus encounters low-lying debris on the obstacle course, we first hope the low-mounted laser range finder to detect the debris and steer around it. If the laser range finder is unable to detect the debris, then, as long as there is a contrast between the debris and the surrounding playing field, the vision system will detect the change in color intensity and treat the debris as a pothole or obstacle, and thus avoid it. Should both the camera and laser range finder fail, we anticipate Maximus has enough available torque to power through or over the debris.

8 . Other Design Issues

8.1 Safety

Our design team put safety at the utmost importance in all aspects of the design. Some of the safety features include an emergency stop button and fail safe emergency brakes. 24 V rechargeable NiCd batteries are safer and easier to handle as compared to lead acid batteries. The small size and reduced weight of the vehicle also contribute to its overall safety. Furthermore, the faculty advisor and team made safety and safety training the highest priority issues in every aspect of the project, including machine shop fabrication, electronic work and vehicle testing.

8.2 Vehicle Cost

Table 2 shows a comprehensive cost analysis of Maximus.

Table 2. Maximus component cost breakdown

Component	Retail value	Actual cost to the team
Laser Range Finder, Sick Optics	\$5,000	\$2,000
Frame, Bosch Aluminum	\$750	\$750
Caster balls w/ mounts	\$250	\$250
8mm camcorder, Canon ES55	\$300	\$300
Plastic panels for sides of vehicle	\$225	\$225
Velcro for top access hatch	\$30	\$30
Amplifiers for motors, Copley	\$380	\$380
Various electronics supplies	\$80	\$80
Batteries, DeWALT	\$1,500	\$0
Battery handles, DeWALT	\$150	\$0
Computer, Industrial Computers .Com	\$5,000	\$0
Drive motors, Bodine	\$1,500	\$0
Motor controller, Galil	\$2,000	\$0
Total	\$17,165	\$4,015

9. Conclusion

Maximus has been engineered to compete well in all four areas of competition at the IGVC. The vehicle's modular and robust design set high standards for future competitions. Maximus is relatively inexpensive for a research prototype vehicle, and its simple design emphasizes manufacturing ease. Forged in innovation, Maximus integrates the technology of tomorrow for the needs of today.